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Indicators for waste management

How representative is global warming as an indicator for environmental performance of waste management?

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DTU Environment
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PhD Thesis
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The thesis will be available as a pdf-file for downloading from the homepage of the department: www.env.dtu.dk

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Preface

The work presented in this PhD thesis, "Indicators for waste management: How representative is global warming as an indicator for environmental performance of waste management?" was conducted at the Department of Environmental Engineering at the Technical University of Denmark from February 2005 to June 2009 under the supervision of Professor Thomas Højlund Christensen. The project was funded by the Technical University of Denmark.

The thesis is accompanied by the following five scientific journal papers in which the main results from the PhD work are presented. In the text, these are referred to as, e.g., Merrild et al. (I). The papers are not included in this www-version but may be obtained from the library at DTU Environment, Miljoevej, Building 113, Technical University of Denmark, DK-2800 Kgs. Lyngby (library@env.dtu.dk).

Paper I: Merrild H., A. Damgaard and T.H. Christensen, (2008). Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. *Resources, Conservation & Recycling*, 52(12), 1391-1398.

Paper II: Merrild H., A. Damgaard and T.H. Christensen, (2009). Recycling of paper: Accounting of greenhouse gases and global warming potentials. Submitted to *Waste Management & Research*.

Paper III: Larsen A.W., H. Merrild and T.H. Christensen, (2009). Recycling of glass: Accounting of greenhouse gases and global warming potentials. Submitted to *Waste Management & Research*.

Paper IV: Merrild H., A.W. Larsen and T.H. Christensen, (2009). Material-based life cycle assessment of municipal waste in Denmark: Recycling versus incineration with efficient energy recovery**.** Submitted to *Resources, Conservation & Recycling*.

Paper V: Larsen A.W., H. Merrild, J. Møller and T.H. Christensen, (2009). Waste Collection Systems for Recyclables: an Environmental and Economic Assessment for the City of Aarhus (Denmark). Submitted to *Waste Management.*

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Also many thanks to Torben Dolin for making my sometimes chaotic-looking figures into something clear and good-looking.

Last, but not least I would like to thank my family. Thank you mum and dad for always encouraging me in my path of life. Thank you Peter for supporting me through the last four and a half years, listening to me talking about waste, life cycle assessment and other very interesting work-related subjects. And thank you for letting me impose my (strange) interest of waste on Astrid. I am not sure all girls her age show such an interest for the “skraldebil”. Finally, even though you cannot read yet: Astrid, thank you for showing me what really is important in life!

Summary

The use of the waste hierarchy in Danish waste policy-making has meant that recycling is highly prioritized and that the success of waste management systems is measured by increased recycling rates. However, as incineration has become the main treatment option for household waste in Denmark, and as incineration with efficient energy recovery has also become an integrated part of the energy system, the assessment of the environmental performance of recycling compared with incineration is now more complex. European waste legislation and Danish waste strategies have also developed from being based mainly on the principles of the waste hierarchy to also recognising life-cycle thinking as an important foundation for achieving the overall best environmental waste management systems. Additionally, the legislation and strategies have increased focus on limitation of greenhouse gas emissions, and global warming seems to be a priority criterion for good environmental performance. This development constitutes the background for the focus of this thesis. The aim of the thesis was to examine and discuss:

- The environmental performance of recycling compared with that of incineration for a number of recyclable fractions in household waste, as well as which aspects are important for the outcome of life cycle assessments comparing these two waste management options.
- If global warming can be used as a representative indicator for the environmental consequences of waste management, by examining how well the global warming indicator correlates with other environmental impacts arising in the waste management system, based on the preceding comparisons between recycling and incineration.

The environmental assessments were conducted using life cycle assessment and the modelling was done in the EASEWASTE model (Kirkeby et al., 2006a). Data for the modelling were collected through literature studies and through data collection in a case study area.

The work performed showed that comparison of the environmental performance of recycling and incineration for recyclable materials that have relatively high energy contents, i.e. paper, cardboard, and plastic, are more sensitive to assumptions regarding system boundaries and energy aspects than those materials that do not have such high energy contents, i.e. glass and metals, as the

former fractions are not only valuable materials but also valuable fuels at the incineration plants. The initial investigations showed that selection of technology inventory data and the choice of system boundaries were of importance for the global warming results when comparing recycling with incineration of waste paper. Modelling showed that different combinations of datasets could lead to opposite conclusions, i.e. depending on the given combination, increased recycling could lead to either higher or lower global warming impact. Expansion of the system to include utilization of saved biomass as a fuel changed the results in a manner that meant that increased recycling in all cases led to decreased global warming.

