Evaluating waste incineration as treatment and energy recovery method from an environmental point of view

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During the last 10-20 years, several research groups as well as consultants have been analysing the environmental impacts of incineration in comparison to other waste treatment options. Methods and models for describing these systems have been developed. System studies on local, regional and national level have also been performed using a wide range of different modelling approaches.

This project maps out the above research field in order to gather relevant system studies made on local, regional and national levels in Europe. By thoroughly analysing these studies, this project describes the environmental performance for incineration with energy recovery in comparison with other options for both waste treatment/recovery and energy production. The project focuses on mixed waste and on waste fractions where there has been a lot of controversy whether the material should be recycled, incinerated or treated biologically (e.g. paper, plastics, compostable material).

Furthermore, this project describes the differences between the studies and points out why results differ between the studies. This results in a set of key factors that largely determines the outcome from the studies. Based on these key factors, we discuss and draw conclusions on the environmental benefits and drawbacks from using waste incineration in Europe today and in two alternative scenarios for Europe 2030.
Executive summary

The role of waste incineration in the waste and energy systems is controversial from an environmental point of view. Today there are many research groups, companies, organisations etc which have an opinion on whether waste incineration is a correct solution for the combustible waste or not.

The aim for this project is to map out the research field of environmental systems analysis of waste management in order to gather relevant system studies made on local, regional and national levels in Europe. By thoroughly analysing these studies, this project describes the environmental performance for incineration with energy recovery in comparison with other options for both waste treatment/recovery and energy production. The project focuses on mixed waste and on waste fractions where there has been a lot of controversy whether the material should be recycled, incinerated or treated biologically (e.g. paper, plastics, compostable material).

The work has been conducted in separate phases:

Phase 1 Mapping out the research field
We sent out an inquiry regarding relevant studies for the project to our networks of both researchers and consultants worldwide and to other relevant organisations such as FEAD and ISWA. In total, around 150 persons active in the waste management field in Europe, as researchers, consultants or practitioners, have received this inquiry. We have performed searches in data bases for peer-reviewed papers and other relevant reports. In total, this mapping generated around 70 studies, which we found relevant for the work. Out of these studies, we made a selection of 31 case studies based on a set of criteria for the relevance for this project.

Phase 2 Brief examination
The 31 case studies were examined and the main conclusions were summarised. Based on this examination, we selected 12 case studies for a detailed examination.

Phase 3 Detailed examination
The 12 case studies were examined in detail and the environmental impacts results were summarised in colour-coded tables.

Phase 4 Identification of key factors
This phase was mainly performed using two sources: a) the systems analyses in phase 3, and b) so called key factor studies, where other researchers have drawn general conclusions on important parameters for the choice of waste treatment method. The key factor studies were based on reviews of earlier studies and are focused either on separate waste fractions (e.g. paper) or on mixed waste such as MSW.

Phase 5 Scenario analysis
Based on a selection of the key factors in phase 4, the environmental role of waste incineration in comparison with other treatment methods was then discussed for Europe today and for two alternative scenarios 2030.
Results and conclusions

Main conclusions

- Landfilling is the main treatment option in Europe. It is also clearly the worst environmental option according to the system studies.

- Material recycling, waste incineration and biological treatment are complementary options that all need to be expanded in order to replace landfilling.

- To reach the best environmental results for material recycling and biological treatment of organic combustible material, waste incineration is necessary for treating residues arising during pre-treatment and processing at the material recycling facilities and the biological treatment plants.

- Due to different local conditions and opportunities for development, the distribution of waste being treated by material recycling, waste incineration and biological treatment must be allowed to vary.

- Regional differences will lead to different distributions being optimal for different regions in Europe.

Brief examination of 31 case studies

- Material recycling and biological treatment are normally compared with incineration for separate fractions. Very few studies examine how all parts of the mixed waste should be treated if incineration is replaced. Although material recycling and biological treatment could lead to lower impacts for the separate fractions, it is not obvious that the total environmental impact for mixed waste would be lower than for incineration, if the fractions that cannot be recycled or treated biologically must be landfilled.

- For well source-separated and clean material fractions, material recycling generally leads to lower environmental impacts than incineration. For biodegradable waste, the choice between incineration, composting and anaerobic digestion is not obvious. Landfilling is the worst option in almost all studies.

Detailed examination of 12 case studies

In the report, we have summarised results regarding the environmental impacts of incineration with energy recovery in comparison with other treatment options. We have limited the comparison to the impact categories GWP, acidification, eutrophication, photooxidants and toxicity (human, aquatic, terrestrial etc.) as the majority of the 12 studies covered these. The results are shown in colour-coded tables in the report. One of these 12 tables is shown here in order to illustrate how these results are presented. The table selected compares incineration with composting, see table 1. Green colour means that incineration is the best alternative; red means the opposite and yellow means that the difference is small. All references are numbered and can be found in Appendix A.
Table 1 Results from the detailed examination of the 12 case studies. Incineration versus composting

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photooxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Food waste</td>
<td>Composting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Easily bio-degradable</td>
<td>Composting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Food waste</td>
<td>Composting base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Composting Natural gas ¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Composting GWP, 20 yr ²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Composting GWP, 500 yr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ In the base scenario, biomass is the alternative fuel for district heating. Here, natural gas is the alternative.
² In the base scenario, GWP factors for 100 years are used

Table 1 is needed to understand the results in figure 1 (see next page), where we have here summarised the results from all tables. The results from table 1 are found in the middle of figure 1 under the headline “Incineration versus composting”.

From this examination, we have drawn the following conclusions:

- The outcomes in all studies are sensitive to key factors. Although they do not always change the environmental ranking between two treatment options, they certainly affect the differences in environmental impact between the options.

- Material recycling generally leads to lower environmental impact than incineration. However, this conclusion is valid only if the material recycling is based on well source-separated and clean material fractions that can be efficiently recycled and replace virgin production of the original product. Nevertheless, for some paper products incineration could lead to lower environmental impact regarding GWP, photooxidants and toxicity. The same goes for eutrophication and toxicity in the case of plastics.

- For easily biodegradable waste, the differences between waste incineration and anaerobic digestion are small for the studied impact categories. Regarding acidification and eutrophication, anaerobic digestion might be the better alternative according to the results of these studies. For toxicity, an advantage for incineration could be observed.

- In comparison to composting of easily biodegradable waste, waste incineration is generally preferable in the studies regarding GWP, acidification, and photooxidants. For eutrophication, composting is a better alternative in the studies.

- With few exceptions, incineration leads to a lower environmental impact than landfilling in all the examined studies.
Figure 1 Results from the detailed examination of the 12 case studies

Ideal conditions are assumed for most of the material recycling in the studies. This means that the fractions are clean and completely separate and used for replacing virgin production of the same material.

- Incineration is the best alternative [lowest environmental impact].
- Incineration is not best alternative.
- The difference between incineration and the alternative is small.
Identification of key factors
In tables 2-7, we present the key factors that we have identified. When evaluating the results from a systems analysis, it is essential to examine how these key factors have been handled. They can change the environmental ranking between treatment options for one or more environmental impacts and they do affect the differences in environmental impact between the options.

Table 2 Key factors of general importance for the environmental ranking of treatment methods

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time perspective</td>
<td>Important underlying condition. Affects assumptions on all data in the waste management systems, as well as in the surrounding systems and the modelling of the systems.</td>
</tr>
<tr>
<td>Technology development</td>
<td>Assumptions, based e.g. on promising results from pilot plants, can crucially improve the efficiency of the technologies both regarding emissions and the quality and amount of the end products.</td>
</tr>
<tr>
<td>Local conditions</td>
<td>Can strongly affect the environmental value of different treatment options. For example, in the case of incineration, the existence of a district heating system enables a higher energy recovery.</td>
</tr>
<tr>
<td>Alternative electricity and heat generation</td>
<td>Decisive for avoided emissions due to energy recovery (incineration) or energy savings (recycling). The assumptions in the studies range from use of fossil fuels (predominantly coal or natural gas) to renewable fuels (solid biofuels or wind).</td>
</tr>
<tr>
<td>Renewable energy supply in Europe</td>
<td>Important for the assumptions on alternative electricity and heat generation, especially for results regarding GWP.</td>
</tr>
<tr>
<td>Waste transports by passenger car</td>
<td>Important when a large fraction of the waste is transported by passenger car for one treatment option, but not for the other.</td>
</tr>
</tbody>
</table>

Table 3 Key factors for the environmental ranking of waste incineration

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission level</td>
<td>Mainly dependent on the waste incinerated, the waste incineration technology and the flue-gas treatment. The lower, the better the environmental performance of incineration.</td>
</tr>
<tr>
<td>Energy recovery</td>
<td>The larger, more avoided emissions from alternative electricity and heat generation.</td>
</tr>
<tr>
<td>Time perspective and fate of landfilled residue</td>
<td>No general agreement on the time perspective that should be used on modelling of landfills. The stabilisation method of fly ashes and the time perspective used are crucial for the modelling of the environmental impact of landfilled residues from incineration.</td>
</tr>
</tbody>
</table>
Table 4 Key factors of importance for the environmental ranking of material recycling when compared with incineration

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market/demand for recycled material</td>
<td>Important for the environmental benefits of material recycling. Ideally, the recycled material should replace virgin material for the same product.</td>
</tr>
<tr>
<td>Substitution factor</td>
<td>Important for the environmental benefits of material recycling. If some of the recycled material cannot be used due to qualitative reasons, this will lead to a lower substitution factor. In effect, more recycled material must then be used to replace a certain amount of virgin material.</td>
</tr>
<tr>
<td>Energy consumption and emissions at material production from virgin and from recycled materials</td>
<td>The larger the reduction of energy consumption and emissions through recycling, the better the environmental performance of material recycling compared to incineration.</td>
</tr>
<tr>
<td>Fate of saved biomass in the forest (paper and cardboard recycling)</td>
<td>The fate of biomass that is saved due to less virgin production can be different: it can be left in the forest, it can be cut down and used for other material production, or it can be used for energy production, thus replacing alternative electricity and/or heat generation. Depending on the choice made, the environmental performance of material recycling in comparison with incineration is clearly affected.</td>
</tr>
</tbody>
</table>

Table 5 Key factors of importance for the environmental ranking of biological treatment (anaerobic digestion, composting) when compared with incineration

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission level</td>
<td>Important at the treatment processes, but also at the refining/distribution of biogas (anaerobic digestion) and at spreading of digestion residue/compost</td>
</tr>
<tr>
<td>Market/demand for digestion residue/compost</td>
<td>Only when there is a demand from the farmers to use digestion residue/compost is it possible to close the loop for recycling of the nutrients in the waste, leading to replacement of other fertilizer production. When there is no market/demand, the digestion residue/compost must be used for other purposes (e.g. land reclamation or as a top layer when old landfills are covered), where the environmental benefits are much smaller.</td>
</tr>
<tr>
<td>Topsoil value of digestion residue/compost</td>
<td>Can improve the environmental benefits of biological treatment in European regions where the topsoil layer is very thin at agricultural production.</td>
</tr>
</tbody>
</table>

Table 6 Key factors of importance for the environmental ranking of using waste fuels in cement kiln/power plant when compared with incineration

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission level at combustion of waste (fuel)</td>
<td>Mainly dependent on the waste incinerated, the waste combustion technology and the flue-gas treatment. The lower, the better the environmental performance of co-combustion.</td>
</tr>
<tr>
<td>Alternative fuel used in cement kiln/power plant</td>
<td>Normally use of fossil fuels associated with large environmental impact are reduced when waste (fuel) are utilised.</td>
</tr>
</tbody>
</table>
**Table 7 Key factors of importance for the environmental ranking of landfilling when compared with incineration**

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>The modelling of the landfill (time frame)</td>
<td>Modelling of landfills is generally more difficult and uncertain compared to modelling of other treatment options. Furthermore, there is no general agreement on the time perspective that should be used on modelling of landfills. The longer time frame, the larger the emissions to the environment.</td>
</tr>
<tr>
<td>Mechanical-biological pre-treatment</td>
<td>This clearly reduces the possible future emissions from the landfill, e.g. the methane formation is significantly reduced.</td>
</tr>
<tr>
<td>Carbon sink</td>
<td>Of interest when a short time frame is chosen and renewable materials (e.g. paper, wood) are considered. The cellulose, hemicellulose and lignin in these waste fractions are only partly degraded. The rest of the carbon is thus “stored” in the landfill. In comparison with incineration, where the carbon directly is oxidised to CO2, this means that CO2-emissions are avoided during the short time frame. This could change the order between landfilling and incineration from a GWP perspective.</td>
</tr>
</tbody>
</table>

**Scenario analysis**

The environmental performance of waste incineration in comparison other treatment options is discussed for Europe today and in two scenarios for 2030.

Scenario 1 - Greenhouse gases of large importance - means an increased pressure for reduction of greenhouse gases compared to today.

Scenario 2 - Greenhouse gases of less importance - means the opposite, i.e. that the reduction of greenhouse gases would become of lower environmental priority than today. However, in scenario 2 the reduction of greenhouse gas emissions is not totally abandoned and remains a pressing issue.

In both scenarios, we can observe a development towards higher energy recovery than today, which improves the environmental performance of waste incineration. Waste incineration is an important option that should be expanded together with material recycling and biological treatment in order to reduce landfilling. After waste prevention and re-use, it is clear that a combined strategy of material recycling, waste incineration and biological treatment replacing landfilling of organic combustible waste, would be the most efficient way to reduce the environmental impact from waste management. The distribution of waste being treated by material recycling, waste incineration and biological treatment will vary and should not be decided on a common European level. Regional differences will lead to different distributions being optimal for different regions.
Preface
This study was conducted under commission of CEWEP (Confederation of European Waste-to-Energy Plants) during the spring 2004.

The project group at Profu consisted of the following persons: Johan Sundberg, Mattias Olofsson and Jenny Sahlin. Beside their work at Profu, all three are active as researchers in the Waste Management Group at the Department of Energy Technology, Chalmers University of Technology, Sweden.
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1. **Introduction**

The role of waste incineration in the waste and energy systems is controversial from an environmental point of view. Today there are many research groups, companies, organisations etc., which have an opinion on whether waste incineration is a correct solution for the combustible waste or not. During the last 10-20 years, several research groups as well as consultants have been analysing the environmental impacts of incineration in comparison to other waste treatment options. Methods and models for describing these systems have been developed. System studies on local, regional and national level have also been performed using a wide range of different modelling approaches. Results and suggestions of improvements have been presented. The most commonly used approach for the studies is LCA (Life Cycle Assessment) or LCA inspired techniques for describing the total environmental impact. However, there are also other types of approaches, e.g. cost-benefit analyses.

