

# Environmental impacts of landfilling of solid waste compared to other options

## – assumptions and boundaries in Life Cycle Assessment

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## **Abstract**

In the present paper the validity of the waste hierarchy for treatment of solid waste is tested. This is done by using the tool Life Cycle Assessment on recycling, incineration with heat recovery and landfilling of recyclable waste for Swedish conditions. A waste hierarchy suggesting the environmental preference of recycling over incineration over landfilling is found to be valid as a rule of thumb. There are however assumptions and value choices that can be made which make landfilling more preferable. This is the case for some waste fractions and for some of the environmental impacts studied when only a limited time period is considered. When transportation of waste by passenger car from the households is assumed for the other treatment options but not for landfilling, landfilling also gains in preference in some cases. The paper concludes that assumptions made including value choices with ethical aspects are of importance when ranking waste treatment options.

Key words: Landfill, Life Cycle Assessment, waste, hierarchy, time perspective, carbon sink, transport

## 1 Introduction

Waste is generated as a consequence of most of our daily activities. How to take care of this waste in the most efficient way and with the least negative impacts arising is a question of concern. A waste hierarchy is often suggested and used in waste policy making. Different versions of the hierarchy exist but in most cases it suggests the following order:

1. Reduce the amount of waste
2. Reuse
3. Recycle materials
4. Incinerate with energy recovery
5. Landfill

The first priority, to reduce the amount of waste, is in general accepted. However, the remaining waste needs to be taken care of as efficiently as possible and the hierarchy after the top priority is often contested and discussions on waste policy are in many countries intense. Especially the order between recycling and incineration is often discussed, but as will be discussed later in this paper the order between incineration and landfilling may also change depending on assumptions made and system boundaries set.

The present paper summarises some of the results from a study performed at the Environmental Strategies Research Group (fms) where different strategies for treatment of solid waste are evaluated based on a life-cycle perspective (Finnveden *et al.* 2000). The aim of this paper is to test the validity of the waste hierarchy, focusing on cases where the landfill option may be higher ranked. Assumptions and valuations leading to these cases are also discussed.

## 2 Methodology and assumptions

### 2.1 Methodology

In general, Life Cycle Assessment (LCA) methodology based on standards and guidelines (ISO 1997; Lindfors *et al.* 1995) is used. This methodology is also applicable on LCAs on waste management (Clift *et al.* 2000; Finnveden 1999). The methodology used is described in more detail in Finnveden *et al.* (2000). LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. from cradle to grave) from raw material acquisition through production, use and disposal (ISO 1997). LCAs focus on products, or rather functions that products provide. Products can include not only material products but also service functions, for example taking care of a certain amount of solid waste. This is an appropriate perspective when comparing different options for waste management.

When comparing different options fulfilling a similar function it can be important to consider the complete life cycle and not only consider one phase, e.g. production or use. This is because environmental impacts and benefits may occur at different phases of the life cycle and phases leading to the main impacts may not be the same, comparing two options. Included is also any additional functions produced by a system, e.g. the production of a recycled material or the recovery of heat from waste treatment systems. To make possible the comparison of systems producing different additional functions the systems are credited the resources used and emissions produced if producing the additional function in some other way, so called avoided production. An example is that production of newspaper from wood with all related resources used and emissions is credited the studied system recycling of waste newspaper.

An LCA consists of four different phases which are performed in an iterative manner. They are, according to ISO (1997), *Goal and scope definition*, *Life cycle inventory analysis*, *Life cycle impact assessment* and finally *Interpretation* using results from all three previous steps. Within the impact assessment step classification, characterisation and weighting of the inventory results are performed. The classification is an assignment of the inventory data to selected impact categories. The categories included in this study are presented in Table 1.

Table 1. Impact categories used in the study.

Impact categories	
Total energy	SO <sub>x</sub>
Non-renewable energy	NO <sub>x</sub>
Abiotic resources	Acidification excluding SO <sub>x</sub> and NO <sub>x</sub>
Non-treated waste	Aquatic eutrophication excluding NO <sub>x</sub>
Global warming	NH <sub>3</sub>
Depletion of stratospheric ozone	Eco-toxicological impacts
Photo-oxidant formation	Human toxicological impacts

Following the classification, the contributions to the impact categories are quantified, so called characterisation. For this a number of established methods are used (Finnveden *et al.* 1992 (photo-oxidant formation); Finnveden & Östlund 1997 (abiotic resources); Houghton *et al.* 1996 (global warming); Lindfors *et al.* 1995 (acidification and eutrophication); Solomon & Wuebbles 1995 (depletion of stratospheric ozone)). Two different methods are applied to characterise toxicological impacts, the toxicity parts of the Danish EDIP method (Hauschild *et al.* 1998a; Hauschild *et al.* 1998b) and the Dutch model USES-LCA (Huijbregts 1999). The results from the characterisation are further processed by weighting. This means converting and aggregating results across impact categories. For this a method based on Swedish taxes, Ecotax 98, is used (Johansson 1999). Details about the impact assessment are presented in Finnveden *et al.* (2000). The results are interpreted using the outcomes from all steps of the assessment.