As global warming is a priority criterion in policy, this indicator should always be included in any decision-supporting assessment of the environmental impacts of waste management options. The work performed has, however, shown that the global warming indicator should not stand alone as the representativeness of global warming as an indicator for the environmental performance of waste management systems seems relatively poor. Acidification and nutrient enrichment seem to be the only two impact categories, of those included in the case study, that could be reasonably well represented by the global warming category. Even though these two impact indicators did not show the same rating of the modelled waste management scenarios as did the global warming indicator, they showed the same trend, i.e. savings appeared concurrently and loads appeared concurrently. However, one should always be aware of system specific circumstances that could bring about emissions that contribute to the load in these impact categories. For the impact categories photochemical ozone formation, human toxicity, persistent toxicity and the resource consumption categories, global warming did not seem to be representative. Whereas global warming, acidification and nutrient enrichment were highly dependent on the energy aspects of the study, the results in these other impact categories were affected by other parts of the system, e.g. photochemical ozone formation was mainly linked to emissions from the collection and transport phase.

The work showed that by applying a system approach, the life cycle assessment can encompass a number of aspects which cannot be captured in material based modelling. These aspects, e.g. the influence of the waste composition, the recycling rates, the performance of the incineration plant, the influence of changes to the residual waste, can be captured only when modelling the full

system. For instance, the case study showed that a material fraction with a high environmental benefit from recycling on a tonne basis, e.g. aluminium, on a system basis might not result in any significant benefits due to the low amount in the waste and the low recycling rates.

The work has led to an increased understanding of which factors play an important role in the assessment of recycling and incineration, as well as which material fractions in household waste have the largest potential in regards to reduction of environmental impact. The work has also shown that life cycle assessment is a good decision-support tool for evaluating the environmental impact of waste management systems, provided that the modelling is system-specific, and that it is a useful complement to the waste hierarchy as it can give a more nuanced picture of different waste treatment options' environmental performance.

Sammenfatning

Anvendelsen af affaldshierarkiet i dansk affaldspolitik har betydet, at genanvendelse er højt prioriteret, og at succesen af affaldshåndteringssystemer typisk ligestilles med en høj genanvendelsesprocent. Da affaldsforbrænding i dag er den mest udbredte behandlingsform for husholdningsaffald i Danmark, og da forbrænding med effektiv energiudnyttelse ligeledes er en integreret del af energisystemet, er vurderingen af de miljømæssige forhold ved genanvendelse sammenlignet med dem ved forbrænding imidlertid blevet mere komplicerede. Europæisk lovgivning på affaldsområdet og danske affaldsstrategier har udviklet sig fra primært at være baserede på affaldshierarkiets principper til også at anerkende livscyklustankegangen som et vigtigt fundament for at opnå den miljømæssigt bedste affaldshåndtering. Desuden er der i lovgivning og i affaldsstrategier kommet øget fokus på at begrænse udledningen af drivhusgasser, og drivhuseffekt ser ud til at være en afgørende parameter i forhold til hvorvidt en løsning bedømmes som miljømæssig god eller dårlig. Denne udvikling udgør baggrunden for denne afhandling. Formålet med afhandlingen er at undersøge og diskutere:

- De miljømæssige forhold ved genanvendelse sammenlignet med de miljømæssige forhold ved forbrænding for en række genanvendelige fraktioner i husholdningsaffald, samt hvilke aspekter der er vigtige for resultatet af miljøvurderinger, hvor disse to behandlingsalternativer sammenlignes.
- Hvorvidt drivhuseffekt kan bruges som indikator for de miljømæssige konsekvenser af affaldshåndtering, gennem at se på hvor godt drivhuseffekt som påvirkningskategori korrelerer med andre miljøpåvirkninger, der opstår i forbindelse med affaldshåndtering, baseret på de foregående sammenligninger mellem genanvendelse og forbrænding.

Miljøvurderingerne blev udført ved hjælp af livscyklusvurderinger og modelleringer udført i EASEWASTE-modellen (Kirkeby et al., 2006a). Data anvendt i modelleringerne blev indsamlet gennem litteraturstudier og gennem indsamling af data i et casestudy-område.

Det udførte arbejde viste, at en sammenligning af de miljømæssige forhold ved genanvendelse og forbrænding af genanvendelige materialer med relativt høje

energiindhold, dvs. papir, pap og plast, er mere følsom over for antagelser vedrørende systemafgrænsninger og energimæssige aspekter end en sammenligning af materialer, der ikke har disse høje energiindhold, dvs. glas og metaller. Det skyldes, at den første gruppe materialer er værdifulde brændsler ved forbrænding, og ikke kun værdifulde som genanvendelige materialer. De indledende undersøgelser viste, at valget af teknologidata og fastsættelse af systemgrænser er af stor betydning for den beregnede potentielle drivhuseffekt, når man sammenligner genanvendelse og forbrænding af papiraffald. Modelleringer viste, at forskellige kombinationer af datasæt kan føre til modsatrettede konklusioner, dvs. afhængigt af den givne kombination af data kan øget genanvendelse føre til enten højere eller lavere potentiel drivhuseffekt. En udvidelse af systemet til også at omfatte udnyttelse af sparet biomasse som brændsel, ændrede resultaterne således, at øget genanvendelse i alle tilfælde førte til reduceret potentiel drivhuseffekt.