Results from the system studies vary, although thoroughly done and considered objective. While many case studies indicate that incineration is an important option for reducing a number of pollutants and solves other goals (e.g. reducing the needs for landfills), others show the opposite. There are obviously differences in the input to these studies (data, system boundaries, methods etc), which can explain the differences in the final results. Unfortunately, it is not an easy task to make these results transparent since they cover large technical systems such as waste management systems, energy systems (both electricity and heat) and material recovery systems.

**Aim and scope**

To present objective facts about the total environmental impact from waste-to-energy plants is of large interest, especially when we consider the ongoing work “Towards a thematic strategy on the prevention and recycling of waste” within the European Commission. The aim for this project is to map out the above research fields in order to gather relevant system studies that have been made on local, regional and national levels in Europe. By thoroughly analysing these studies, this project describes the environmental performance of incineration with energy recovery in comparison with other options for both waste treatment/recovery and energy production. Furthermore, this project describes the differences between the studies and points out why results differ between the studies. This results in a set of key factors that largely determines the outcome from the studies. Based on these key factors, we discuss and draw conclusions on the environmental benefits and drawbacks from using waste incineration in Europe today and in two alternative scenarios for Europe 2030.

This study is limited to environmental impacts of waste incineration in comparison to other treatment options. The economic consequences for different options are outside the scope of the study.

The aspect that waste incineration plants can function as pollutants sink, removing pollutants such as e.g. mercury from exposure to humans, is implicitly included in all
studies since they consider the flue gas cleaning. However, the studies have not been extracted with a focus on this benefit.

Regarding waste-to-energy technologies, there are many possible concepts. In this report, the focus is on waste incineration with energy recovery. The waste fractions are combusted in a grate or fluidised bed and the plants specifically erected with the main purpose of treating the waste. Throughout this report, all incineration is assumed to be conducted with energy recovery, i.e. incineration with no energy recovery where the sole purpose is destruction of the waste is not included.

Other waste-to-energy technologies are included in the report, but they are not studied as extensively as waste incineration. These technologies include RDF-production and subsequent combustion of the RDF, feedstock recycling using gasification and a blast furnace, and co-combustion of waste fuels with other fuels in cement kilns and power plants. In chapter 3.2, waste incineration is compared with these technologies in a few studies. In chapter 3.3, we illustrate the main key factors affecting the environmental performance of waste incineration in comparison with co-combustion of waste fuels with other fuels in cement kilns and power plants.

**Outline**

Chapter 2 describes the methodology in the project. This includes e.g. the gathering of relevant data and the selection of studies included. Chapter 3 presents the results from the studies, and key factors for the results are identified. Chapter 4 discusses the results from a European perspective and we draw general conclusions on the environmental performance of waste incineration in comparison to other waste treatment options.
2. **Methodology**

2.1 **General**

This work is mainly a meta-study based on earlier performed systems analyses of waste management, where incineration with energy recovery has been at least one out of two or more options. By analysing earlier studies, we identify key factors for the results and draw conclusions on the environmental performance of incineration in comparison with other waste treatment options.

When doing the meta-study, it is essential to thoroughly map out the research field and the studies conducted. We have done this through different approaches:

- As researchers and consultants, we have performed a large number of systems analyses of waste management. Beside the experiences and insights gained from the work, we have established extensive networks of both researchers and consultants worldwide, which we have contacted for this work.

- We have performed searches in databases for peer-reviewed papers and other relevant reports.

- We have sent out an inquiry to members of various organisations, apart from CEWEP, regarding relevant studies for the project; FEAD (European Federation of waste management and Environmental Services), and ISWA (International Solid Waste Association). This inquiry has been sent to the International Expert Group on Waste Management, the Joint Research Center Institute for Environment and Sustainability (IES) and participants of the international workshops “Systems Engineering Models for Waste Management” (Gothenburg, 1998), “Workshop on System Studies of Integrated Solid Waste Management” (Stockholm, 2001) and “Integrated Waste Management & Life Cycle Assessment Workshop and Conference” Prague, 2004). In total, approximately 150 persons active in the waste management field in Europe, as researchers, consultants or practitioners, have received this inquiry.

This mapping encompasses roughly 70 studies, which we found relevant to consider for this project. Sections 2.2 and 2.3 describe the further division of the studies.

2.2 **Studies included in the analysis**

Out of the around 70 studies, we chose 31 case studies for a brief examination. We chose the studies based on their relevance for this project:

- In all studies, waste incineration have been evaluated from an environmental perspective as one of two or more options for treatment of mixed waste or certain waste fractions, e.g. packaging, paper or plastic waste.

- The studies picked ensured a good geographical coverage, thus capturing discrepancies between the conditions in different European countries.
Furthermore, only studies published after 1995 have been considered. The studies are listed in Appendix A.

Out of these 31, we selected 12 for a detailed examination (see table 2.1).

*Table 2.1 Case studies included for a detailed examination. The number refers to the number in Appendix A, where the full references are written.*

<table>
<thead>
<tr>
<th>Nr</th>
<th>Country/region</th>
<th>Name of the study</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Austria</td>
<td>Comparison of ecological effects and costs of communal waste management systems</td>
</tr>
<tr>
<td>2</td>
<td>Austria</td>
<td>Stoffliche Verwertung von Nichtverpackungs-kunststoffabfällen. Kosten-Nutzen-Analyse von Maßnahmen auf dem Weg zur Realisierung einer umfassenden Stoffbewirtschaftung von Kunststoffabfällen (in German)</td>
</tr>
<tr>
<td>5</td>
<td>Denmark</td>
<td>Madavfall fra storkøkkener (Waste food from catering canters) (in Danish)</td>
</tr>
<tr>
<td>8</td>
<td>Europe (EU-15)</td>
<td>Waste management options and climate change. Final report to the European Commission</td>
</tr>
<tr>
<td>11</td>
<td>France</td>
<td>Analysis of technical and environmental parameters for waste-to-energy and recycling: household waste case study</td>
</tr>
<tr>
<td>13</td>
<td>Germany</td>
<td>Comparison of plastic packaging waste management options – Feedstock recycling versus energy recovery in Germany</td>
</tr>
<tr>
<td>14</td>
<td>Germany</td>
<td>Grundlagen für eine ökologisch und ökonomisch sinnvolle Verwertung von Verkaufsverpackungen (Bases for an ecologically and economically reasonable recycling of sales packaging) (In German)</td>
</tr>
<tr>
<td>18</td>
<td>Italy</td>
<td>The environmental performance of alternative solid waste management options: a life cycle assessment study</td>
</tr>
<tr>
<td>20</td>
<td>Italy</td>
<td>Life cycle assessment of a plastic packaging recycling system</td>
</tr>
<tr>
<td>23</td>
<td>Sweden</td>
<td>Hur skall hushållsavfallet tas omhand? Utvärdering av olika behandlingsmetoder. (How should the household waste be treated? Evaluation of various treatment methods.) (in Swedish)</td>
</tr>
<tr>
<td>25</td>
<td>Sweden</td>
<td>Life Cycle Assessment of Energy from Solid Waste – Part 1: General Methodology and Results</td>
</tr>
<tr>
<td>28</td>
<td>Switzerland</td>
<td>Ecology, which technologies perform best?</td>
</tr>
</tbody>
</table>

We used the following criteria for the selection:

- Transparency and data availability must be high
- The study must be financed by a “neutral” player such as the EU, governments and/or national environmental agencies or authorities. If not, the study must be peer-reviewed in order to be included.
- Geographical discrepancies, e.g. regarding the infrastructure for waste management and energy supply, must be covered.
- As many waste fractions as possible should be included. However, we have also included studies only focusing of parts of the waste, e.g. packaging, food waste and paper.
- The number of environmental impact categories should be high. However, a few studies with only a limited amount of environmental impacts studied have also been included.
Beside the case studies, we have also included a number of papers, reports etc, where general key factors affecting the choice between different waste treatment options have been discussed. The majority of the studies are meta studies, where the authors base their conclusions on overviews of earlier case studies. In Appendix B, we have listed these key factor studies.

2.3 Other studies

During this process, we have received a significant amount of interesting and relevant studies from various contact resources. Although they were not included in the selected studies above, they have given us valuable information and input to our study. We have listed these studies in Appendix C.
3. Results from system analyses

3.1 Brief examination of 31 case studies

In this project, we have completed a brief examination of 31 studies, which we believe provide a good overview of systems analyses of waste management for different European conditions. In Appendix D, we have summarised what waste fractions, environmental impact categories and treatment options were included in these studies. Furthermore, we have also included the main conclusions drawn in these studies.

When only making a brief examination of systems analysis study, it is difficult to form conclusions on the importance of e.g. the quality of the input data, the system boundaries chosen and the modelling of different waste treatment options. For this, a detailed examination is necessary, which we have performed with 12 studies in chapter 3.2. However, we have concluded some general observations based on the brief examination:

- On the choice of environmental impact categories, almost all studies included both GWP and energy use. This probably illustrates the importance of the enhanced greenhouse gas effect. Other impact categories that can be found in many studies are acidification and eutrophication and (to a lesser extent) toxicological impacts on nature and humans. Some studies have weighted the environmental impact into a total environmental cost or benefit that is also compared.

- The majority of the studies concentrates on separate fractions of the waste, e.g. food waste, paper, plastic, metals etc., but also studies including treatment of mixed waste (e.g. MSW) are included. Material recycling and biological treatment are normally compared with incineration for separate fractions. Very few studies examine how all parts of the mixed waste should be treated if incineration is replaced. This is mainly done for landfilling and RDF-production with subsequent energy recovery in cement kilns or power plants. Although material recycling and biological treatment could lead to lower impacts for the separate fractions, it is not obvious that the total environmental impact for mixed waste would be lower than for incineration, if the fractions that cannot be recycled or treated biologically must be landfilled.

- Regarding the main conclusions of these studies, we have made the observations that for well source-separated and clean material fractions, material recycling generally leads to lower environmental impacts than incineration. For organic waste, the choice between incineration, composting and anaerobic digestion is not obvious. Landfilling is the worst option in almost all studies.
3.2 Detailed examination of 12 case studies

In the following tables, we have summarised results regarding the environmental impacts of incineration with energy recovery in comparison with other treatment options. We have limited the comparison to the impact categories GWP, acidification, eutrophication, photooxidants and toxicity (human, aquatic, terrestrial etc.) as these are covered by most studies.

The other impact categories or emissions included in the studies can be found in appendix D, but are not compared or included here. For example, we have included a study that records the impacts of dioxins in appendix D. The emission levels of dioxins are often discussed in connection with waste incineration. Dioxins were only included in one study and are thus not included in the summary below. All studies do not include the same emissions in each impact category. This is marked in the tables below, as it has been defined in the studies.

The tables are numbered as follows:

3.1 Incineration with energy recovery in comparison with material recycling; mixed waste
3.2 Incineration with energy recovery in comparison with material recycling
   Studies only including separate fractions: paper, cardboard etc.
3.3 Incineration with energy recovery in comparison with material recycling
   Studies only including separate fractions: plastics
3.4 Incineration with energy recovery in comparison with anaerobic digestion
   Studies including biodegradable waste fractions
3.5 Incineration with energy recovery in comparison with composting
   Studies including biodegradable waste fractions
3.6 Incineration with energy recovery in comparison with RDF production followed by incineration
3.7 Incineration with energy recovery in comparison with incineration with heavy metal recovery.
3.8 Incineration with energy recovery in comparison with feedstock recycling
3.9 Incineration with energy recovery in comparison with landfiling
   Studies including mixed waste
3.10 Incineration with energy recovery in comparison with landfiling
   Studies only including separate fractions: plastics
3.11 Incineration with energy recovery in comparison with landfiling
   Studies only including separate fractions: paper, cardboard etc.
3.12 Incineration with energy recovery in comparison with landfiling
   Studies only including separate fractions: food waste

The summary is coded by colours with the following meaning:

<table>
<thead>
<tr>
<th>Colour</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>Incineration show lower emissions/lower environmental impact than the alternative treatment method</td>
</tr>
<tr>
<td>Yellow</td>
<td>The difference between incineration and the alternative treatment method is small</td>
</tr>
<tr>
<td>Red</td>
<td>Incineration show higher emissions/lower environmental impact than the alternative treatment method</td>
</tr>
</tbody>
</table>

By studying the dominating colour in each table, the idea is to give the reader an impression whether or not waste incineration is a better or worse treatment option.
than the alternative treatment option in each table. However, conclusions should be
drawn with care, as each study includes specific assumptions and limitations that
affect the environmental results.

Therefore, before moving on to the environmental results of specific studies, some
comments on the uncertainties are necessary. In such comprehensive studies as the
studies below, various types of uncertainties appear and have to be taken into
consideration when evaluating the results and before drawing conclusions. Some of
the most frequent uncertainties are: data gaps, uncertainties based on
methodological issues, weighting uncertainties and uncertainties of the performance
of new technologies.

In the case of gaps in input data e.g. on the composition of the waste to be treated,
the studies have made assumptions based on other studies, earlier experiences or
similar. Unless these assumptions had a key impact on the results, we have not
considered the correctness of such assumptions, and thus we have relied on them to
be valid for the area in focus.

The uncertainties based on methodological issues have been handled at an earlier
stage of this study (see chapter 2.2). Studies where this kind of uncertainty is large
have not been included in the studies below except for one special case. In the
special case, this type of uncertainty is exemplified with three different methods for
evaluation of the toxic effects of some emissions. The different methods resulted in
different rankings between the waste treatment methods.

Some studies use weighting methods in order to group the emissions with the same
type of effect. This is the case when i.e. expressing total greenhouse gases as CO2-
equivalents etc. We have not studied the used weighting methods, since they have
been developed through extensive international research, and therefore we rely on
how they have been used in the studies.