The different waste management options studied are landfilling, incineration, recycling of paper and plastic fractions and digestion and composting of food waste (Finnveden *et al.* 2000). The household waste fractions used as input to the systems are the combustible and recyclable or compostable ones; food waste, newspaper, corrugated cardboard, mixed cardboard and five plastic fractions. In this paper the focus is on the paper and plastic fractions. The waste management options are studied in a base scenario, which is complemented with a range of “what-if” scenarios.

Data for the materials recycling processes are from literature and databases (Baumann *et al.* 1993 (newspaper); FEFCO *et al.* 1997 (corrugated cardboard); Person *et al.* 1998 (polyethylene terephthalate, PET); Sas 1994 (polystyrene, PS, polypropene, PP, and polyvinyl chloride, PVC); Sundqvist *et al.* 2000 (mixed cardboard and polyethylene, PE). The incineration and landfill models are, somewhat modified, from Björklund (1998). The incineration model is based on a modern Swedish plant with flue gas condensation, ashes are landfilled. Energy generated at the plant is assumed to be used for district heating. The landfill model is representative of average Swedish municipal landfills. The model includes landfill fires (Fliedner 1999; Sundqvist 1999) and treatment of 80% of the leakage water during the first 100 years (Fliedner 1999; Nielsen & Hauschild 1998), leakage treatment sludge is landfilled according to Björklund (1998). The landfill gas formed during the methane phase is collected with 50% efficiency and combusted generating electricity and heat.

## 2.2 Time aspects

### 2.2.1 Time perspectives

One important difference between landfilling and most other processes in an LCA is the time frame. Emissions from landfills may prevail for a very long time, often thousands of years or longer. The potential emissions from landfilling have to be integrated over a certain time-period. It is important to determine which time period is of interest. There is currently no international agreement on this question (Finnveden and Huppes 1995). Using the LCA definition as a starting point, it can be argued that emissions should be integrated until infinity. In practise however, a shorter time frame (decades and centuries) has usually been chosen (see Finnveden (1999) for a review). The choice of the time period can have a significant influence on the results for materials that are persistent (e.g. plastics) and for substances which are only slowly leaching out, e.g. metals from municipal solid waste and ashes (Finnveden 2000).

The choice of the time frame is clearly a value choice for the inventory analysis of an LCA. It is related to ethical views about impacts on future generations (Finnveden 1997). It is clearly a question that deserves more attention. Important aspects to discuss include the possibilities and consequences of different choices as well as the ethical discussion, which apparently can not be avoided. A similar situation may occur for different parts of the life cycle impact assessment. The choice made by the SETAC-Europe working group on Life cycle impact assessment is to consider first the infinite time period, then a short time period of 100 years and finally if wanted other time periods (Udo de Haes et al. 1999a, Udo de Haes et al. 1999b).

Here a hypothetical infinite time period is used when inventorying emissions, which is considered to be in line with the precautionary principle. This may be seen as a “worst case”, assuming complete degradation and spreading of all landfilled material (Finnveden *et al.* 1995). To evaluate the effects of choosing another, shorter, time perspective this is also tried. A limit in time is then set after the 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. For municipal solid waste landfills this is defined as the time it takes for the landfill to reach the later part of the methane phase when gas production is diminishing and this time is approximated to be one century (Finnveden *et al.* 1995). For landfilling of incineration ashes the surveyable time period is defined as the period during which the soluble chloride salts are leached out (Sundqvist *et al.* 1997).

### 2.2.2 Carbon sink

Common practise in LCAs is to disregard biotic CO<sub>2</sub>-emissions. This can be motivated from different perspectives (Dobson 1998). One includes an expansion of the system boundary to include also the uptake of the CO<sub>2</sub> in the growing tree. This expansion is often done as a thought experiment rather than an actual modelling. Another perspective can be the assumption that when biotic resources are harvested, new resources are planted which will take up an equivalent amount of CO<sub>2</sub>. Again this modelling is normally not done explicitly. Yet another perspective is the assumption that if the biotic resources, e.g. trees, had not been harvested, they would have been left in the forest and degraded there. This degradation can however be quite slow, and the time frame has to be extended to several centuries before all biotic materials have been degraded (Zetterberg and Hansén 1998).