Da drivhuseffekt i dag er et væsentligt politisk kriterium, bør denne indikator altid indgå i enhver beslutningsstøttende vurdering af de miljømæssige konsekvenser ved affaldshåndtering. Det udførte arbejde har imidlertid vist, at indikatoren drivhuseffekt ikke bør stå alene, da drivhuseffekt relativt dårligt repræsenterer de miljømæssige forhold for affaldshåndteringssystemer. Ud af de seks miljøpåvirkningskategorier der indgik i casestudiet, forekom forsuring og næringssaltbelastning at være de eneste to kategorier, der i rimelig grad korrelerede med drivhuseffekten. Selvom disse to påvirkningsindikatorer ikke viste helt den samme rating af de modellerede affaldshåndteringsscenarier, som drivhuseffekten gjorde, viste de den samme tendens, dvs. besparelser optrådte samtidigt og belastninger optrådte samtidigt. Man bør dog altid være opmærksom på særlige omstændigheder i det specifikke system, der kunne medføre emissioner, som vil bidrage til en belastning i de to pågældende miljøpåvirkningskategorier. For miljøpåvirkningskategorierne fotokemisk ozondannelse, human toksicitet, persistent toksicitet og for ressourceforbrugskategorierne, forekom drivhuseffekt ikke at være repræsentativ. Mens resultaterne for drivhuseffekt, forsuring og næringssaltbelastning var meget afhængige af energiaspekter, var resultaterne i de andre påvirkningskategorier afhængige af andre dele af systemet, f.eks. var påvirkningen i kategorien fotokemisk ozondannelse hovedsageligt knyttet til emissioner fra indsamling og transportfasen.

Arbejdet viste, at ved at anvende en systemtilgang kan livscyklusvurderingen omfatte en række aspekter, som ikke kan opfanges i en materialebaseret modellering. Disse aspekter, f.eks. betydningen af affaldssammensætningen, genanvendelsesprocenter, forbrændingsanlæggets virkningsgrad og røggasrensningsniveau samt ændringer af restaffaldssammensætningen, kan kun opfanges, når det fulde system modelleres. Casestudiet viste for eksempel, at et genanvendeligt materiale der ved modelleringer på ton-basis viste store miljømæssige besparelser ved genanvendelse, f.eks. aluminium, i et systemperspektiv ikke nødvendigvis resulterer i betydelige fordele på grund af små mængder i husholdningsaffaldet og lav genanvendelsesprocent.

Arbejdet har ført til en øget forståelse af, hvilke faktorer der spiller en vigtig rolle i vurderingen af genanvendelse og forbrænding, samt hvilket materialer i husholdningsaffald der har det største potentiale mht. reduktion af affaldssystemets miljøpåvirkning. Arbejdet har også vist, at livscyklusvurderinger er et godt redskab til evaluering af de miljømæssige konsekvenser ved affaldshåndtering, forudsat at modelleringerne er system-specifikke. Endvidere er en livscyklusvurdering et godt supplement til affaldshierarkiet i beslutningsprocessen, da den kan give et mere nuanceret billede af forskellige behandlingsmuligheders miljøpåvirkninger.

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1 Introduction

1.1 Waste policy

Since the end of the 1970s waste management in Denmark and other EU countries has been founded on the principles of the waste hierarchy, a guideline for ranking of waste management options. The waste hierarchy advocates waste management options in the following order: waste prevention, reuse, recycling, recovery and disposal. The waste hierarchy has been a good aid for decision-makers over the years and has generally helped in improving the environmental performance of waste management systems. Various initiatives in Denmark have led to an increase in the recycling rate for household waste from 14% to 18% over ten years (1994–2005) and at the same time have reduced the amount of landfilled household waste from 12% to less than 1%; the rest is incinerated with energy recovery (Danish Environmental Protection Agency, 2007). The use of the waste hierarchy has meant that recycling has been highly prioritized and that the success of waste management systems has been measured by increased recycling rates. As incineration has become the main treatment option for waste in Denmark, and as incineration with energy recovery, producing both electricity and heat, is today an integrated part of the energy system, prioritization between recycling and incineration has become more complex. The development of the waste management system suggests that the waste hierarchy might not be adequate as the only decision support tool if environmentally preferable waste management is to be achieved, and that success of waste management systems cannot be measured by recycling rates only.