The new waste treatment methods evaluated are normally not proven with reference
to emission data or operational reliability to the same extent as the existing
technologies. This is normally commented and taken into account in the evaluated
studies, and pointed out in the comments to the tables below.
**Incineration with energy recovery in comparison with material recycling**

When incineration with energy recovery was compared to a combination of material recycling, composting, anaerobic digestion and landfilling, the results were sensitive to the assumption of replaced electricity (see table 3.1). If the energy recovered through incineration of waste was assumed to replace an average mix of electricity produced in the EU, the recycling option was preferred in the impact category **GWP** (the only category included in that study). On the other hand, if electricity from coal was assumed to be replaced instead, incineration with energy recovery led to lower GWP, when all incinerators were operating in CHP mode.

*Table 3.1 Incineration with energy recovery in comparison with material recycling; mixed waste*

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Mixed*</td>
<td>Average EU (electricity)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Coal (electricity)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Incineration of mixed waste is compared to a combination of material recycling, composting, anaerobic digestion and landfilling. The largest amounts of waste goes to material recycling, therefore the alternative is placed in this table.

In the comparison of the environmental effects of incineration with energy recovery or material recycling of various types of waste paper and cardboard results are varying (see tables 3.2a and 3.2b below).

For **GWP** more studies showed an advantage for material recycling than incineration regarding the type of paper or cardboard in focus. The studies that show better performance for incineration with energy recovery than for recycling, comment that the avoided burdens due to the energy recovery are important as well as the energy efficiency of the incineration process. Energy production from natural gas, oil or coal is avoided in these studies.

According to these studies, **acidification** is generally prevented when paper and cardboard is recycled instead of incinerated. This is mainly due to the prevention of emissions of SOx and NOx, when the production from virgin materials is prevented. Study nr 25 did not include SOx and NOx in the total impact on acidification, but did present those emissions separately. The effects of SOx and NOx are therefore not included here.

Regarding **eutrophication** the results show that recycling can be preferred. The study that shows the opposite (for newsprint paper only) does not include emissions of NOX, which could explain this discrepancy.
In the environmental impact category **photooxidants**, these studies show different results and no general conclusions can be drawn.

**Table 3.2a Incineration with energy recovery in comparison with material recycling.**
*Studies only including separate fractions: paper, cardboard etc.*

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Paper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Paper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Paper carton composites</td>
<td>Current technology</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>New technology</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carton for liquids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Paper packaging</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Newspaper</td>
<td>base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Natural gas alt for heat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corrugated cardboard</td>
<td>base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mixed cardboard</td>
<td>base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.2b Incineration with energy recovery in comparison with material recycling**
*Studies only including separate fractions: paper, cardboard etc. Toxicity results for study 25*

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Eco-toxicological effects</th>
<th>Human toxicological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EDIP’ USES min USES max</td>
<td>EDIP USES min USES max</td>
</tr>
<tr>
<td>25, base scenario</td>
<td>Newspaper</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corrugated cardboard</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mixed cardboard</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 SOx and NOx mainly
2 Current sorting/recycling technology (Status Quo)
3 Terrestrial and aquatic
4 New automatic sorting technology (SORTEC)
5 Excl SOx and NOx
6 Aquatic (excl NOx)
7 EDIP Environmental design of Industrial Products
8 USES Uniform system for the Evaluation of Substances (minimum and maximum weights are used in this study, thereby the two cases)
In the category **toxicity** the studies show different results and no general conclusions can be drawn. The toxicity is in one study compared through three different methods (see table 3.2b above), all of which show different results. This is one example of the uncertainties in studies of this kind, when different weighting methods end up at different results.

In the comparison of the environmental effects of incineration with energy recovery or material recycling of various types of waste plastics results are also varying (see tables 3.3a and 3.3b below).

**GWP**: Recycling of plastic is mainly preferred regarding GWP. One study shows the opposite in one scenario, due to the assumption that the plastic recycled does not substitute virgin plastic production but wood.

**Acidification**: The results are not definite but may show that recycling is preferred. However, the results vary with types of plastic compared, but also if SOX and NOX are included or not in the substances causing acidification.

**Eutrophication**: No definite conclusions can be drawn, except that it is important for the results if virgin plastic or wood is assumed to be avoided.

Regarding emissions of **photooxidants**, recycling of plastic is generally preferred.

**Toxicity**: Again the results vary and no definite conclusions can be drawn (see tables 3.3a and 3.3b).
Table 3.3a Incineration with energy recovery in comparison with material recycling
Studies only including separate fractions: plastics

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b</td>
<td>Plastics</td>
<td>Separate collection</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2⁹</td>
<td>Plastics (non-packaging)</td>
<td>Separate collection</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Plastic</td>
<td>Separate collection</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>air</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>Plastic packaging, bulk</td>
<td>Current technology</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>human</td>
</tr>
<tr>
<td></td>
<td>Plastic packaging, small items, small foils, composites</td>
<td>New technology</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>human</td>
</tr>
<tr>
<td>19</td>
<td>Plastics</td>
<td>Separate collection</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23</td>
<td>Plastic pack</td>
<td>Separate collection</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>PE</td>
<td>Base</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>PP</td>
<td>Base</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>PS</td>
<td>Base</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>PET</td>
<td>Base</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>PVC</td>
<td>Base</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Mix of the plastics above</td>
<td>Replacing wood palis.¹³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.3b Incineration with energy recovery in comparison with material recycling
Studies only including separate fractions: plastics. Toxicity results for study 25

<table>
<thead>
<tr>
<th>Ref, base scenario</th>
<th>Waste fractions</th>
<th>Eco-toxicological effects</th>
<th>Human toxicological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EDIP</td>
<td>USES min</td>
</tr>
<tr>
<td>25, base scenario</td>
<td>PE</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PP</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PS</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PET</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PVC</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

⁹ Emission of TOC and primary energy consumption also studied (beneficial for recycling)
¹⁰ Terrestrial (green for aquatic)
¹¹ Excl SOx and NOx
¹² Aquatic (excl NOx)
¹³ Palisades made of recycled, mixed plastics are assumed to replace palisades made from impregnated wood.
Incineration with energy recovery in comparison with biological treatment

For GWP it is difficult to say which option is to be preferred when comparing incineration with anaerobic digestion. Anaerobic digestion (see tables 3.4a and 3.4b below) could or could not be preferred, depending on various factors; i.e. if the fuel is used for district heating (dh), electricity (e) or transportation fuel (bus or f), or whether biomass or oil is assumed to be the alternative fuel for the produced energy. In both cases, where oil is the alternative for heat production, instead of biomass, incineration is favoured. If natural gas is the alternative source for district heating, the difference is small between the treatment options.

Regarding acidification and eutrophication, anaerobic digestion is the best alternative according to the results of these studies. The difference is small, though, if the gas from the anaerobic digestion is used as a fuel for transportation instead of for district heating and electricity. It should also be noted that in study 23 and 25, the energy recovery from incineration does only generate district heating and no electricity. In study 5, both electricity and district heating are generated from incineration.

In the case of photooxidants, the studies show different results.

The result for toxicity again varies with the evaluation method used, but there might be an advantage for incineration.
Table 3.4a Incineration with energy recovery in comparison with anaerobic digestion
Studies including biodegradable waste fractions

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Food waste</td>
<td>Anaerobic digestion (El + dh)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>23</td>
<td>Easily bio-degradable</td>
<td>Anaerobic digestion (Bus)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anaerobic digestion (Bus) oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anaerobic digestion (El + dh)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anaerobic digestion (El + dh) oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>Food waste</td>
<td>Anaerobic digestion heat/el base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anaerobic digestion (f) Biomass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anaerobic digestion (f) Natural gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.4b Incineration with energy recovery in comparison with anaerobic digestion
Studies including biodegradable waste fractions. Toxicity results for study 25

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Eco-toxicological effects</th>
<th>Human toxicological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EDIP USES min USES max</td>
<td>EDIP USES min USES max</td>
</tr>
<tr>
<td>25, base</td>
<td>Anaerobic dig h/e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>scenario</td>
<td>Anaerobic dig f</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

14 In the base scenario, biomass is the alternative fuel for district heating. Here, oil is the alternative.
15 Waste incineration produces district heating and biomass is saved, in the base scenario. Gas from the anaerobic digestion is used in a combined heat and power plant (CHP). The heat and electricity is assumed to substitute the fuels biomass and coal condensing power, respectively.
16 Excl SOx/NOx
17 Aquatic (excl NOx)
18 Gas from the anaerobic digestion is used as a transportation fuel. Biomass is assumed to be the avoided heat source for district heating from incineration.
19 Natural gas is assumed to be the avoided heat source for district heating.
Compared to composting (see tables 3.5a and 3.5b below), incineration is preferred in the majority of the cases regarding **GWP**. This is not the case, however, if biomass is the alternative fuel for heat production as in the base case of study 25.

Incineration is to be preferred also regarding the **acidification** potential compared to composting.

In the case of the potential for **eutrophication** the studies show different results.

Regarding **photooxidants** incineration is to be preferred compared to composting.

The result for **toxicity** again varies with the evaluation method used. An advantage to incineration may be seen.

---

**Table 3.5a Incineration with energy recovery in comparison with composting**

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Food waste</td>
<td>Composting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Easily bio-degradable</td>
<td>Composting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Food waste</td>
<td>Composting base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Composting Natural gas$^{22}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Composting GWP, 20 yr$^{23}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Composting GWP, 500 yr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.5b Incineration with energy recovery in comparison with composting**

<table>
<thead>
<tr>
<th>Ref, Waste fractions</th>
<th>Eco-toxicological effects</th>
<th>Human toxicological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>25, base scenario</td>
<td>EDIP, USES min, USES max</td>
<td>EDIP, USES min, USES max</td>
</tr>
</tbody>
</table>

---

$^{20}$ Excl SOx / NOx
$^{21}$ Aquatic (excl NOx)
$^{22}$ In the base scenario, biomass is the alternative fuel for district heating. Here, natural gas is the alternative.
$^{23}$ In the base scenario, GWP factors for 100 years are used
Incineration with energy recovery in comparison with other waste-to-energy technologies

Table 3.6 Incineration with energy recovery in comparison with RDF production followed by incineration\(^{24}\).

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>MSW RDF-prod+ inc</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The impact categories studied are **GWP** and **acidification**, both positive for incineration in that study.

Table 3.7 Incineration with energy recovery in comparison with waste incineration with heavy metal recovery.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>MSW PECK(^{25}) (heavy metal recovery)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**GWP**, **acidification**, **eutrophication**: PECK is concluded to perform about the same as waste incineration.

**Toxicity**: PECK performs better than incineration without heavy metal recovery.

Table 3.8 Incineration with energy recovery in comparison with feedstock recycling\(^{27}\).

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>plastic Feedstock recycling(^{26})</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The **GWP** category is better for feedstock recycling, than for incineration, because of the direct substitution of raw materials and their use in efficient processes. The conclusion regarding **acidification** in the study was that the difference between feedstock recycling and incineration is “negligible”.

\(^{24}\) In study 18, the same incineration plant is assumed to either incinerate RDF (table 3.6) or Rest Waste (table 3.9).

\(^{25}\) Results valid if the practical performance meets the set targets.

\(^{26}\) Toxicity: Human, freshwater and marine aquatic, freshwater sedimentary, terrestrial, marine sedimentary, terrestrial eco-toxicity.

\(^{27}\) Feedstock recycling is defined as a change in the chemical structure of the material, where the resulting chemicals are used for another purpose than producing the original material. The feedstock generated includes synthesis gas (CO and H2). Energy released during these processes is generally used or recovered.

\(^{28}\) In study number 13, the technologies compared to incineration are: BASF thermolysis, SVZ gasification and methanol synthesis and blast furnace.
Incineration with energy recovery in comparison with landfilling

For mixed waste (see table 3.9), all categories **(GWP, acidification, eutrophication, photooxidants and toxicity)** are better for incineration than landfilling.

Table 3.9 Incineration with energy recovery in comparison with landfilling

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>Rest waste</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23</td>
<td>MSW</td>
<td>Mechanical-biological treatment(^{29})</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>28</td>
<td>MSW</td>
<td>Landfilling</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

From the studies regarding plastics (see tables 3.10a and 3.10b below), it is not possible to say which treatment option is the best regarding **GWP**. The cases with negative outcome for incineration are due to the time perspective used for landfilling. In the short term, the GWP is lower for landfilling than for incineration, as only a small fraction of the plastic is assumed to be degraded.

With few exemptions, incineration is better than landfilling for plastic in all remaining categories **acidification, eutrophication photooxidants, and toxicity** (see table 3.10b).

\(^{29}\) Mechanical-biological pre-treatment does in this case consist of a iron scrap recovery, separation of high-calorific value waste for incineration and biological treatment of the rest waste followed by landfilling.
### Table 3.10a Incineration with energy recovery in comparison with landfilling

*Studies only including separate fractions: plastics*

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Non-packaging</td>
<td>Separate collection</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>Plastic</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>Bulk packaging</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>Plastic packaging</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>PE</td>
<td>Base</td>
<td>32</td>
<td>32</td>
<td>33</td>
<td>34</td>
<td>Table 3.10b</td>
</tr>
<tr>
<td>PP</td>
<td>Base</td>
<td>32</td>
<td>33</td>
<td></td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS</td>
<td>Base</td>
<td>32</td>
<td>33</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PET</td>
<td>Base</td>
<td>32</td>
<td>33</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVC</td>
<td>Base</td>
<td>32</td>
<td>33</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.10b Incineration with energy recovery in comparison with landfilling**

*Studies only including separate fractions: plastics. Toxicity results for study 25*

<table>
<thead>
<tr>
<th>Ref, base scenario</th>
<th>Waste fractions</th>
<th>Eco-toxicological effects</th>
<th>Human toxicological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>PE</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PET</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PVC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

30 Emission of TOC and primary energy consumption also studied (beneficial for incineration)
31 Terrestrial and aquatic
32 Excl SOx and NOx
33 Aquatic (excl NOx)
34 Same effect for all plastics. In the base scenario, the infinite time perspective is used, thus assuming all fossil plastics in the landfill to be oxidised to CO2. In the surveyable time period, only a few percent are degraded.
Regarding treatment of paper and cardboard (see tables 3.11a and 3.11b below), the negative results for incineration compared to landfilling in the GWP category are due to the time perspective considered. In the short term when the landfill is considered as a carbon sink, the GWP is lower for landfilling than for incineration, as a fraction of the paper (constituted of hemicellulose, cellulose and lignin) is only partly degraded. In the short term, there are no GHG-emissions from the landfilling from this non-degraded fraction, and emissions are thus avoided in comparison with incineration where this fraction is oxidised into CO₂.