The biological carbon is thus seen as part of a cycle, where carbon is sequestered by and released from renewable sources continuously. However, if the surveyable time period is set as a boundary in time this cycle is interrupted. Then, one may consider landfills to be carbon

sinks keeping carbon from being released to the atmosphere. With this perspective the landfilling option may be credited the avoidance of the global warming potential the trapped biological carbon would have had as carbon dioxide in the atmosphere. This is done by subtracting carbon dioxide emissions corresponding to the amount of biological carbon trapped (Finnveden *et al.* 2000). However, this concept is as noted above a value choice neglecting potential effects on future generations.

### 2.3 Assumptions and scenarios

In the base scenario, the following major assumptions are made:

- distances for transportation of waste are moderate,
- heat production, which is credited waste treatment systems where heat is produced, is from incineration of forest felling residues,
- electricity is produced from hard coal,
- recycled material is credited waste treatment systems using data for production of virgin material of the same kind and
- the time perspective is a hypothetical infinite time period.

Several “what-if” scenarios are used to discover parameters of importance for the outcome of the study (Finnveden *et al.* 2000). The following are discussed here:

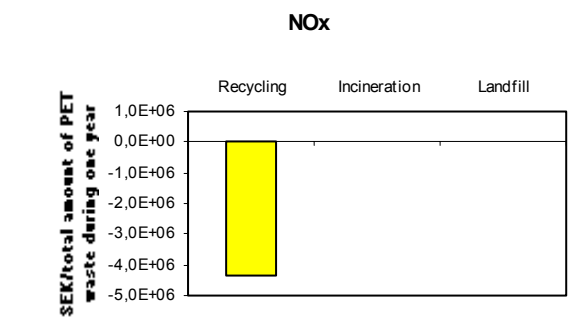
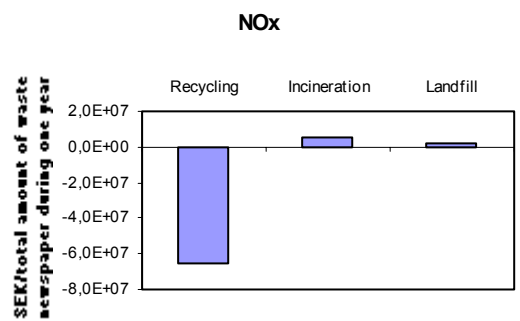
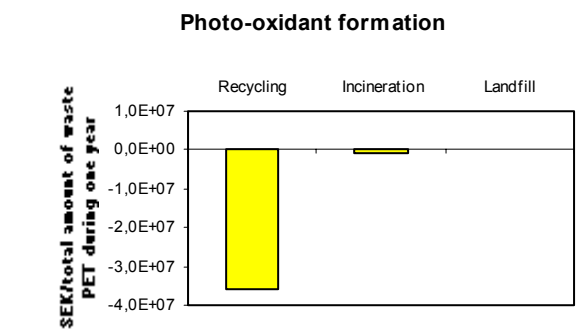
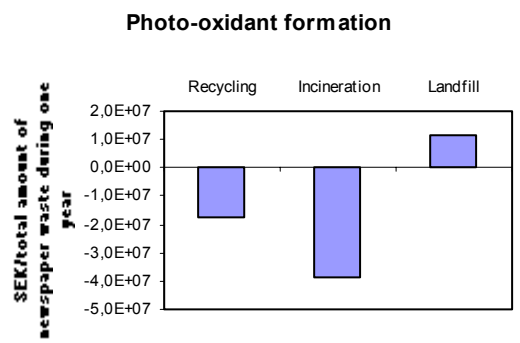
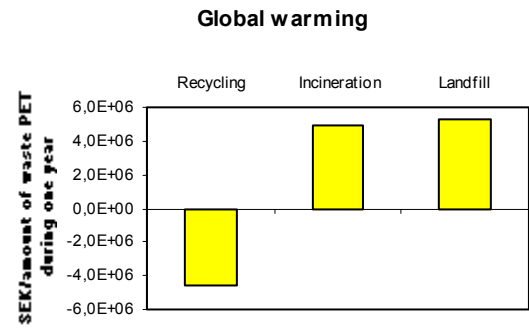
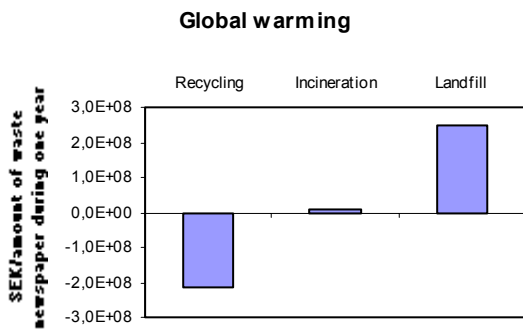
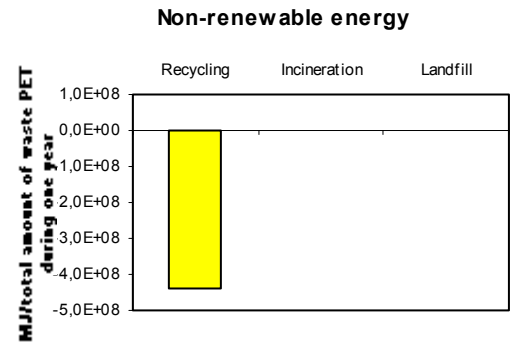
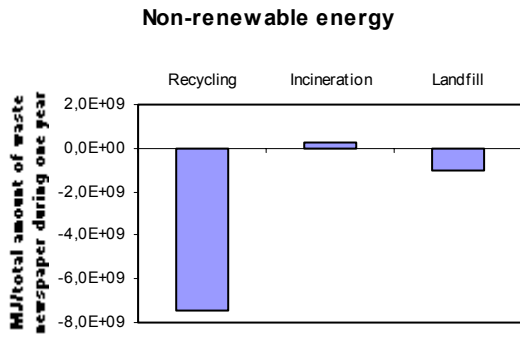
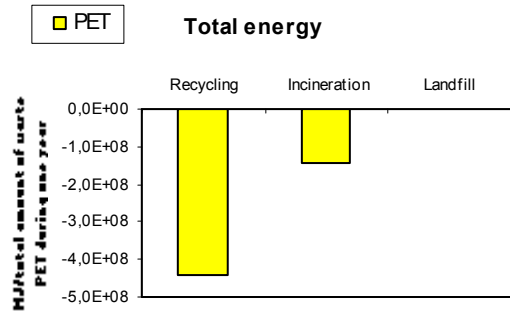
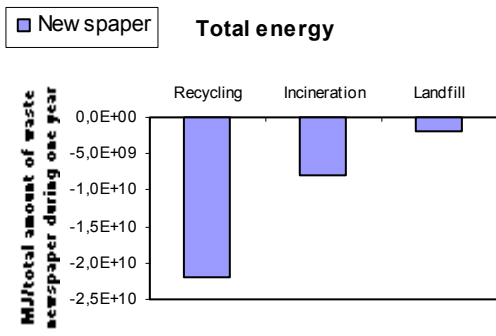