Legislation and waste management strategies have developed to include aspects other than the waste hierarchy, which nevertheless is still an important part of the policy making. In the European waste framework directive (Directive 2008/98/EC), the waste hierarchy is, as it was in previous legislation, the fundamental pillar for prioritization in waste management. However, in addition the directive clearly states that when the waste hierarchy is applied, measures should be taken that encourage the options that result in the overall best environmental outcome. This implies that departing from the hierarchy might be necessary when justified by life-cycle thinking (European Commission, 2008). The packaging and packaging waste directive (Directive 94/62/EC) also acknowledges that strictly following the waste hierarchy may not always result in the best environmental solution. For example, it states that member states shall, where appropriate, encourage energy recovery where it is preferable to material recycling for environmental and cost-benefit reasons. However, the directive also declares that deviation from the hierarchy must be knowledge-based by stating that until scientific and technological progress is made with regard to recovery processes, recovery, defined as both material and energy recovery, reuse and recycling should be considered preferable in terms of environmental impact. In the directive, life cycle assessment is acknowledged as a useful instrument for gaining this knowledge and that it can be used to justify a clear hierarchy between reusable, recyclable and recoverable packaging (European Parliament and Council, 1994).

Previous and current national Danish waste strategies have used, and are using, the waste hierarchy as a guiding principle. In the Danish national strategy for waste management for the years 1998–2004, the main focus was still on waste amounts and recycling percentages, defining a goal of 30% recycling and 70% incineration by 2004 (Miljø- og Energiministeriet, 1999). However, qualitative goals were also included. Higher quality of waste treatment was described as less environmental impact and better utilization of resources in an economically sustainable manner. In the subsequent waste strategy for 2004–2008, published by the Danish Government in 2003, it was recognized that the waste hierarchy on its own is not always adequate for choosing the best treatment of waste (Regeringen, 2003). Even though goals were set to reach 65% recycling by 2008, it was also recognized that using higher recycling rates as an indicator of success does not necessarily give the environmentally best solution. Therefore new indicators were introduced to complement the recycling rates. The purpose of introducing the new indicators was to improve the basis on which decisions about waste treatment are made, e.g. if a particular waste fraction should be recycled instead of incinerated. In addition to volume of waste, three indicators were established: resource consumption, energy consumption and landfilling requirements. The strategy stated that these indicators should be supplemented with an evaluation of each material's environmental and health effects as well as being combined with cost-benefit analyses. It was also stated that further life cycle assessment-based indicators should be developed, but it was not stated for which environmental impacts. In the newest national waste strategy for 2009–2012 it is stated that environmental assessments and welfare economical assessments shall be used as a basis for decision making (Regeringen, 2009).

This again indicates that the policy-makers are acknowledging the need for the waste hierarchy to be supplemented with knowledge-based decision support.

The national waste strategy for 2009–2012 also reflects the increased public and political focus on greenhouse gas emissions, which seems to have followed the publication of the Stern Review and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Stern, 2007; IPCC, 2007a). There is still focus on quantities, resource consumption (both material and fuel resources), environmental effects, health effects as well as economic considerations in the strategy but, in addition, reduction of greenhouse gas emissions is included as an essential part.

These changes in waste management policy and strategy, the recognition that the waste hierarchy is not adequate as the only policy making tool and the movement towards life-cycle thinking requires more systematic methods to assess the effects of waste management. The increased focus on greenhouse gas emissions also makes it interesting to examine how well the environmental impact of these emissions, expressed as global warming, correlates with or represents the overall environmental impact from waste management treatment.

1.2 Life cycle assessment and waste management

The use of different assessment methods for systematic analysis of waste treatment alternatives and waste management systems has become increasingly frequent concurrently with life-cycle thinking gaining ground in policy making. The increased use of system analysis could be linked to the insight that knowledge-based policy might be superior to, or at least complementary to, policy founded on the value-based waste hierarchy.

The waste management sector in itself is a large complex system and as links to other sectors, such as material manufacturing and energy production, are considered, the system grows even more complex and thus it is useful to analyse the system in a structured manner. Several methods are available for performing systematic analysis, life cycle assessment being one of the methods commonly used for environmental assessment. The advantage of using life cycle assessment in evaluations of waste management systems is that the processes involved and the impacts related to these are presented in a comprehensive manner (Finnveden et al., 2007).

Life cycle assessment has been applied within the field of waste management in a number of studies assessing treatment alternatives for specific waste material fractions, e.g. (Edwards and Schelling, 1999; Arena et al., 2003; Finnveden et al., 2005), and integrated waste management systems, e.g. (Kirkeby et al., 2006a; Rigamonti et al., 2009; Banar et al., 2009). Most of the studies apply multiple environmental impact indicators, but a few studies have been identified that present results for greenhouse gas emissions only, e.g. (Thorneloe et al., 2002; Mohareb et al., 2008; Zhao et al., 2009), or use greenhouse gas emissions (or global warming) as a priority criterion in the presentation of results and in the conclusions, e.g. (Beigl and Salhofer, 2004; Dahlbo et al., 2007). The conclusions, if any were drawn, from these previous studies could be expected to give us an indication of the environmental performance of waste management treatment. However, as the studies model different systems and use different assumptions in regards to, e.g. energy recovery at the incineration plant, there is a lack of consistency between them. This sometimes led to ambiguous results, and it is thus difficult to compare the result from an assessment of recycling of one material in one study with the result from an assessment of another material in another study. For the same reason it is also difficult to correlate the results from assessments performed on a material fraction basis with the results from a full-scale system study.