For the other categories (acidification, eutrophication, photooxidants, and toxicity) incineration is better than landfilling.

Regarding treatment of food waste (see tables 3.12a and 3.12b below), incineration is better than landfilling in all categories (GWP, acidification, eutrophication, and photooxidants) except toxicity. There the evaluation methods used, affects the result, but in no case, landfilling is better than incineration.
Table 3.11a Incineration with energy recovery in comparison with landfilling
Studies only including separate fractions: paper, cardboard etc.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photooxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Carton composites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carton for liquids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Newspaper</td>
<td>base</td>
<td>36</td>
<td>35</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Natural gas (heat)</td>
<td></td>
<td>36</td>
<td>35</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Corrugated</td>
<td>base</td>
<td>36</td>
<td>35</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>cardboard</td>
<td></td>
<td>37</td>
<td>35</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Mixed cardboard</td>
<td>base</td>
<td>36</td>
<td>35</td>
<td></td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.11b Incineration with energy recovery in comparison with landfilling
Studies only including separate fractions: paper, cardboard etc. Toxicity results for study 25

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Ecotoxicological effects</th>
<th>Human toxicological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EDIP</td>
<td>USES min</td>
</tr>
<tr>
<td>25, base scenario</td>
<td>Newspaper</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corrugated cardboard</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mixed cardboard</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

35 Terrestrial and aquatic
36 Excl SOx and NOx
37 Aquatic (excl NOx)
38 Surveyable time only + carbon sink
39 For corrugated cardboard it is also still a better option, from a global warming perspective to incinerate than to landfill. The difference between this paper fraction and the other two may be a consequence of the material composition, where a larger part of the carbon in corrugated cardboard is assumed to be degraded during the surveyable time.
Table 3.12a Incineration with energy recovery in comparison with landfilling
Studies only including separate fractions: food waste

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Alternatives</th>
<th>GWP</th>
<th>Acidification</th>
<th>Eutrophication</th>
<th>Photo-oxidants</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Food waste base</td>
<td>base</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.12b Incineration with energy recovery in comparison with landfilling
Studies only including separate fractions: food waste. Toxicity results for study 25

<table>
<thead>
<tr>
<th>Ref</th>
<th>Waste fractions</th>
<th>Eco-toxicological effects</th>
<th>Human toxicological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>25, base scenario</td>
<td>Food waste</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

40 Excl SOx and NOx
41 Aquatic (excl NOx)
3.3 Identification of key factors

In this chapter, we present identified key factors that can change the environmental ranking (for one or more emissions/impacts) between incineration and the other treatment/recovery methods. The key factors have been identified mainly using two sources: a) the systems analyses in chapter 3.2, and b) so called key factor studies, where other researchers have drawn general conclusions on important parameters for the choice of waste treatment method. The key factor studies are based on reviews of earlier studies and are focused either on separate waste fractions (e.g. paper) or on mixed waste such as MSW. The key factor studies are listed in Appendix B.

This chapter starts with key factors that are of general importance, i.e. that are important for all treatment methods. Then we continue with key factors for incineration. After that, we describe the identified key factors for material recycling, biological treatment, waste fuels used in cement kiln/power plant, and finally landfilling. For other treatment options than incineration, we focus on key factors that affect their ranking in relation to incineration.

General key factors

The following key factors, we have found to be of general importance for the environmental ranking of treatment methods:

- Time perspective
- Technology development
- Local conditions
- Alternative electricity and heat generation
- Renewable energy supply in Europe
- Waste transports by passenger car

The time perspective is fundamental for the modelling of the processes in the waste management system as well as for the assumptions/modelling of surrounding systems (e.g. the energy system or the material production system) that are affecting the results. Furthermore, the time perspective can also affect the choice of data in LCAs, illustrated here by a quote from Finnveden et al (2004):

“The goals of an LCA can be analysed in several dimensions. A first fundamental dimension is concerned with whether the study is change-orientated (prospective) or descriptive (retrospective)……. If the study is change-orientated, it analyses the consequences of a choice; ideally, the data used should reflect the actual changes taking place, and may depend on the scale of the change and the time over which it occurs. With regard to time, a distinction can be made between a very short time frame (less than a year), short (years), long (decades) or very long (centuries). “

The choice of time perspective might affect what technologies are available. On a short term, only existing facilities are available, which can lead to certain technologies being omitted due to lack of capacity.
The choice of time perspective is also an underlying factor behind assumptions made for **technology development**. These assumptions, based e.g. on promising results from pilot plants, can crucially improve the efficiency of the technologies both regarding emissions and the quality and amount of the end products. In Christiani et al (2001) for example, the new sorting technology for light-weight packaging in Germany, meant an improved result for material recycling compared to the technology used at the time of the study (1998). For some of the environmental impacts evaluated, this changed the ranking between material recycling and incineration (see study 14, tables 3.2a and 3.3a in chapter 3.2).

The **local conditions** strongly affect the environmental value of different treatment options. For example, if there is no market/demand for compost due to strong requirements on a low level of heavy metals in fertilizers, composting is not a viable option. In the case of incineration, the existence of a district heating system enables a higher energy recovery compared to the case where only electricity production is possible. Furthermore, the local conditions can also decisively influence the importance of different environmental parameters. For example, for some regions acidification might be of larger relevance than eutrophication and vice versa. This can change the overall environmental ranking between different options.

The choice of **alternative electricity and heat generation** has a large impact on the results where energy is either recovered directly (e.g. waste incineration) or indirectly\(^{42}\) (material recycling), but also generally for the all treatment options where electricity and heat are consumed. The assumptions in the studies range from use of fossil fuels (predominantly coal or natural gas) to renewable fuels (solid biofuels or wind). In between these options, national or EU averages both for electricity and heat production have been used. The choice depends on the time perspective and on the local conditions. For example, if the study is change-orientated, marginal data should be used instead of average data, thus reflecting the effects of the change. The local conditions are more important for the alternative heat generation, which unlike electricity cannot be transmitted over large distances. For example, in the case of district heating, mainly fossil fuels are used in Germany, while in Sweden a large share of the district heat production is based on biofuels.

The alternative fuels are not always obvious. Waste incineration is a typical base load technology in district heat production. Normally, using waste as a fuel would mean that other base load fuels would be replaced. This is true when a new waste incineration plant replaces an old base load plant or if waste fuels are used for co-combustion with other fuels in an existing base load plant. However, it is also possible to build a new waste incineration plant without replacing an old base load plant. In such systems, the waste incineration will replace production mainly from the plants with the highest variable costs for every period of the year. The plants with the highest variable costs vary throughout the year, depending mainly on the demand for district heating. During winter, when there is a high demand, all available capacity must be used and the plants with the highest variable costs in Sweden are typically using oil. During summer, when the heating demand is much lower, the plants with the highest variable costs might instead be bio-fuelled plants. This results in a mix of

---

\(^{42}\) At the material recycling, energy is consumed. But the material recycling replaces virgin production, leading to energy savings. The net is normally an energy reduction.
fuels being replaced during the whole year. This is exemplified in figure 3.1 for the city of Göteborg, Sweden.

Figure 3.1 Replaced district heat production at the expansion of waste incineration in Göteborg 2008. The left figure shows what fuels are replaced every month. The right figure shows the annual replaced fuel mix. The waste incineration plant increases from managing 460 ktonnes/year to 550 ktonnes/year. This means an extra district heat production of 240 GWh per year.

In a long-term perspective where both the fixed and the variable costs are accounted for, it is however reasonable to assume that other base load production is replaced. In such cases, the main base load alternative should be identified and used for comparison with waste incineration.

Considering the goals of the Kyoto protocol and its implications on waste management, the renewable energy supply in Europe is also a relevant key factor. In chapter 3.2, only the systems analyses made for Sweden assume that the alternative heat production can come from solid biofuels. For the other countries, fossil fuels are generally assumed both for electricity and heat production. The choice of coal/natural gas or biofuels for heat production not only has large impact on the GWP-results, but also on other results (see e.g. tables 3.1, 3.2a and 3.4a). In long term studies, it is thus relevant to evaluate if fossil fuels or renewable fuels (predominantly biofuels) will be the alternative heat production. For example, could the Kyoto targets stimulate a development of domestic resources of biofuels in Europe?

Finally, in principal all evaluated systems studies have shown that the large-scale collection and transportation of waste by truck is of much less environmental importance than the choice of treatment option. However, there is one type of transport that can change the ranking of different treatment options. Due to its low fuel efficiency, waste transports by passenger car means large emissions per tonne of waste transported, if the sole purpose of the transport is to deliver the waste (and not do other errands such as shopping etc, to which the emissions could be allocated). In some studies, an assumed increase in waste transports by passenger car has been very negative for the environmental performance of material recycling and incineration.
Key factors for incineration

Besides the general key factors above, we have found the following key factors to be of relevance for incineration:

- Emission level
- Energy recovery
- Time perspective and fate of landfilled residue

The emission level is mainly dependent on the waste incinerated, the waste incineration technology and the flue-gas treatment. The Waste Incineration Directive means harder restrictions on emissions from incineration throughout the whole EU. The directive regulates a large amount of different emissions, and will lead to better environmental performance, when fully implemented and followed. The more efficient the process works, the less are the environmental impacts from regulated as well as unregulated emissions.

Another key factor for incineration is the efficiency of the energy recovery, i.e. the amount of energy in the waste that can be transformed into useful energy such as electricity, steam for industrial purposes or heat for residential heating. When electricity is produced, the energy efficiency ranges between 20 and 30 %. However, if it is possible to produce district heat, the energy efficiency can amount to around 90 %. This fact, in combination with the local conditions regarding alternative electricity and heat generation, has a large impact on the environmental performance of waste incineration.

Waste incineration generates slag and flue-gas cleaning residues. While the former can be sorted and reused to a large extent, the latter normally needs to be landfilled due to a high level of substances such as heavy metals, dioxins etc. When modelling incineration, it is essential to include the direct and future impacts of this landfilled residue. The time perspective and fate of the landfilled residue can differ from study to study. The longer the time perspective, the larger the amount of substances leaching out of the landfill into the environment. Some studies assume an infinite perspective where all substances leach out to the environment (e.g. Finnveden et al 2004), while other only include the emissions during a “surveyable” time of around one century (Sundqvist et al 2002). Hellweg et al (2003) comment that the time perspective is important when analysing the performance of normal versus newer incineration technologies. In the short-time perspective, the better incineration technologies with recovery of heavy metals from the slag are not credited for their prevention of emissions that would have appeared from the landfill in the long run. Furthermore, it is also important to assess how sensitive the recipient of the leachate is. The evaluation of the sensitivity of the recipient is seldom done. Instead, emissions are added together without consideration of background levels and recipient buffer capacity.

43 However, the exergy value of electricity is higher than heat, which means that electricity is a more “valuable” energy form than heat. To make them equal, one has to consider the effort of producing them with alternative methods. In the draft BREF/BAT “waste incineration” so-called energy equivalents are to be used (Reimann 2003). The conversion of absolute (abs) into equivalent (equ) values is: 1 MWh electricity abs = 2,6316 MWh equ (corresponding to an efficiency of 38 %), and 1 MWh heat abs = 1,0989 MWh equ (corresponding to an efficiency of 91 %). See also chapter 4.2

44 See also below where key factors for landfilling are discussed.
However, it has to be considered that several operators of WtE plants, e.g. from Austria, Switzerland, The Netherlands and Germany bring their residues to salt mines which could be considered as an environmentally sound storage on the long term as no aftercare is necessary due to the final exclusion from the biosphere. Sometimes the residues are used as filler and thus replace natural resources, which would have had to be used alternatively to refill the salt mine.

**Key factors for material recycling**

For material recycling, we have found the following key factors to be of importance when compared with incineration:

- Market/demand for recycled material
- Substitution factor
- Energy consumption and emissions at material production from virgin and from recycled materials
- Fate of saved biomass in the forest (paper and cardboard recycling)

Ideally, the recycled material can replace virgin material for the same product. Even though there is a market/demand for the recycled material, due to qualitative reasons some of the recycled material cannot be used, leading to a lower substitution factor. In effect, more recycled material must then be used to replace a certain amount of virgin material.

Furthermore, if there is an international market for collection and sales of recyclables, as for instance for paper, increased collection in one place might lead to decreased collection in another place (see e.g. Ekvall 1999). The replacement of virgin production would thus not be affected, and the net effect would be; increased recycling in one place leads to increased alternative treatment in another place.

Due to high quality standards, the recycled material might not meet the demands of the market, and thus the material might be “down-cycled”, replacing virgin material to some other products (e.g. recycled plastics in plastics palisades replacing wooden palisades).

The choice above has large impacts since it decides what alternative production from virgin materials is avoided. The net benefit of material recycling is also dependent on what the energy consumption and the emissions are from the production from recycled and virgin material respectively. The larger the reduction of energy consumption and emissions through recycling, the better the environmental performance of material recycling compared to incineration.

For paper and cardboard recycling specifically, it is also relevant to note the fate of saved biomass in the forest. When these waste fractions are recycled, virgin production of paper and cardboard can be replaced, thus leading to a lower consumption of biomass in the forest. The fate of this saved biomass can be different: it can be left in the forest, it can be cut down and used for other material production, or it can be used for energy production, thus replacing alternative electricity and/or heat generation. Depending on the choice made, the environmental performance of material recycling in comparison with incineration is clearly affected (see e.g. Ekvall 1999 and Finnveden et al 2004).
Key factors for biological treatment (anaerobic digestion, composting)
For biological treatment, we have found the following key factors to be of importance when compared with incineration:

- Emission level
- Market/demand for digestion residue/compost
- Topsoil value of digestion residue/compost

Compared to incineration, the emission level for biological treatment facilities is less regulated, and there is thus a larger probability for variations throughout Europe compared to incineration. Today, the processing and the spreading of the rest products on farmland lead to methane and nitrogen emissions (as $\text{N}_2\text{O}$ and $\text{NH}_3$). These emissions contribute negatively on the environmental performance.

Analogous to material recycling, the environmental performance of biological treatment is dependent on a market/demand for digestion residue/compost. Only when there is a demand from the farmers to use the products is it possible to close the loop for recycling of the nutrients in the waste, leading to replacement of other fertilizer production. When there is no market/demand, the digestion residue/compost must be used for other purposes (e.g. land reclamation or as a top layer when old landfills are covered), where the environmental benefits are much smaller.