- *the natural gas scenario*, where heat production credited waste treatment systems with heat recovery is from natural gas,
- *the surveyable time period scenario*, where a limit in time regarding landfill emissions is set after approximately one century,
- *the carbon sink scenario*, which has the same time limit as the surveyable time period scenario, but also credits landfills for the biological carbon which is not emitted – the landfill is regarded as a carbon sink
- *the increased transports scenario*, where longer transport distances by truck to incineration and recycling facilities are assumed, and
- *the passenger car scenario*, where waste for recycling and incineration is source separated and transported by car to collection points. This variant is tried both for recycling and incineration due to the possible development towards separate incineration of different waste fractions for better efficiency and also towards small-scale and co-incineration using specific fractions, even though these incineration techniques are not specifically modelled here.

## 3 Results and discussion

In the following presentation only a selection of results are shown, for a full presentation of results see Finnveden *et al.* (2000).

### 3.1 General results

The results of the LCA of the base scenario indicate that landfilling is in general the least preferred option, results for some of the impact categories are presented in Figure 1. As the systems are credited for producing additional functions by subtracting emissions and resources used that would have been resulting from avoided production the results presented here may be negative. Negative results are thus avoided impacts. The results presented are for waste newspaper and PET (polyethylene terephthalate) representing paper and plastic waste. In Figure 1 exceptions, where landfilling is not lowest ranked, can also be seen for non-renewable energy use and NO<sub>x</sub>.