The environmental benefit of recycling versus incineration is sometimes debated, in particular, there are three issues that play an important role in the debate. One issue is related to renewable energy sources being high on the political agenda and that today Danish incinerators are effective waste-to-energy plants with high energy recovery rates, producing both electricity and heat. The recovered energy is likely to substitute fossil-based energy and thus ascribes significant greenhouse gas emissions savings to the incineration of waste. A second issue is related to the fact that waste incinerators now frequently recover both magnetic iron as well as aluminium for recycling. The third issue is related to recyclables currently being traded on a world market; they are thus often subject to long transport distances, contributing to the environmental burden of the material recycling. These three issues reduce the benefit of recycling versus incineration. Thus there is a need for a closer assessment of the environmental performance of material recycling in comparison with the environmental performance of incineration with high energy recovery rates.

1.3 Indicators

Using analytical tools for supporting objective decision-making involves balancing detail and overview. Indicators can be useful when communicating scientific results to the non-scientific community as these can describe complex results in a more comprehensible and condensed format, decreasing the number of parameters used in the presentation of the results. The main purpose of using indicators is to enhance communication, and indicators should thus be relevant and understandable for decision-makers.

Indicators can be used for several purposes, e.g. comparison of environmental performance over time, identification of improvement potentials, decision support and benchmarking, and it is thus also important that the indicators harmonize with the purpose for which they are intended. Thus indicators should be designed for comparison of either different systems, e.g. a recycling and an incineration, or different parts of a system, e.g. waste collection and waste treatment. The element of comparison requires that indicators are quantitative and that the values have a common denominator, e.g. tonne household waste.

Villeneuve et al. (2009) differentiates between two types of indicator: impact indicators and performance indicators. Impact indicators are indicators commonly used in the presentation of life cycle assessment results and are related to parameters in the inventory (e.g. greenhouse gas emissions or heavy metal emissions). The performance indicators are related to the more traditional criteria for successful waste management (e.g. recycling rates). Impact indicators are applicable both for decision making and performance measurement, whereas performance indicators, as inherent in the name, are more suitable for performance measurement.

When presenting results from an environmental assessment with the help of indicators and when choosing the set of relevant indicators for the presentation, one must consider the balance between complex but transparent results and simpler but more uncertain results. In the life cycle assessment context the impact assessment methodologies can be grouped into two groups based on the type of indicator they use: those presenting the results with midpoint indicators and those presenting the results with endpoint indicators. A midpoint indicator can be defined as a parameter located on the impact pathway at an intermediate position between the life-cycle inventory results and the ultimate environmental damage (Jolliet et al., 2004). A midpoint indicator could, for instance, be acidification or global warming. Endpoint indicators express the damage at the end of the cause-effect chain, e.g. damage to the natural environment and damage to human health. The benefits of endpoint indicators are that these might increase the understanding of the impacts for decision- makers and be more relevant in terms of what the decision-makers want to know. However, there is a high degree of uncertainty related to the modelling of the whole cause-effect chain. The benefit of midpoint indicators is that they lower the uncertainty, but at the same time they also make the interpretation of results more complex because different impact categories have to be held up against each other.

Only few previous studies addressing the influence of the choice of indicators for reporting on the overall conclusions have been identified in literature, none focus on waste management. Weidema et al. (2008) discussed the strengths and weaknesses of carbon footprints and raised the point that focusing on global warming alone is a crude approach that in certain cases may give a misleading picture of the impacts compared with life cycle assessment which uses multiple indicators. Udo de Haes (2006) concluded that the cumulative energy demand seems to be an indicator that gives a reasonable overall picture of environmental impact but he also concluded that the high correlations found may be due to overemphasis on energy-related processes in the life-cycle inventory databases.

This limited knowledge of the representativeness of the global warming indicator combined with the fact that an increasing number of presentations of life cycle assessment results are limited to presenting the global warming indicator, or use global warming as a priority criterion when concluding, highlights the importance of elaborating on this subject.

1.4 Aim of the study

As the public awareness and political focus on greenhouse gas emissions and related environmental problems have increased, global warming has become an important priority criterion in decision making. The aim of the study was to study how robust global warming is as an indicator for environmental performance within waste management.

This was done by comparing the environmental impacts from recycling with the environmental impacts from incineration with efficient energy recovery for a number of common recyclables in household waste: paper, cardboard, glass, plastic packaging and metal packaging. Recycling and incineration was compared as these are the two treatment options in the waste hierarchy which the Danish waste management decision-makers today in practice can prioritize between subsequent to the waste reaching the municipal collection system. Waste prevention is not something that can be regulated or affected at this level of decision, reuse is normally a parallel system to the municipal waste management system and landfilling is for many of the materials no longer an option.