Normally the digestion residue/compost is credited after its content of phosphorous and nitrogen and sometimes for the content of potassium. The emissions for industrial production of the same amount of these fertilisers are thus deducted from the overall emission. However, in southern Europe there are examples of soils where the topsoil layer is very thin. For these conditions, it might be relevant to attribute a topsoil value of digestion residue/compost, since they contribute to thicken the topsoil layer. Sundqvist et al (2002) shows through a simplified example that the energy balance would be significantly improved for anaerobic digestion compared to incineration, if it was assumed that the use of digestion residue would replace peat as soil improver. However, the same authors state that it is difficult to evaluate the topsoil value with conventional LCA methodology.

Key factors for waste fuels used in cement kiln/power plant
For these options, we have found the following key factors to be of importance when compared with incineration:

- Emission level at combustion of waste fuel
- Alternative fuel used in cement kiln/power plant

From a recovery perspective, these options aim at recover the energy content of the waste. In that perspective, they are similar to incineration. However, the emission restrictions have generally been weaker for use of waste fuels in cement kilns and power plants throughout Europe. This should be changed by the latest by December 28, 2005 when the Waste Incineration Directive (WID) will come into force for existing facilities. Co-combustion of waste fuels in cement kilns and power plants then should in principle have the same regulation for the waste part of the fuel as incineration plants. However, there are exemptions in the WID, which likely can lead to higher
overall emissions from co-combustion than from waste incineration plants. As discussed for incineration above, the emission level can also vary between individual plants.

Another key factor is the alternative fuel used in cement kiln/power plant. This fuel have in these studies normally been coal, which is associated with large environmental impact. One can assume that if the alternative fuel had been a renewable fuel, a substitution with waste would not have been interesting. The alternative fuel often has decisive impacts on the environmental performance of these options.

Key factors for landfilling
For landfilling, we have found the following key factors to be of importance when compared with incineration:

- The modelling of the landfill (time frame)
- Mechanical-biological pre-treatment
- Carbon sink

Compared to other treatment methods, landfilling is harder to model since the emissions are occurring over a long time period. For example, while CO₂ is emitted directly from incineration, methane from landfilling is mainly emitted during 40-80 years. The task of measuring the emissions is also much harder. One of the specific interests in the modelling of landfills is the time frame chosen. This decides how much of the environmentally harming substances will leave the landfill as gas or with the leachate water. There is no general international agreement on how to choose the time frame when modelling landfills. Some modellers use a practical time frame which might range from a couple of decades up to around a century. Others use a so-called surveyable time period. This is the period until the landfill has reached a pseudo steady state, a time period corresponding to approximately one century. As a “worst case” some modellers also use a hypothetical infinite time period, where a complete degradation and spreading of all landfilled material is assumed (Moberg et al 2004). As an example, if only degradation during a century is accounted for, only a small fraction of the plastics are degraded. The major part remains in the landfill unaffected. From a GWP perspective, this makes landfilling of plastics a better option than incineration. However, if a hypothetical infinite time period is chosen, all plastics in the landfill is degraded and emitted as CO₂, thus making incineration the better option.

Another key factor for landfilling is if there is mechanical-biological pre-treatment. This clearly reduces the possible future emissions from the landfill, e.g. the methane formation is significantly reduced. In i.e. Hellweg et al (2003) the mechanical-biological pre-treatment improves the performance of landfilling, but not as much as the ranking between the alternative treatment options is changed.

Finally, another key factor is whether the landfill can be regarded as a carbon sink. This is of relevance for the landfilling of renewable material, e.g. paper, wood etc. During a surveyable time period, the cellulose, hemicellulose and lignin in these waste fractions are only partly degraded. The rest of the carbon is thus “stored” in the
landfill. In comparison with incineration, where the carbon directly is oxidised to CO$_2$, this means that CO$_2$-emissions are avoided during the surveyable time. This could change the order between landfilling and incineration from a GWP perspective. Of course, it is important to stress that this way of modelling emissions contributing to GWP, is only valid when a surveyable time period or shorter is evaluated. For a longer time period, the cellulose, hemicellulose and lignin will degrade into CH$_4$ and CO$_2$, thus leading to higher GWP for landfilling than incineration.
4. Discussion and conclusions

In chapter 3.1 and 3.2, we illustrated the main environmental results in the included studies. Based on these studies and other, so-called key factor studies, we identified a number of key factors, which we described in chapter 3.3. In this chapter, we discuss and draw conclusions on the environmental role of waste incineration in comparison with other treatment methods. We are thus making our own interpretation of the results in chapter 3. The discussion is focused on waste fractions where there has been a lot of controversy whether the material should be recycled, incinerated or treated biologically. This means that we delimit the discussion to mainly organic combustible waste fractions (e.g. paper, plastics, and compostable material). For these waste fractions, the systems analyses in chapter 3.2 show that landfilling generally is the worst option. In our discussion, we have thus focused on waste incineration in comparison with material recycling and biological treatment.

To facilitate this discussion, we have divided the chapter into the following sections:

4.1 Key factors and extreme cases
4.2 Europe today
4.3 Europe 2030 – two alternative scenarios
4.4 Concluding remarks

In chapter 4.1, we select the key factors in chapter 3.3 that we believe are the most important for the discussion. We also illustrate two extreme cases, where we choose the level of the key factors to either benefit or disadvantage incineration as much as possible. These extreme cases are thus only theoretical, but they help us structure the subsequent discussion. In chapter 4.2, we discuss the present situation in Europe. In chapter 4.3, we discuss the future European situation 2030 in two alternative scenarios. Finally, chapter 4.4 provides concluding remarks regarding the development of the environmental role of waste incineration between today and 2030.

4.1 Key factors and extreme cases

Key factors

Based on the key factors in chapter 3.3, we believe that the following are the most important for the environmental performance of waste incineration in comparison with material recycling and biological treatment in a European perspective:

- **The time perspective** (as an underlying condition for what level to choose for the other key factors)
- **Energy recovery from incineration**
- **Alternative electricity and heat generation**
- **The material recycling efficiency** (as a net effect of the market/demand for recycled material, the substitution factor and the energy consumption and emissions at material production from virgin and from recycled materials)
- **The biological treatment efficiency** (as a net effect of the emission level, the market/demand for digestion residue/compost and the topsoil value of digestion residue/compost)
The reasons behind choosing these key factors are:

1) They have a large impact on the results
2) They differ to a large extent within Europe
3) There is no consensus in the waste management systems analysis on how to handle these factors.

Extreme cases
These extreme cases are developed for all the key factors but the time perspective. The time perspective is an underlying condition for what level to choose for the other key factors, and we handle that in chapters 4.2 and 4.3 by looking at the European situation today and 2030.

Table 4.1 Level of key factors in Extreme case A and B

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Level in Extreme case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A (Positive for waste inc.)</td>
</tr>
<tr>
<td>Energy recovery from incineration</td>
<td>High, CHP, power-to-heat ratio = 0.4, 90 % of energy in waste recovered</td>
</tr>
<tr>
<td>Alternative electricity and heat generation</td>
<td>Based on coal</td>
</tr>
<tr>
<td>The material recycling efficiency</td>
<td>Low, mainly &quot;down-cycling&quot;, replacement of other products than the original, large material losses</td>
</tr>
<tr>
<td>The biological treatment efficiency</td>
<td>Low, compost/digestion residue used for land reclamation and covering of landfills, no reuse of nutrients, no value as topsoil, large losses/emissions of methane at biogas production/use</td>
</tr>
</tbody>
</table>

In Table 4.1, we show the levels of the key factors in the two Extreme cases A and B. The former maximises the benefits for waste incineration, while the latter does the opposite. The energy recovery decides how much alternative electricity and heat generation can be replaced. This is important since only 10-25 % of the MSW constitutes of coal of fossil origin (IPCC 2001). With Extreme case A, all the alternative electricity and heat generation is based on coal with large emissions. In Extreme case B, instead renewables are used with much smaller emissions. The low efficiency at material recycling and biological treatment further benefit the incineration in Extreme case A, while the opposite occurs in Extreme case B.

If we look at the system analyses in chapter 3.2, we can conclude that none of them exactly resembles the Extreme cases A or B. The energy recovery from incineration varies in the studies. Less than half (4 out of 12) of the studies included are assuming an energy recovery only producing electricity. The remaining studies assumed combined heat and power production, or only heat or steam for district heating or industries, with a higher total efficiency. The alternative electricity and heat generation is mainly fossil-based or based on assumptions that the national or European average mix is replaced. For the alternative heat production, the Swedish studies are different since they assume that biofuel would be the alternative fuel at
heat generation. The material recycling efficiency is assumed to be high as a base case in most studies. In sensitivity analyses, cases with lower efficiencies are evaluated (see e.g. table 3.3a). For biological treatment a fairly high efficiency is assumed since the compost/digestion residue is assumed to be used in agriculture. However, the emissions levels could be further reduced and there is no topsoil value given to the compost/digestion residue.

Although neither of the system analyses in chapter 3.2 exactly resembles the Extreme cases A and B, we believe they can be used to support the following conclusions:

- In Extreme case A, we find that waste incineration is a very competitive environmental alternative, which show better performance than all alternatives for most environmental parameters. This even includes GWP for plastics due to the low material recycling efficiency. (See again table 3.3a, where recycling of mixed plastics into plastic palisades replacing wood palisades means an increase of GWP compared to incineration. It should also be noted that in that study, waste incineration is assumed to replace district heating produced with biofuels. The effect would have been higher if a fossil fuel would have been replaced.)

- In Extreme case B, we find that waste incineration has a worse environmental performance than material recycling and biological treatment for most environmental parameters. Compared to landfilling, incineration is still a competitive alternative.
4.2 Europe today

To draw conclusions on environmental performance of waste incineration in Europe, it is important to discuss first the levels of the key factors. In no European country, we find the levels of the key factors as in the Extreme cases A or B. However, for different regions, we can find levels that make either of the Extreme cases more relevant than the other.

Starting with the first key factor, figure 4.1 shows the energy recovery per ton waste incinerated for a number of European countries. Although energy recovery might differ some due to the energy content of the waste, the figure shows the importance of energy system infrastructure, where opportunities of district heating production enables a higher absolute energy recovery. In Sweden, but also in Austria, Switzerland, Norway and Denmark, the absolute energy recovery is much higher than in the other countries.

However, the exergy value of electricity is higher than heat, which means that electricity is a more “valuable” energy form than heat. To make them equal, one has to consider the effort of producing them with alternative methods. In the draft BREF/BAT\textsuperscript{45} “waste incineration” so-called energy equivalents are to be used (Reimann 2003). The conversion of absolute (abs) into equivalent (equ) values is:

1 MWh electricity abs = 2,6316 MWh equ (corresponding to an efficiency of 38 % in a power plant), and
1 MWh heat abs = 1,0989 MWh equ (corresponding to an efficiency of 91 %).

The energy recovery expressed in energy equivalents is shown for the same countries in figure 4.2. The differences between the countries are reduced using this method, but still it is clear that the highest energy recovery is reached in Sweden, Austria, Switzerland, Norway and Denmark. In these countries, we thus have a situation with a relatively high energy recovery (closer to the level in Extreme case A than in Extreme case B). For the other countries, the opposite is true. Since the latter countries represent a large share of the total waste incineration, the average level based on the countries in figure 4.2 is relatively low (closer to the level in Extreme case B than in Extreme case A).

\textsuperscript{45} BAT = Best Available Technique, BREF = Best available techniques ReFerence documents, currently being developed due to IPPC-directive 96/61/EC (Integrated Pollution and Prevention Control).
Figure 4.1 Absolute energy recovery from MSW incineration 1999, expressed as electricity and/or heat per ton waste incinerated (ISWA 2002, RVF 2000)

Figure 4.2 Energy recovery from MSW incineration 1999, expressed as energy equivalents (equ) per ton waste incinerated (based on ISWA 2002, RVF 2000 and Reimann 2003)

46 Heat is also recovered in the Netherlands, but the economic value is low. According to AOO (2003) around 0.5 MWh electricity/ton incinerated waste and 0.2 MWh heat/ton incinerated waste were recovered 2002.
The next key factor is the **alternative electricity and heat generation**. Looking at the systems analyses in chapter 3.1 and 3.2, the marginal electricity production that is replaced by waste incineration is mainly assumed to be coal power. However, some of the systems analyses choose alternative marginal power sources (e.g. natural gas combined cycle gas turbine), which they motivate with future developments of the power sector leading to technology changes. Since they look at the life-time of the incineration plant, they find it more relevant to use another marginal power source.

In this section, we are interested in the European conditions of today. Looking at the overall electricity generation in EU-15 in 2001 (see figure 4.3), it is obvious that coal is an important fuel. Nuclear power and hydro power normally have the lowest variable costs and are thus used for base load production during the whole year. They are thus more or less unaffected by marginal changes as increase/decrease of electricity generation through changes in the waste management system. The other fuels have higher variable costs and are used during shorter time of the year. Coal (lignite or hard coal) is today normally the fuel used for covering marginal changes in most countries.

**Figure 4.3 Distribution of gross electricity generation in EU-15 2001 (Eurostat 2003)**

For alternative heat generation, there is no common marginal heat source for all Europe. In Sweden, biofuel is the main alternative heat source (Sahlin 2003), but for a large share of the rest of Europe today, fossil fuels are the main alternative (see e.g. Euroheat & Power 2003). For most European countries, the level of the key factor is closer to Extreme case A than to Extreme case B.
What the alternatives are for heat and electricity production is of large importance for the overall results from the environmental evaluation. We illustrate this for GWP in figures 4.4-4.7. These figures are based on results from Sundqvist et al (2002), who compared different waste management options in the Swedish city of Uppsala with 186,000 inhabitants.

Starting first with figure 4.4, the resulting change of GHG-emissions when material recycling of plastic and cardboard is replaced with incineration is illustrated for four cases. The material recycling efficiency is assumed high in all cases. The differences between the cases are the assumptions on the energy recovery level at incineration, and on the fuels used for alternative electricity and heat generation (see table 4.2). The results in case A are directly from Sundqvist et al (2002). The results for cases B-D are a result of our calculations where we have started with case A and then changed the energy recovery of incineration and/or the fuels used for alternative electricity and heat generation.

In figure 4.5, the resulting change of GHG-emissions when material recycling of plastic and cardboard is replaced with incineration is illustrated for four other cases (E-H). The material recycling efficiency is assumed high in all cases. In these cases, coal is assumed to be the fuel for alternative electricity generation. The conditions in cases E-H are illustrated in table 4.3.