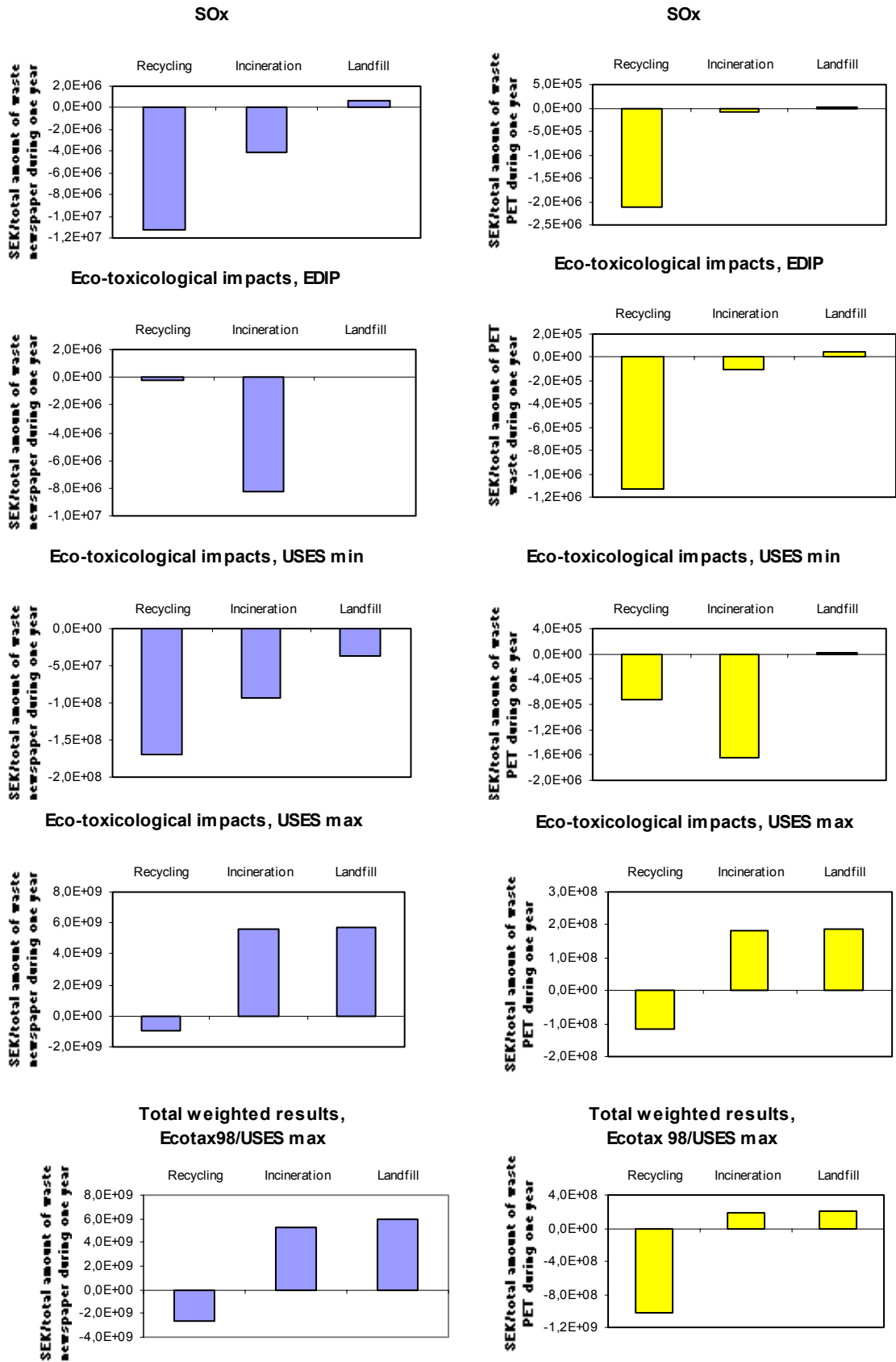


Figure 1. The diagrams are showing the rankings of waste treatment options for the waste fractions newspaper and PET (polyethylene terephthalate) for a selection of impact categories. Total weighted results of one of the impact assessment methods are also presented. The energy categories are presented as MJ and the other categories as SEK. This is because weighted figures are used, this however does not affect the relations within each impact category. Three different versions of the impact category eco-toxicological impacts are presented. The differences are due to different characterisation methods, EDIP and USES, and also to different weighting factors, USES min and USES max.



The total weighted results give the ranking recycling before incineration before landfilling, which is exemplified by results from the Ecotax 98/USES max method in Figure 1.

Looking at the total energy balance, landfill is ranked as the least preferable option. However, the non-renewable energy balance is dependent on assumptions concerning the origin of the energy production avoided when heat is produced from waste incinerators or landfill gas combustion. In the base scenario the origin is forest felling residues, when this is changed to natural gas, a non-renewable fuel, the ranking is changed, lowering landfilling to least preferred option. This is a consequence of more energy being recovered through incineration than through landfilling.