The environmental assessments were conducted using life cycle assessment. Several life cycle assessments with different scopes were performed. Firstly, a study was done focusing on the importance of the technology inventory data and the choice of system boundaries for the outcome of a comparison between recycling and incineration. The findings from this study are presented in Merrild et al. (I). Secondly, two studies, described in Merrild et al. (II) and Larsen et al. (III), examined the greenhouse gas emissions related to the waste management of the recyclable materials paper and glass. Finally, a case study was conducted in two parts. The first part, presented in Merrild et al. (IV), examines the environmental effects of moving waste from incineration to recycling on a material fraction basis and compares the magnitude of the environmental benefit of recycling, if any, with the environmental impacts caused by the extra effort needed in relation to collection and transport. The material fractions included in the case study were paper, cardboard, glass, plastic, steel, and aluminium. Larsen et al. (V) present the second part of the case study. This part examines the consequences of altering the collection systems, and thus the recycling rates, for the recyclable fractions paper, glass and packaging waste (including plastic, steel and aluminium) in an integrated waste management system.

The life cycle assessment modelling was done in the EASEWASTE model (Kirkeby et al., 2006a) and the EDIP1997 method with updated normalization references were used (Wenzel et al., 1997; Stranddorf et al., 2005). It is either the characterized or normalized results that are presented in the studies, i.e. midpoint indicators are used. The characterized results are expressed in kg-equivalents of a substance compared to a reference substance, e.g. kg CO_2-equivalents. The normalized results are presented in the unit person equivalents (PE), and one PE expresses the average environmental impact in the given category caused by all activities of one person in one year. There is no scientific basis for reducing life cycle assessment results to a single overall score or number, since weighting requires value choices (ISO, 2006a) and in regard to assessing global warming as a representative indicator for environmental performance of waste management, the midpoint indicators are more suitable, as it is difficult to compare endpoint indicators directly with global warming. The resource consumption results are presented in the unit person reserves (PR), which expresses the resource consumption in relation to the supply horizon.

In addition to performing these environmental assessments, a literature study was conducted, both in relation to material fraction studies and integrated waste management system studies, to investigate the previous findings in relation to global warming as a representative indicator.

2 Life cycle assessment within waste management

Life cycle assessment is an internationally standardized methodology for environmental assessment. It addresses the environmental aspects and potential environmental impacts throughout a product's[1] life-cycle from the life-cycle stage raw-material acquisition through the stages production, use, end-of-life treatment and recycling to the final disposal stage. It can be used for identification of environmental hotspots and opportunities for optimising environmental performance in a product's life-cycle, for informing decision-makers, for selection of relevant environmental performance indicators as well as for environmental marketing (ISO, 2006a). In the framework of waste management, the life-cycle stages are somewhat different from the life-cycle stages of a physical product, constituting only the three stages: collection, treatment and final disposal. The different life-cycle stages of a product system and a waste management system are shown in Figure 1.

Even though life cycle assessment is a standardized method, the standard as such leaves room for a number of methodological choices. This includes, e.g. selection of functional unit, selection of application approach, selection of system boundary and selection of impact categories. The consequences of different choices for these four parameters, as well as choice of datasets, are discussed in the following sections.

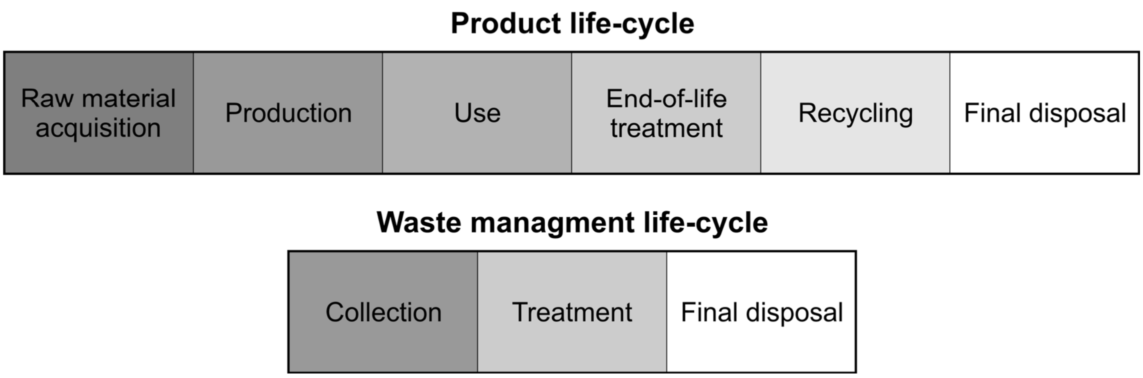

Figure 1: ***Product life-cycle stages as described by ISO (ISO, 2006a) and waste life-cycle stages.***

[1] A product is defined as any goods or service (ISO, 2006a).