Figures 4.6 and 4.7 are analogues to figures 4.4-4.5. However, here the resulting change of GHG-emissions when anaerobic digestion or composting of easily biodegradable waste is replaced with incineration is illustrated. The biological treatment efficiency is fairly high in all cases. Observe that the scale is the same as in figures 4.4-4.5, which shows that the treatment choice is of less importance from a GWP perspective than the choice between material recycling and incineration.

For the figures 4.4-4.7, the emission changes vary greatly with the efficiency of the incineration and the alternative power and heat generation. From a greenhouse gas perspective the figures shows that incineration is the preferred option if the incineration plant is a combined heat and power plant and if heat and electricity otherwise would have been produced using coal. This is an accurate description for some places in Europe but certainly not all. For instance, these boundary conditions are, as mentioned earlier, not relevant for describing the situation in e.g. Sweden where biofuels are an important fuel for heat generation. For countries with a high availability of biofuels, the results show that recycling is the preferred option, at least for plastic.
Table 4.2 Assumptions on the energy recovery level at incineration and on the fuels used for alternative electricity and heat generation.

<table>
<thead>
<tr>
<th>Case</th>
<th>Energy recovery from incineration</th>
<th>Alternative electricity generation based on</th>
<th>Alternative heat generation based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>High, only heat production</td>
<td>Natural gas</td>
<td>Biofuels</td>
</tr>
<tr>
<td>B</td>
<td>High, only heat production</td>
<td>Natural gas</td>
<td>Natural gas</td>
</tr>
<tr>
<td>C</td>
<td>High, combined heat and power production</td>
<td>Natural gas</td>
<td>Natural gas</td>
</tr>
<tr>
<td>D</td>
<td>Low, only electricity production</td>
<td>Natural gas</td>
<td>Natural gas</td>
</tr>
</tbody>
</table>

Figure 4.4 Changes of GWP, expressed as ton CO2-ekvivalents/ton material, when incineration replaces material recycling of plastic and cardboard. The different conditions in cases A-D are described in table 4.2. Case A is from Sundqvist et al (2002). Case B-D are based on own calculations using data from Sundqvist et al (2002).
Table 4.3 Assumptions on the energy recovery level at incineration and on the fuels used for alternative electricity and heat generation.

<table>
<thead>
<tr>
<th>Case</th>
<th>Energy recovery from incineration</th>
<th>Alternative electricity generation based on</th>
<th>Alternative heat generation based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>High, only heat production</td>
<td>Coal</td>
<td>Biofuels</td>
</tr>
<tr>
<td>F</td>
<td>High, only heat production</td>
<td>Coal</td>
<td>Coal</td>
</tr>
<tr>
<td>G</td>
<td>High, combined heat and power production</td>
<td>Coal</td>
<td>Coal</td>
</tr>
<tr>
<td>H</td>
<td>Low, only electricity production</td>
<td>Coal</td>
<td>Coal</td>
</tr>
</tbody>
</table>

Figure 4.5 Changes of GWP, expressed as ton CO2-ekvivalents/ton material, when incineration replaces material recycling of plastic and cardboard. The different conditions in cases E-H are described in table 4.3. Case E is from Sundqvist et al (2002). Case F-H are based on own calculations using data from Sundqvist et al (2002).
Figure 4.6 Changes of GWP, expressed as ton CO2-ekvivalents/ton material, when incineration replaces anaerobic digestion or composting of easily biodegradable waste. The different conditions in cases A-D are described in table 4.2. Case A is from Sundqvist et al (2002). Case B-D are based on own calculations using data from Sundqvist et al (2002).

Figure 4.7 Changes of GWP, expressed as ton CO2-ekvivalents/ton material, when incineration replaces anaerobic digestion or composting of easily biodegradable waste. The different conditions in cases E-H are described in table 4.3. Case E is from Sundqvist et al (2002). Case F-H are based on own calculations using data from Sundqvist et al (2002).
The situation for the next key factor, **material recycling efficiency**, is more complex in a European perspective. There have been many discussions during the past ten years about the recycling schemes that have been launched in European countries. Especially these discussions have regarded the recycling of packaging materials. To obtain clean and homogenous streams for each recycled waste fraction, is very important for the total effect of the material recycling, both from an economic and environmental point of view. Unfortunately, this is a problem for some materials covered by the packaging recycling schemes of today. For materials where source-separation results in clean fractions that can be recycled into original products with fairly small material losses, the material recycling efficiency is high (clearly closer to Extreme case B than Extreme case A), e.g. material recycling of newspaper, glass and ferrous metals. This is especially true for source-separation at industries where large homogenous waste fractions arise, which can be easily sorted and collected separately.

For other materials, such as composite materials and plastics, a lower material recycling efficiency (closer to Extreme case A than Extreme case B) can be observed throughout Europe.

The **biological treatment efficiency** (the last key factor) is steadily improving in Europe. However, we have found that this key factor is varying. Depending on the local conditions, the level is either closer to Extreme case A or to Extreme case B. One must keep in mind that this technology is not as mature as the waste incineration technology. There is still a potential to reduce the emissions with the processing of the waste, also with the spreading of the residues and at the refinement of biogas at anaerobic digestion. Problems have been observed with the demand from agriculture for using compost/digestion residue. This is due to perceived risks regarding contamination of heavy metals, pesticides and diseases.

In table 4.4, we have summarised the discussion of the levels of the key factors for Europe today.

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Level in Europe today</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy recovery from incineration</td>
<td>Varying from low - relatively high</td>
</tr>
<tr>
<td>Alternative electricity and heat generation</td>
<td>Electricity: mainly based on coal Heat: Varying for different regions (coal, biofuels, natural gas), for the majority based on fossil fuels</td>
</tr>
<tr>
<td>The material recycling efficiency</td>
<td>Varying from low – high, depending on the waste fractions</td>
</tr>
<tr>
<td>The biological treatment efficiency</td>
<td>Varying from low - relatively high, depending on local conditions</td>
</tr>
</tbody>
</table>

Based on this, we draw the following **conclusions** for the management of organic combustible waste fractions:

- The levels of the key factors vary across Europe. Consequently, the environmental performance of waste incineration compared to the other treatment options depends on the local conditions and the waste fractions considered.
For Europe as a whole, the energy recovery and thus the environmental performance of waste incineration can clearly be improved.

Where material recycling efficiency is high, material recycling has generally a better environmental performance than waste incineration. However, where the material recycling efficiency is low, and the energy recovery of waste incineration is relatively high, the opposite can be true.

For biodegradable waste, the choice between waste incineration and anaerobic digestion/composting is not obvious, and depends largely on local conditions. However, where the biological treatment efficiency is low, and the energy recovery of waste incineration is relatively high, it is clear that waste incineration is the preferable alternative.
4.3 Europe 2030 – two alternative scenarios

The discussion made so far in this chapter describes the situation today. To present the best option from an environmental point of view in the future is a much more difficult task. We do not know if the set of key factors we have selected here are relevant for the situation year 2030. Nevertheless, we understand the decisions for the future regarding for example incineration are made today. Therefore, it is best to make assumptions for the key factors based on the decisions being made now in order to handle some of the uncertainties for how the systems will develop.

We have selected two scenarios for the development of the waste management system, one where greenhouse gases are of large importance in the society and one where greenhouse gases turn out to be of less importance. The regulations, goals, taxes etc for handling CO2 emissions and other greenhouse gases are today the main environmental focus for the governments in their efforts of controlling the development of the waste and energy systems. Greenhouse gases (GHG) also do play an important role for the results in all the environmental studies that have been investigated in this report. The key factors discussed in this chapter also indicate that there may be large differences in the net emissions of GHG dependent on the assumptions made for these key factors.

Scenario 1: Greenhouse gases of large importance

In this scenario, the reduction of greenhouse gas emissions becomes an even higher environmental priority in society than today. The GHG-emissions thus become more important for the environmental ranking of different waste management options than today. Ambitious post-Kyoto reduction targets put increased pressure on all activities in society to reduce the GHG-emissions. Naturally, this also affects levels of the key factors, which is described in the following.

The demand for decreased GHG-emissions will imply that the energy efficiencies at all energy conversion must be increased. This also goes for the energy recovery from incineration, which will increase and move towards the level in Extreme case A. The higher energy recovery is reached through expansion of district heating systems, increased use of the district heating systems in Eastern Europe, increased use of steam for industrial production and improved opportunities for electricity generation due to cleaner waste (better source-separation) where the risk of corrosion at high steam data is reduced.

Conclusion: High energy recovery for most incineration plants in Europe.

The demand for decreased GHG-emissions will also imply fuel switches in the energy system, which will affect the alternative electricity and heat generation. The use of coal will be sharply reduced due to its high CO2-emissions. Instead, the use of natural gas and renewables will expand. Since these fuels emit less CO2 per energy unit, they will become more competitive as the costs of emitting CO2 arises. Depending on the availability of natural gas and renewables in different European regions, the price will differ. Consequently, for some regions it will be more profitable to use natural gas for GHG-emission reduction. In others, renewables are the more profitable alternative. For Europe as a whole, the stronger GHG-emission reduction
targets will thus make natural gas and renewables the fuels for covering marginal changes. Consequently, increases/decreases of waste incineration will lead to mainly decreased/increased use of natural gas or renewables. In cement kilns, however, coal might still be used. Increased use of waste fuels in cement kilns would thus replace coal. Looking at the overall situation in Europe the waste amounts that can be used in cement kilns is rather small, which means that natural gas and renewables still would be the dominating alternative fuels.

**Conclusion:** Natural gas and renewables are the main fuels for alternative electricity and heat generation.

The results from the case studies discussed in this report shows that material recycling generally is beneficial over incineration from a GWP perspective, as long as the source-separation generates clean fractions that are recycled with small material losses (i.e. as long as a high material recycling efficiency is achieved). In this scenario, it will be even more important to increase this type of recycling in order to reduce the total emissions of GHG.

Material recycling of paper products (e.g. newspaper and cardboard) is a special case that needs to be addressed. For cardboard, we showed in figure 4.4 (cases B and C) that incineration could be a better alternative, if the alternative electricity and heat production was based on natural gas. However, material recycling of paper products means that less forest has to be used for paper production. Therefore, by increasing the material recycling, more forest is “saved” and could be used for energy use in order to reduce the GHG-emissions. In this scenario, this “saved” forest could be used for electricity and heat generation and replace natural gas in regions where natural gas is the fuel for alternative electricity and heat generation. However, waste incineration of the paper would also replace natural gas in the same regions. In effect, replacing material recycling with incineration would then lead to no changes in natural gas use due to the electricity/heat recovered at incineration. Instead, emissions from combustion of solid biofuels would be avoided. Therefore, case A in figure 4.4 would be more relevant to describe the changes of GHG-emissions, i.e. the difference between material recycling and incineration of cardboard is small. In the case of newspaper, the high electricity consumption at virgin production would likely make material recycling beneficial compared to incineration (see e.g. Finnveden et al 2000). Through material recycling virgin production, using electricity from natural gas would be avoided, which would favour material recycling.

It is important to stress that the material recycling efficiency must be high, which might restrict the expansion of the amounts to material recycling. To expand the material recycling from the waste fractions that are recycled today, will mean that more “filthy” material than today must be recycled with a high efficiency. This means

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47 Observe that this would require a high value of wood for energy use. Today, the major part of the solid biofuels in Sweden arises as by-products at sawmills and at pulp and paper production. The wood is thus cut down for material use primarily, which can be explained with higher value for material use than energy use. Increased material recycling, leading to less virgin production of paper, could then lead to reduced felling of wood and consequently to less by-products available for energy use. In such situation, material recycling would instead reduce the available amount of biofuels at a competitive price.
that the quality of source-separation and/or the technology for central separation must be further developed from the levels achieved today. In this scenario, we are assuming that this is possible.

**Conclusion:** The material recycling efficiency is high for all waste fractions that today are possible to recycle. Furthermore, the material recycling is further developed to manage a larger share of the generated waste.

The Landfill Directive will stimulate expansion of biological treatment as an alternative for biodegradable waste that cannot be landfilled after 2016. Due to the strong focus on reduction of GHG-emissions in this scenario, we find it probable that anaerobic digestion will be the main option for biological treatment (cf. figures 4.6 and 4.7, where anaerobic digestion is clearly favourable over composting in all cases A-H) due to its higher energy recovery through biogas. The total costs for anaerobic digestion compared to composting are relatively high today. However, we assume in this scenario that taxes and regulations will force the development in this direction. This development is also stimulated through the EU ambitions on increasing the share of renewable fuels in vehicles, where the biogas from anaerobic digestion becomes an important alternative. Research and development thus make the **biological treatment efficiency** high for anaerobic digestion. Composting will be of less importance and the biological treatment efficiency will only increase slowly compared to the current situation.

**Conclusion:** Anaerobic digestion will be the main biological treatment alternative. It will have a high biological treatment efficiency.

In table 4.5, we have summarised the discussion of the levels of the key factors in scenario 1.

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Level in scenario 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy recovery from incineration</td>
<td>Relatively high- high</td>
</tr>
<tr>
<td>Alternative electricity and heat generation</td>
<td>Based on natural gas and renewables</td>
</tr>
<tr>
<td>The material recycling efficiency</td>
<td>High (for more materials than to today are possible to recycle)</td>
</tr>
<tr>
<td>The biological treatment efficiency</td>
<td>High for anaerobic digestion Medium for composting</td>
</tr>
</tbody>
</table>

Based on this, we draw the following conclusions for the management of organic combustible waste fractions:

- Material recycling is the best environmental option for well source-separated, “clean” materials.

- For the biodegradable part of waste that cannot be treated with a high material recycling efficiency, waste incineration and anaerobic digestion are the preferable alternatives from a GWP perspective. The difference between
waste incineration and anaerobic digestion is small, and will probably depend on local conditions.

- For the waste that cannot be treated by either material recycling or anaerobic digestion with a high efficiency, waste incineration is the preferable alternative from a GWP perspective.

- To efficiently reduce the GHG-emissions, a combination of material recycling, anaerobic digestion and incineration is the best strategy. Compared to today, this would mean that all these methods would expand in order to replace landfiling, which is the worst option.