In Figure 1 three different results are presented for the category eco-toxicological impacts. The differences are in characterisation method used, EDIP or USES, and in weighting values, USES min and USES max, using different weights within the Ecotax 98 weighting method. As can be seen, the rankings are dependent on which method that is being used. This is a way of illuminating the large uncertainties related to the toxicological impact categories. For some of the other waste fractions the ranking of the landfill option may also change in this category, depending on method used.

### 3.2 Time perspective

In the surveyable time period scenario a large part of the metals, but also most of the fossil carbon, e.g. in waste plastics are not emitted from the landfill at all. A total cut-off after the surveyable time, approximately one century, has passed is made. The incineration option is also affected by the assumption of a shorter time perspective, since ashes are landfilled and e.g. the major part of the metals within the ashes are not emitted in this scenario.

When a shorter time perspective than in the base scenario is used concerning emissions from landfills the resulting rankings of the different waste management strategies may change. For newspaper and PET the categories where this happens are global warming and eco-toxicological impacts.

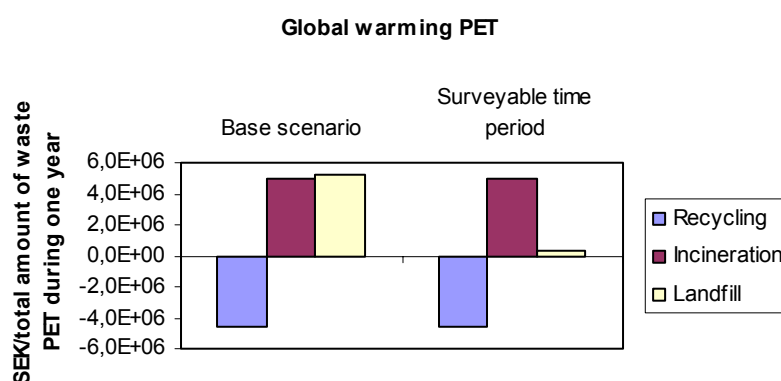


Figure 2. Results for the impact category global warming for waste PET. The results are shown for the base scenario and for the surveyable time period scenario.

For all the plastic fractions landfilling becomes preferable to incineration concerning global warming, recycling is still ranked as the most preferable option when a short time perspective is used. This is illustrated with PET as an example in Figure 2. Emissions of carbon to air from landfilling of plastic waste mainly occur subsequent to the surveyable time period, and are thus omitted in this scenario. When incinerating plastic waste, all carbon is immediately

emitted as carbon dioxide and thus landfilling of plastic waste is contributing less to global warming during the surveyable time period. In the case of landfilling newspaper, and other paper fractions, the major contribution to the global warming impact category is from emissions of methane during the surveyable time period and only a smaller difference is seen which, as shown in Figure 4, does not change the ranking of the treatment options.