2.1 Selection of functional unit

A key stage in a life cycle assessment study is to clarify which question the study should to be able to answer; this will undoubtedly affect the formulation of the functional unit. In waste management studies the functional unit is commonly expressed as the treatment of one tonne of waste or as the treatment of the total amount of waste in a certain area studied. The results in Merrild et al. (IV) illustrate that the formulation of the functional unit can have an influence on the conclusions drawn from a life cycle assessment study. The results showed that on a material fraction basis (the functional unit defined as treatment of one tonne of a specific material fraction) recycling of, e.g. aluminium, is highly beneficial. But if the actual amount of this material fraction in the waste was included (the functional unit defined as treatment of one tonne of household waste), the same benefits could be reached by recycling other materials. This suggests that on a system level it is important to know the composition of waste regarding the material fraction distribution. The chemical composition is also of importance in relation to emissions from incineration, e.g. the amount of fossil C influences the results in the global warming impact category and the amount of heavy metals the results in the toxicity impact categories.

2.2 Selection of application approach

Two different approaches can be applied when performing a life cycle assessment: attributional or consequential. The attributional approach, also called average approach, provides an estimate of the potential environmental impacts of a system itself assuming status quo; the consequential approach, also called marginal approach, provides an estimate of the potential environmental impacts appearing as a response to changes in a system.

The purpose of the life cycle assessment, and the type of question that it should answer, often defines which approach should be chosen. For example, the question “How large are the impacts from the collection phase of the system?” can be answered by applying the attributional approach, while the question “What are the consequences of increased recycling?” can be answered by applying the consequential approach. The choice of application approach has an influence on which parts of the life-cycle should be included in the modelling, the choice of data, and the allocation procedure. The attributional approach includes the whole life-cycle in the assessment and the background systems are modelled with average data. Allocation between co-products is performed in relation to production proportion, e.g. either by mass or economic means. In the consequential approach only the part of the system that is affected by the investigated change should be included, the background system modelled with marginal data and allocation avoided by system expansion.

Ekvall and Andræ (2006) and Thomassen et al. (2008) applied both attributional and consequential approaches to the studied systems in question (solders and milk respectively). The results from the two studies showed that the choice of approach did not influence the overall conclusions, but that there were differences in the size of the global warming impact potentials and differences concerning which parts of the system contributed the most to the environmental impact. These differences were mainly due to the different systems modelled when applying the two different approaches.

Using life cycle assessment as a decision support tool in a waste management context would often entail the investigation of a change to the waste management system and, in general, all actions in the waste management system can be expected to have marginal effects on the production systems for materials and energy (Ekvall et al., 2007). It is thus justifiable to use a consequential approach when studying waste management systems.

2.3 Selection of data

Applying a consequential approach implies that marginal data should be used in the assessment of waste management options and systems. In the ideal consequential life cycle assessment, the system under study is expanded to include all the processes that are actually affected by an increase or decrease in the flow to or from the life-cycle investigated (Ekvall and Weidema, 2004). This might, however, be difficult as marginal technologies cannot be identified or the actual consequences of a change might not be known.

For incineration it is reasonably straightforward to identify the marginal technology as it is usually known at which incineration plant the waste will be treated. One difficulty in relation to modelling of incineration is connected to uncertainties concerning the consequences of producing energy at the plant. Electricity produced at the incineration plant is distributed to the regional grid and can thus be assumed to replace the same amount of electricity on this grid.

Identifying the marginal electricity source requires a thorough analysis of the supply and demand on the regional electricity grid. In the short-term perspective coal-based electricity production seems to be a reasonably realistic marginal for Danish conditions (Weidema, 2003; Eriksson et al., 2007). The production of marginal heat is normally easier to identify as the distribution of heat is limited to a local grid.

Defining the marginal technologies for recycling is more difficult than defining the marginal incineration technology. The number of publicly available datasets for reprocessing is high for some material fractions and low for other fractions, depending on the history of using recyclable material in processing, willingness of the industry to publish transparent data, and the frequency that the material fraction has been studied within a life cycle assessment framework. For example, seemingly, the number of datasets for paper reprocessing is fair, while the number of datasets for metal and plastic reprocessing is much lower.

Merrild et al. (I) illustrated the effect on greenhouse gas emissions when modelling recycling of paper with different combinations of reprocessing technology datasets and avoided virgin processing technology datasets. The global warming results for 14 combinations of reprocessing technologies and virgin processing technologies are presented in Figure 2. The modelling showed that, depending on what dataset is chosen, the greenhouse gas emissions ranged from -1.3 to 0.4 tonne CO_2-equivalents/tonne waste paper treated (a negative number represents a saving and a positive number represents a load). The differences are mainly due to differences in energy consumption, both in regards to the form of the energy (electricity or heat) and the fuel (fossil or renewable). This suggests that the choice of dataset is important for the outcome of a study, and care should be taken to try to define the marginal. However, it is difficult to identify the marginal technology for recycling as the recyclable material is often sold on to a broker and thus it is unknown at which plant the recyclable material is reprocessed. In addition, it is difficult to identify the marginal technologies for processes further down the consequence chain, e.g. production of the same material from virgin raw material or production of a product based on a different material but with the same functionality.