**Scenario 2: Greenhouse gases of less importance**

In this scenario, the reduction of greenhouse gas emissions becomes a lower environmental priority in society than today. The reduction of greenhouse gas emissions is not totally abandoned and remains a pressing issue. For Europe, the targets of the Kyoto protocol are not met. Although measures are taken to curb the emissions, by 2030 the total European emissions are higher than today due to increased material and energy consumption.

Compared to scenario 1, the lower importance of GHG-emission reductions will imply that the energy recovery from incineration is not increased to the same level. However, we believe that the energy recovery will increase compared to the level of today. An important reason for this development is the EU ambitions on reducing its dependence on imported fuels. Furthermore, increased energy recovery is also demanded by the EU as one important requirement for defining waste incineration as a recovery method instead of a disposal method.

**Conclusion:** Higher energy recovery for most incineration plants in Europe than today. The energy recovery level is slightly lower than in scenario 1.

Compared to scenario 1, the reduced pressure for GHG-emission reductions means a slower expansion of the use of renewables. However, use of renewables is expanded as a mean for Europe to reduce its dependence on imported fuels and to achieve CO2 reduction demands. For alternative heat generation this means that biofuels are used, to a larger extent, in regions where the local conditions makes it cost efficient. In other regions, fossil fuels such as natural gas and coal will still be used. For Europe as a whole, the alternative heat generation is thus produced through a mix of fuels (coal, natural gas and biofuels), where the major part is of fossil origin.

The alternative electricity generation is changed compared to today. The major GHG-reductions due to the Kyoto Protocol come from increased use of renewables in stand-alone plants (e.g. wind power plants), increased efficiencies in coal power plants, co-combustion of solid renewables (e.g. biofuels) in coal power plants and cement kilns and through fuel switches from coal to natural gas. Depending on the availability of fuels as at a competitive price, the solution differs between regions. This means that the marginal electricity production will differ between different regions. For Europe as a whole, the alternative electricity generation is produced
through a mix of fuels (coal, natural gas and renewables), where the major part is of fossil origin.

**Conclusion:** Alternative electricity and heat generation will differ within European regions. For Europe as a whole, they will constitute a mix of fuels (coal, natural gas and renewables), where the major part is of fossil origin.

The results from the case studies discussed in this report shows that material recycling is beneficial over incineration also regarding regional and local environmental impacts such as e.g. acidification (see e.g. tables 3.2a and 3.3a). Again, it must be stressed, this requires that the material recycling efficiency is high. In this scenario, we find it probable that existing material recycling will be developed and reach a high efficiency for most waste fractions. However, we have assumed that the lower interest for GHG compared to scenario 1, will lead to less technology development to expand the material recycling to handle the “filthier” material as well.

**Conclusion:** The material recycling efficiency is high for most waste fractions that today are possible to recycle.

Also in this scenario, we find it probable that the Landfill Directive will stimulate expansion of biological treatment as an alternative for biodegradable waste that cannot be landfilled after 2016. Although anaerobic digestion shows a better potential for reducing regional and local environmental impacts than composting in the studies in chapter 3.2 (cf. tables 3.4a and 3.5a), we still find it possible that composting can be a viable option through emission reduction at the process and at spreading of the residue. Furthermore, composting can be an alternative since it can handle a larger range of biodegradable waste than anaerobic digestion. In regions where biogas only would be used to replace renewable fuels in alternative electricity and heat generation, the competitiveness of composting is further enhanced. Overall, for both technologies, we believe that the lower interest for GHG compared to scenario 1 lead to less technology development. The biological treatment efficiency will thus be lower than in scenario 1.

**Conclusion:** Anaerobic digestion and composting will both be biological treatment alternatives. The biological treatment efficiency will increase compared to today, but it will not be as high as in scenario 1.

In table 4.6, we have summarised the discussion of the levels of the key factors in scenario 1. Based on this, we draw the following conclusions for the management of organic combustible waste fractions:

- Material recycling is the best environmental option for well source-separated, “clean” materials. In comparison with scenario 1, less waste fractions would be treated through material recycling due to less technology development.

- For the biodegradable part of waste that cannot be treated with a high material recycling efficiency, waste incineration and anaerobic digestion are the preferable alternatives from a GWP perspective. However, since GWP is of less importance in this scenario, composting is also a strong alternative. If the
biological treatment would constitute a mix of anaerobic digestion and composting, waste incineration would generally be preferred over biological treatment from a GWP perspective.

- For the waste that cannot be treated by either material recycling or biologically with a high efficiency, waste incineration is the preferable alternative from a GWP perspective.

- To efficiently reduce the GHG-emissions, a combination of material recycling, biological treatment and incineration is the best strategy. Compared to today, this would mean that all these methods would expand in order to replace landfilling, which is the worst option.

Table 4.6 Level of key factors in scenario 2

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Level in scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy recovery from incineration</td>
<td>Medium-relatively high</td>
</tr>
<tr>
<td>Alternative electricity and heat generation</td>
<td>Based on a mix of fuel (coal, natural gas, renewables), where the major part is of fossil origin</td>
</tr>
<tr>
<td>The material recycling efficiency</td>
<td>High (for most waste fractions recycled today)</td>
</tr>
<tr>
<td>The biological treatment efficiency</td>
<td>Medium-relatively high</td>
</tr>
</tbody>
</table>
4.4 Concluding remarks

Delimitations
It is important to stress that the conclusions in 4.2 and 4.3 are valid when we look at the environmental performance of waste management options only. Since the evaluation does not include any analysis of the costs of the different options, we cannot judge to what levels it is reasonable to e.g. expand the material recycling. From the viewpoint of the whole society, there might be other measures (e.g. improvement of transport efficiency, increased energy conservation etc.) that will give a better environmental improvement at the same cost as expanded material recycling. To make this evaluation, the costs and benefits of the waste management options must be compared with other measures for reduced pressure on the environment, which is a task beyond the scope of this work.

The systems analyses included in this study are based on a technical modelling of waste management. However, one must keep in mind that models are always simplified versions of reality. The models are designed to give information regarding the environmental impacts of different waste management options. Although some of them can be used for evaluating costs and benefits, they normally fail to capture other important aspects of waste management such as:

- Social values and social impacts
- Flexibility
- Work environment

In effect, the results from systems analyses can never be the sole criteria for decisions regarding waste management. They give important information that should be evaluated together with other information regarding aspects that are not covered in the systems analyses.

Environmental performance of waste incineration
Looking at waste incineration in 4.2 and 4.3, we can observe a development towards higher energy recovery than today in both scenarios, which improves the environmental performance of waste incineration. In both scenarios, waste incineration is an important option that should be expanded together with material recycling and biological treatment in order to reduce landfilling. After waste prevention and re-use, it is clear that a combined strategy of material recycling, waste incineration and biological treatment replacing landfilling of organic combustible waste, would be the most efficient way to reduce the environmental impact from waste management. The distribution of waste being treated by material recycling, waste incineration and biological treatment will vary and should not be decided on a common European level. Regional differences will lead to different distributions being optimal for different regions.
5. References


Ekvall, T., Key methodological issues for life cycle inventory analysis of paper recycling, Journal of Cleaner Production 7, pp 281–294, 1999


IPCC (Intergovernmental Panel on Climate Change), Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, corrected version June 15, 2001


Moberg, A., Finnveden, G., Johansson, J., and Lind, P., Life Cycle Assessment of Energy from Solid Waste – Part 2: Landfilling compared to other treatment methods, paper currently being reviewed, 2004

Reimann, D.O., Determination and importance of characteristic numbers to the energy and plant utilization as well as to efficiencies for the waste incineration, paper presented at ISWA-Beacon Conference, Malmö, October, 2003

RVF, Swedish Waste Management 2000, 2000

List of abbreviations

**Acidification** is a process where air pollution (ammonia, sulphur dioxide and nitrogen oxides) is converted into acid substances. The substances cause damage to forests and lakes.

**Anaerobic digestion (fermentation)** is a biological process that produces biogas, which can be used as a fuel for district heating, electricity or transportation.

**AOX** Adsorbable halogenated organic material

**BAT** Best Available Technique

**BOD** Biological oxygen demand

**BREF** Best available techniques ReFerence documents, currently being developed due to IPPC-directive 96/61/EC (Integrated Pollution and Prevention Control).

**Cd** Cadmium

**CH4** Methane

**CHP** Combined heat and power. Simultaneous production of electricity and heat. The heat can be used for district heating or industrial purposes.

**CHX** Volatile halogenated hydrocarbons

**CO** Carbon monoxide

**CO2** Carbon dioxide

**COD** Chemical oxygen demand

**EDIP** Environmental design of Industrial Products

**EIA** Environmental Impact Assessment

**Eutrophication** is the enrichment of nutrients in an aquatic system. It is typically caused by leached phosphorus or nitrogen containing compounds.

**Feedstock recycling** is a change in the chemical structure of the material, where the resulting chemicals are used for another purpose than producing the original material. The feedstocks generated include synthesis gas (CO and H2). Energy released during these processes is generally used or recovered.

**Gasification** converts carbonaceous materials into combustible gases.

**GHG** Greenhouse gases
**Global warming**: the average temperature of the Earth’s atmosphere and oceans is increasing due to anthropogenic emissions of so-called "greenhouse gases".

**GWP** Global Warming Potential is a substance’s possible contribution to the global warming.

**HCl** Hydro chloride acids

**Hg** Mercury

**LCA** Life Cycle Assessment

**LCI** Life Cycle Inventory

**Mechanical biological treatment** is a pre-treatment of substances to in order to form a stable product for landfilling. It can consist of iron scrap recovery, biological treatment, and separation of waste for incineration.

**MSW** Municipal Solid Waste

**N2O** Nitrous oxide

**NMVOC** Non-methane volatile organic compounds

**NOX** Nitrogen oxides

**Ozone depletion** is the decrease in the atmosphere’s ozone layer. Most scientists say that human-made substances, particularly Chlorofluorocarbons (CFCs), cause the ozone depletion.

**PAH** Polyaromatic hydrocarbons

**PCB** Polychlorinated biphenyls

**Pb** Lead

**PE** Polyethylene

**PECK** Technology for incineration with recovery of iron, copper, zink, and lead

**PET** Polyethylenterephthalat

**Photooxidants** forms through emissions of hydrocarbons (e.g. NMVOC, VOC) and other organic compounds. Through chemical reactions organics and ozone are formed that e.g. give eye irritation and cause severe damage to leafy plants.

**PM10** Particles with a diameter less than 10 micrometer that can be inhaled beyond the larynx.

**PP** Polypropylene
PS Polystyrene

PVC Polyvinyl Chloride

**Pyrolysis** is a form of incineration that chemically decomposes organic materials by heat in the absence of oxygen.

RDF Refused Derived Fuel

SO2 Sulphur dioxide

**SORTEC**hnology 3.0 is the name of the German DSD system's sortation plant in Hannover, Germany. It is the world's first fully automated sorting and recycling plant. It takes curbside packaging and sorts it into tin cans, aluminium, paper drink cartons, PET, PS, PE, and mixed plastics. SORTEC then automatically produces pelletized PS and PE, plus a polyolefin agglomerate that is used in blast furnaces.

ST Surveyable time period

TOC Total organic carbon

**Toxicity** can be human, aquatic, terrestrial, ecological, etc and is a measure to the degree to which something is toxic or poisonous.

USES Uniform system for the Evaluation of Substances

VOC Volatile organic compounds

WID Waste Incineration Directive

WtE Waste-to-Energy
Appendix A. Selected studies for a brief examination


Appendix B. Key factor studies


Ekvall, T., Key methodological issues for life cycle inventory analysis of paper recycling, Journal of Cleaner Production 7, pp 281–294, 1999


Moberg, Å, Finnveden, G., Johansson, J., and Lind, P., Life Cycle Assessment of Energy from Solid Waste – Part 2: Landfilling compared to other treatment methods, paper currently being reviewed, 2004

Sundqvist, J-O., Some Methodological Questions and Issues that are of Great Interest for the Result in LCA, Proceedings from Workshop on System Studies of Integrated Solid Waste Management in Stockholm 2 - 3 April, pp 131-140, 2001

Appendix C. Other relevant studies giving input to this study


COWI (Consulting Engineers and planners AS), *European Commission DG Report A study on the economic valuation of environmental externalities from Landfill disposal and incineration of waste*, Final main report, October, 2000


RDC-Environment (Research Development and Consulting), and Pira International, *Evaluation of costs and benefits for the achievement of reuse and recycling targets for the different packaging materials in the frame of the packaging and packaging waste directive 94/62/EC*, Final Consolidated report, March 2003


### Appendix D Overview of selected systems analyses

**Table D1** Overview of selected systems analyses with focus on the results/conclusions regarding environmental impacts of waste incineration in comparison with other treatment options.