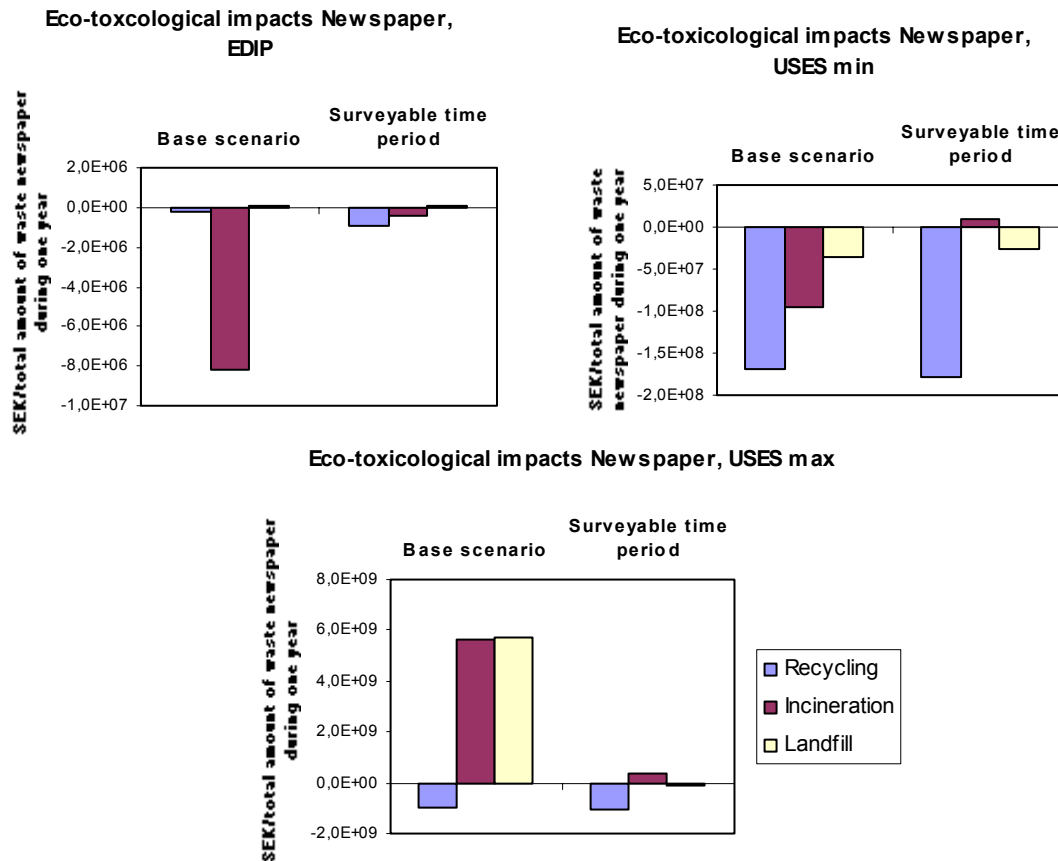


Figure 3. The results for the impact category eco-toxicological impacts for the waste newspaper fractions using three different impact assessment methods. The results are presented for the base scenario and for the surveyable time period scenario.

The other impact category affected by this change in time boundary is eco-toxicological impacts. Here, changes are dependent on how the eco-toxicological effects are modelled in the characterisation methods used. Since a large part of the metal content of the waste landfilled is modelled to leach out subsequent to the surveyable time period studied in this scenario the landfill option is better off here concerning eco-toxicological impacts. However, there are emissions of importance, using the toxicological impacts assessment methods presented earlier, which are counted also in this scenario. For example emissions from vehicles used and from landfill fires. Emissions from landfill fires which are of most importance are dioxins, but also to some extent PAHs. Ranking of waste treatment options concerning eco-toxicological impacts give landfill the ranking first, second and last depending on waste fraction and characterisation method used. In Figure 3, the results for the waste newspaper fraction is presented, changes for PET are similar.

### 3.3 Carbon sink

If, with the limited time perspective, the landfill is considered to be a carbon sink additional advantage for the landfilling option is gained. The additional function of trapping biological carbon leads to more preferable results for the landfilling option concerning global warming for two of the waste paper fractions, newspaper and mixed cardboard. The resulting ranking is

recycling before landfilling before incineration. As can be seen in Figure 4 the difference between landfilling and incineration is here small. The plastic fractions are not affected since their carbon content is of fossil origin.

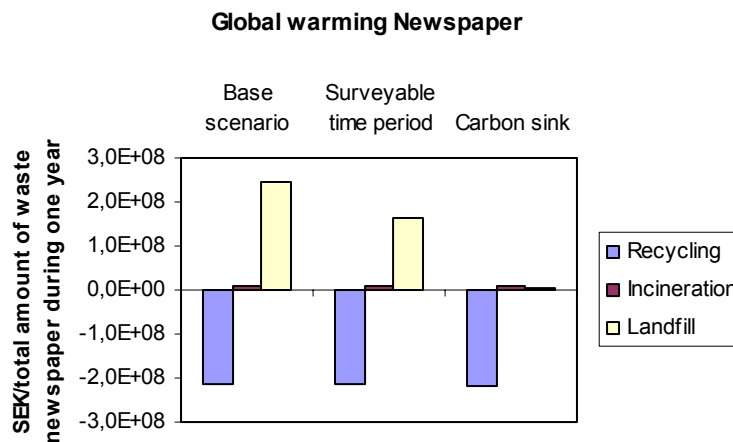


Figure 4. The results for the impact category global warming for waste newspaper. The results are presented for the base scenario, the surveyable time period scenario and for the scenario where the landfill is regarded as a carbon sink.

### 3.4 Transportation of waste

Different distances for transportation of waste by truck to treatment facilities does not influence the rankings of treatment options much (Finnveden *et al.* 2000). However, transportation of waste from the household by passenger car to collection points may influence the results significantly. This can be seen in a scenario where passenger cars are assumed to be used for transportation of sorted waste for recycling and incineration. Major alterations in the resulting rankings are seen for the impact categories photo-chemical oxidant formation and for human and eco-toxicological impacts. In the toxicological categories landfilling is ranked as the most preferred alternative in several cases, when the other options are burdened with passenger car use. In Figure 5 the effects of transportation of waste newspaper management is presented for the eco-toxicological impact category. It can clearly be seen that longer transportation by truck does not affect the other options much, but when passenger car is used the ranking is altered. Similar changes appear for all waste fractions studied.

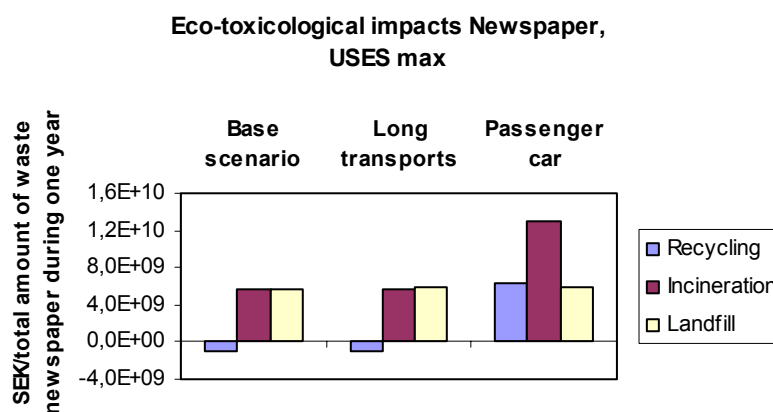


Figure 5. Results for the impact category Eco-toxicological impacts for Newspaper, using the USES characterisation method with maximum weighting according to the Ecotax 98 weighting method.

In cases where new ways of landfilling waste is considered, e.g biocells, source separation of different waste fractions may be relevant also for this option and in these cases possible increased transportation must consequently be taken into account.

### **3.5 Uncertainties**

Many of the effects of altering assumptions and boundaries as described above are seen in the toxicological impact categories. It should be noted that any conclusions drawn from the results for these categories should be drawn with extra care. For example, the uncertainty is assumed to be substantially lower for the global warming impact category, mainly depending on less data gaps and differences in the reliability of the characterisation methods available. In the toxicological impact categories the uncertainties are large. Uncertainties include data gaps, methods for comparing different toxicological impacts and also for estimating the impacts of different emissions, including cumulative and synergetic effects. Since emissions from landfills are also spread over large periods of time, actual emissions are not possible to measure and models and assumptions used include additional uncertainties.

## **4 Conclusions**

One basic difference comparing landfilling of waste to other treatment strategies is that less co-functions are produced. Even though 50% of the landfill gas is assumed to be collected and combusted with energy recovery, this only makes out a part of the potential resource that the waste may constitute if treated by recycling or incineration. This is a draw back for the landfilling option.

Conclusions of the paper are that the waste hierarchy is valid as a rule of thumb. There are, however, certain assumptions and valuations that can lead to exceptions to this rule. Aspects of particular interest for the landfilling option are:

- Which time perspective is chosen. This concerns which emissions that are to be charged the landfilling option,
- If, with a limited time perspective, the landfill shall be credited for trapping biological carbon so far not emitted to the atmosphere,
- Transportation of waste, if this is substantially less in the case of landfilling compared to other waste treatment options. This is in particular relevant for transportation by passenger car.

A general conclusion is that assumptions made including value choices with ethical aspects are of importance when ranking waste treatment options.

It can also be noted that for improving the possibilities for studying and assessing overall impacts of waste management options further work needs to be done, e.g. in the field of landfill modelling, especially concerning long-term processes, and on toxicological assessment in general. One aspect of possible concern is emissions from landfill fires, which can have a potential influence on eco-and human toxicological impacts especially in a shorter time perspective.

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*Table 1. Impact categories used in the study.*

*Figure 1. The diagrams are showing the rankings of waste treatment options for the waste fractions newspaper and PET (polyethylene terephthalate) for a selection of impact categories. Total weighted results of one of the impact assessment methods are also presented. The energy categories are presented as MJ and the other categories as SEK. This is because weighted figures are used, this however does not affect the relations within each impact category. Three different versions of the impact category eco-toxicological impacts are presented. The differences are due to different characterisation methods, EDIP and USES, and also to different weighting factors, USES min and USES max.*

*Figure 2. Results for the impact category global warming for waste PET. The results are shown for the base scenario and for the surveyable time period scenario.*

*Figure 3. The results for the impact category eco-toxicological impacts for the waste newspaper fractions using three different impact assessment methods. The results are presented for the base scenario and for the surveyable time period scenario.*

*Figure 4. The results for the impact category global warming for waste newspaper. The results are presented for the base scenario, the surveyable time period scenario and for the scenario where the landfill is regarded as a carbon sink.*

*Figure 5. Results for the impact category Eco-toxicological impacts for Newspaper, using the USES characterisation method with maximum weighting according to the Ecotax 98 weighting method.*