<table>
<thead>
<tr>
<th>Ref / Region</th>
<th>Waste fractions</th>
<th>Impact categories</th>
<th>Treatment options</th>
<th>Main conclusions drawn in the studies</th>
</tr>
</thead>
</table>
| 1 / Austria  | Biowaste, Plastic packaging, Metals, Rest waste | GWP, Acidification, Net energy use | - Recycling: kerbside or bring system collection  
- No recycling: kerbside collection without separation followed by mechanical-biological treatment + landfill, thermal treatment of paper and plastic | - Waste paper: non-recycling (=incineration with energy recovery) reduces global warming emissions and increase energy savings.  
-Plastic: materials recycling leads to clearly lower global warming emissions (but to high costs) |
| 2 / Austria  | Non-packaging plastic waste from the sectors of building, agriculture, end-of-life vehicles, end-of-life electrical appliances and furniture | Financial + environmental costs/benefits = Net economic cost/benefit  
Environmental costs/benefits based on valuation of energy balance, CO2- and CH4-emissions, TOC-emissions and waste to landfill sites | - Mechanical recycling  
- Incineration with energy recovery 80 %, landfilling 20 % | - Benefits of mechanical recycling are larger than the benefits of the alternative residual waste collection and treatment.  
- The cost-benefit balances were positive for all the recycling routes under investigation.  
- Expanding the mechanical recycling of non-packaging plastic waste would produce additional macro-economic benefits of up to 6,3 million euro p.a.  
- The study shows that the potential for mechanical recycling is extremely limited. For the remaining volume, energy recovery must be aimed at. |
| 3 / Austria  | Packaging plastic waste from commercial and household sector, non- | Financial + environmental costs/benefits = Net economic cost/benefit  
Environmental costs/benefits based on | - Recycling  
- 80 % landfilling and 20 % incineration with energy recovery  
- 80 % incineration with energy recovery and 20 % landfilling | - Increased recycling proved positive effects for all the ecological parameters selected within the system investigated  
- The cost-benefit analysis showed a positive result for recycling of production and non-packaging waste. |

48 Also includes resource use, energy balances, generated waste and costs/benefits when a valuation of emissions to the environment has been performed.
<table>
<thead>
<tr>
<th>Packageing plastic waste, production plastic waste</th>
<th>Valuation of energy balance, CO2- and TOC-emissions and the volumes of waste to landfill</th>
<th>- For recycling of commercial packaging waste, the result was slightly negative. - For recycling of household packaging waste, the result was clearly negative. - Incineration is a better option than landfilling.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/ Denmark</td>
<td>Plastic</td>
<td>GWP, Ozone depletion, Acidification, Eutrophication, Ozone formation, Toxicity, area degradation, physical disturbance</td>
</tr>
<tr>
<td>5/ Denmark</td>
<td>Waste food from catering centres</td>
<td>GWP Ozone depletion Acidification Eutrophication Photochemical oxidants Human toxicity Ecotoxicity Waste Use of: fossil fuels, metals, minerals, water, energy</td>
</tr>
<tr>
<td>6 / Denmark</td>
<td>Organic household waste</td>
<td>GWP, Acidification, Eutrophication, Photochemical oxidants, Consumption of primary energy carriers, non-renewable energy carriers</td>
</tr>
</tbody>
</table>
| 7 / Europe | Combustible waste | Internal and external (social and | - Incineration CHP. - Incineration, only electricity | - The best results are given for the high yield fuel preparation for co-combustion in coal power plants.
<table>
<thead>
<tr>
<th>8 / Europe (EU-15)</th>
<th>MSW</th>
<th>GWP / Private financial costs / Energy used</th>
<th>- Landfill - Mechanical-biological pre-treatment + landfill - Incineration with energy recovery - Composting - Anaerobic digestion - Recycling</th>
<th>- Source separation followed by recycling and composting or anaerobic digestion gives the lowest net flow of greenhouse gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 / Europe (EU-12)</td>
<td>Municipal solid waste</td>
<td>Financial + environmental costs = Net economic cost Environmental costs based on valuation of emissions of CO2, CH4, CO, N2O, SO2, NOX and PM10</td>
<td>- Landfill - Incineration with energy recovery - Recycling: bring, kerbside, commingled - Composting and recycling: commingled or kerbside</td>
<td>- Average total net economic costs are significantly less for recycling compared to incineration and landfilling - Total net economic costs for landfilling are less than for incineration - Savings for composting are outweighed by the net environmental costs</td>
</tr>
<tr>
<td>10 / Europe (EU-15)</td>
<td>Organic Paper Glass Plastics Metal Other</td>
<td>Environmental &amp; health effects (Treated in the same way as in reference 9)</td>
<td>- Landfill - Composting - Recycling - Incineration - Incineration with energy recovery</td>
<td>- If all existing policies are fully implemented and enforced, the EU will be successful in reducing pressures on the environment. - Virgin materials tax on plastic and paper result in an overall prevention of 3%. - Taxation of packaging materials leads to an average reduction of MSW of 3.5%</td>
</tr>
<tr>
<td>11 / France</td>
<td>Household waste</td>
<td>Resource depletion Toxicity Acidification GWP Water pollution Production of waste</td>
<td>- Recycling - Incineration with energy recovery</td>
<td>- Selective collection of waste beneficial, as it allowed improved working conditions for the incinerator. - The environmental benefits induced by waste recycling, were compensated for by use of additional boilers</td>
</tr>
<tr>
<td>12 / France</td>
<td>Municipal solid waste</td>
<td>Consumption of natural resources</td>
<td>- Incineration with electricity production, 15% efficiency</td>
<td>When incineration is used: - It generally has less impacts than landfilling</td>
</tr>
</tbody>
</table>
### 13 / Germany

<table>
<thead>
<tr>
<th>Category</th>
<th>Subcategory</th>
<th>Environmental Impacts</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic packaging</td>
<td></td>
<td>GWP, Acidification, Consumption of energy resources</td>
<td>Incineration with energy recovery (mixed plastics), 3 feedstock recycling methods: Blast furnace, SVZ gasification &amp; methanol synthesis, BASF thermolysis (projected)</td>
</tr>
</tbody>
</table>

### 14 / Germany

<table>
<thead>
<tr>
<th>Category</th>
<th>Subcategory</th>
<th>Environmental Impacts</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightweight packaging waste (13 different types)</td>
<td></td>
<td>Eutrophication, GWP, Acidification, Photochemical oxidants, Human toxicity, Consumption of resources (fossil fuels), Space (including landfill volumes)</td>
<td>Today’s (1998) recycling, Optimisation of today’s recycling, Future recycling, 70% landfilling and 30% incineration with energy recovery, 100% incineration with 70% energy recovery</td>
</tr>
</tbody>
</table>

### 15 / Germany

<table>
<thead>
<tr>
<th>Category</th>
<th>Subcategory</th>
<th>Environmental Impacts</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics from packaging in domestic waste</td>
<td></td>
<td>Energy resources, GWP, Eutrophication, Acidification, Waste amounts (MSW and hazardous waste)</td>
<td>Mechanical recycling, replacing virgin plastics, Mechanical recycling, replacing concrete/wood, Feedstock recycling, 5 types</td>
</tr>
<tr>
<td>Location</td>
<td>Type</td>
<td>Energy Recovery Method</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>------</td>
<td>------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Germany</td>
<td>Post-consumer plastics</td>
<td>- Energy recovery, fluid-bed combustion, 100% efficiency - Waste incineration, 34% efficiency - Landfilling, reference</td>
<td>- Feedstock recycling and energy recovery processes perform moderately well. - Mechanical recycling processes that use the mixed plastics fraction to make substitutes for wooden or concrete products perform the worst, as they substitute energy-rich plastics for products whose conventional manufacture uses little energy.</td>
</tr>
<tr>
<td>Italy</td>
<td>Plastic from agriculture - Domestic - Non-specific industrial</td>
<td>- Average incineration with energy recovery, Germany reference case - Mechanical recycling - Feedstock recycling - Efficient incineration, higher energy recovery - Cement kiln</td>
<td>- All options studied show better performance regarding these two aspects than waste treatment in an average incinerator - The assessment does not support a general recommendation of energy recovery, mainly due to the large difference between the German average and the best available waste-to-energy facilities.</td>
</tr>
<tr>
<td>Italy</td>
<td>MSW household</td>
<td></td>
<td>- Landfilling is the cheapest, but has a high environmental impact - Increased landfilling fees leads the productive system to a more integrated waste management system, which reduces the GWP</td>
</tr>
<tr>
<td>Italy</td>
<td>Plastic packaging</td>
<td></td>
<td>- Landfill shows poor environmental performance. - Mass burn shows lowest environmental impact for energy consumption, crude oil consumption, and CO2 eqv. and highest environmental impacts for water consumption, dust, and water emissions</td>
</tr>
</tbody>
</table>

**Post-consumer plastics**

- **Gross energy, CO2**

- **Energy consumption**
  - GWP (CO2 eqv)
  - Acidification (SO2 eqv)
  - Dust
  - Emissions of organic compounds
  - Water consumption
  - Water emissions
  - Solid waste to landfill

- **Energy recovery**
  - Landfilling
  - Recycling
  - Incineration with electricity production
  - Composting

- **Efficient incineration, higher energy recovery**
  - Cement kiln

- **Landfilling**

16 / Germany

17 / Italy

18 / Italy

19 / Italy

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**Evaluating waste incineration as treatment and energy recovery method from an environmental point of view - final version 2004-05-13**
<table>
<thead>
<tr>
<th>Consumption: energy resources, water, oil</th>
<th>+landfilling</th>
<th>- Mechanical recycling +landfilling +incineration with energy recovery - Mechanical recycling +incineration with energy recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water emissions: Eutrophication Emissions of metals Solid waste volume to landfill</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>20 / Italy</th>
<th>Paper</th>
<th>Dominant impacts: Energy use Greenhouse gases Also considered: Acid gas emissions Water consumption Solid waste volumes.</th>
<th>- Landfilling - Recycling back into paper and board for packaging - Incineration, electricity eff. 27.7%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- Recovery of energy from waste paper is preferred over recycling or landfilling, according to all significant impact categories in the environmental comparison. - The benefits of energy recovery are strong because the primary producer has an energy sector dominated by low-carbon sources, while Italy has a carbon intensive energy sector.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>21 / Norway</th>
<th>MSW, industrial, special, commercial waste</th>
<th>GWP Freshwater aquatic toxicity Seawater aquatic toxicity Terrestrial toxicity Photochemical oxidation Acidification Eutrophication</th>
<th>- Central and local incineration with energy recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- The local, small-scale alternative is better for all impact categories, even costs.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>22/ Spain</th>
<th>Organic waste</th>
<th>Energy use Greenhouse gases</th>
<th>- Composting - Composting + extra kerbside collection round - Composting of organic paper fractions - Composting of organic paper fractions + extra kerbside collection round</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- Adding composting to the current materials recycling and landfill would increase the energy use, but reduce the GWP of the overall system</td>
<td></td>
</tr>
<tr>
<td>Page</td>
<td>Description</td>
<td>Financial economy, welfare economy, GWP</td>
<td>Acidification</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>----------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>23 / Sweden</td>
<td>MSW from households</td>
<td>Financial economy, welfare economy, GWP</td>
<td>Acidification</td>
</tr>
<tr>
<td>24 / Sweden</td>
<td>Household waste, park &amp; yard waste, industrial waste, building &amp; demolition waste</td>
<td>Exergy of abiotic and biotic resource use, GWP, Ozone layer depletion, Human toxicity, Fresh water aquatic ecotoxicity, Marine water aquatic ecotoxicity, Terrestrial ecotoxicity, Photochemical oxidation, Acidification, Eutrophication</td>
<td>Four different combinations of waste treatment options:</td>
</tr>
<tr>
<td>25 / Sweden</td>
<td>Combustible, recyclable or compostable fractions of municipal solid waste</td>
<td>Focus is on energy use and climate change. Other impact categories such as acidification, eutrophication, photo-</td>
<td>- Landfilling</td>
</tr>
<tr>
<td>No</td>
<td>Country</td>
<td>Waste Category</td>
<td>Environmental Impacts Considered</td>
</tr>
<tr>
<td>-----</td>
<td>---------</td>
<td>----------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>26</td>
<td>Sweden</td>
<td>Organic waste from the food industry and households</td>
<td>GWP, Eutrophication, Acidification, Photochemical oxidants, Emission of particles</td>
</tr>
<tr>
<td>27</td>
<td>Sweden</td>
<td>Packaging waste (glass, metal and plastic) and newspaper</td>
<td>Financial + Environmental costs + valuation of consumers’ time for source-separation = Society’s cost Environmental costs based on full LCI (results evaluated with three methods)</td>
</tr>
<tr>
<td>28</td>
<td>Switzerland</td>
<td>MSW</td>
<td>Abiotic depletion GWP Ozone depletion</td>
</tr>
<tr>
<td></td>
<td>Toxicity (various)*&lt;br&gt;Summer smog&lt;br&gt;Acidification&lt;br&gt;Eutrophication</td>
<td>- Grate Incineration with energy recovery&lt;br&gt;- PECK (=Incineration with energy recovery + Fe, Cu, Zn, Pb recovery)</td>
<td>treatment offer inferior performance compared to the thermal technologies, due to low energy efficiency.&lt;br&gt;-Sanitary landfill is the worst treatment option for mixed waste.&lt;br&gt;- Long-term releases of heavy metals to water cause the largest share of impact for all treatment options.&lt;br&gt;-It can generally be stated that using the energy content of the waste efficiently is of great importance – either by material recycling or by thermal recovery of feedstock energy.</td>
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<tr>
<td>29 / United Kingdom</td>
<td>Paper</td>
<td>Primary energy use CO, CH4, NOX, SO2, CO2, particulates Social costs</td>
<td>- Recycling&lt;br&gt;- Incineration 20% electricity&lt;br&gt;- Anaerobic digestion&lt;br&gt;- Landfill (+energy recovery)</td>
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<td>- Recycling of paper may not be the best use of this resource.&lt;br&gt;-Incineration imposes lower environmental costs than recycling and reduced consumption of primary energy&lt;br&gt;-The total freight-tonne-kilometres increases with the increased imports of virgin pulp (via sea freight), but the road haulage diminishes, since incinerators are normally located closer to the cities than paper re-pulping facilities.&lt;br&gt;-The model indicates that solid waste deposited in landfill would reduce by 15% under a high externality scenario, as incineration increases, which reduces emissions of methane (with a greater global warming potential than CO2)</td>
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<tr>
<td>30 / United Kingdom</td>
<td>Household + construction + demolition waste</td>
<td>Net energy use CO2 CH4</td>
<td>- Composting + Landfilling (incl. collection of biogas)&lt;br&gt;- Recycling, kerbside sorting&lt;br&gt;- Incineration without energy recovery&lt;br&gt;-Landfilling&lt;br&gt;- No separate collection of recyclables +material recovery facility (MRF) + RDF</td>
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| | | | - Main differences in environmental burden due to recovery of energy or materials.<br>- The environmental burden caused by CO2 and CH4 changes dramatically between scenarios.
| 31 / United Kingdom | Municipal waste (in a county) | GWP, Resource depletion, Air acidification, Eutrophication, Stratospheric ozone depletion, Emissions of dioxins | Five options are “led” by the following technologies: - 1: mass burn energy from waste facility; - 2: anaerobic digestion; - 3: enhanced recycling and composting, landfill in-county; - 4: enhanced recycling and composting, landfill out-of-county; and - 5: fluidised bed energy from waste facility. | - Options 1 and 5 clearly better than the other options for all impacts except for emissions of dioxins - Small differences between option 1 and option 5 regarding environmental impacts |

*Human toxicity, Freshwater aquatic toxicity, marine aquatic toxicity, Freshwater sediment toxicity, marine aquatic toxicity, freshwater sedimental toxicity, marine sedimental toxicity

** Air: CO2, CO, CH4, NOX, SO2, HCl, NMVOC, dust, CFC, Cd, Hg, Pb. Water: COD, NH4, Cd, Hg, Pb