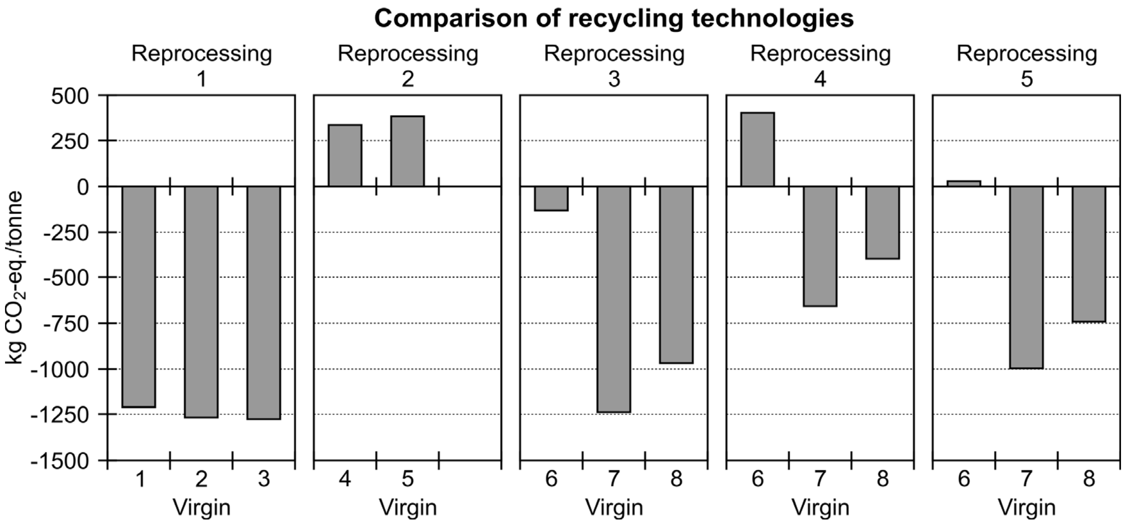

Figure 2: ***Global warming impact potentials for 14 combinations of five reprocessing technology datasets and eight virgin technology datasets (Merrild et al., I).***

2.4 Selection of system boundary

As changes in the municipal waste management system prompt changes in surrounding systems, it is necessary to define the system boundaries carefully to ensure that the consequences of changes in the system are described accurately and, e.g. credited with the environmental benefits that occur outside the municipal waste management system, if relevant. For example, the results in Merrild et al. (II) and Larsen et al. (III) showed that the greenhouse gas emissions from the processes taking place downstream of the waste management operation were of such a magnitude that they would be decisive for the outcome of an assessment of recycling of paper and glass respectively.

The modelling in Merrild et al. (I) showed that the selection of system boundaries can be even more important for the outcome of the results than the choice of dataset. Figure 3 shows the global warming impact potentials as a function of the recycling rate for four combinations of technology data levels and for three different system boundaries. The four combinations of technology levels represent different combinations of a low recycling dataset, a high recycling dataset, a low incineration dataset and a high incineration dataset. Low means that the technology has a low environmental performance and high means a high environmental performance. The original system boundary, which excluded both saved forestry and utilization of saved biomass (virgin wood) for energy purposes, was changed to include saved forestry in one modelling and to include energy production from saved biomass in one modelling. The results demonstrated that when comparing recycling of paper and incineration of paper, changing the system boundary to include energy production from the saved biomass would result in increased recycling being favourable over increased incineration. If the system was not expanded or expanded with saved forestry, the conclusion would depend on the datasets chosen as three of the technology data combinations showed increased global warming and one decreased global warming concurrently with increased recycling rate. The expansion to include energy from biomass can be expected to be valid, also for other material fractions that substitute biomass raw-materials that can be used as a renewable energy source, i.e. cardboard regarding waste fractions in household waste.

The system expansion appears to be less important for other material fractions, e.g. glass, steel and aluminium, as there are no prevailing opportunities to use the raw material for other purposes. The savings for these materials are related mainly to the differences between energy use for reprocessing and production from virgin material. For example, the use of recycled glass cullet as feedstock in glass production can reduce the energy use of the furnace by 2–3% for each 10% cullet in the feedstock (IPPC, 2008b). Recycling of scrap metals can save even more energy, for example, production and refining of recyclable aluminium consumes less than 5% of the energy used when producing virgin aluminium (IPPC, 2008a). Also for plastic it seems that the opportunity to save energy in material recycling compared with virgin production is the most important aspect and the saved raw materials are of less importance. If the virgin raw material for plastic production were used directly for energy production this energy could be assumed to substitute other fossil fuel. However, the energy production from the saved raw material would probably substitute energy production from the same raw material and thus merely increase the availability of these resources in the short term. When assessing plastic, system expansion to include energy production from saved raw materials thus seems unnecessary from an environmental perspective.

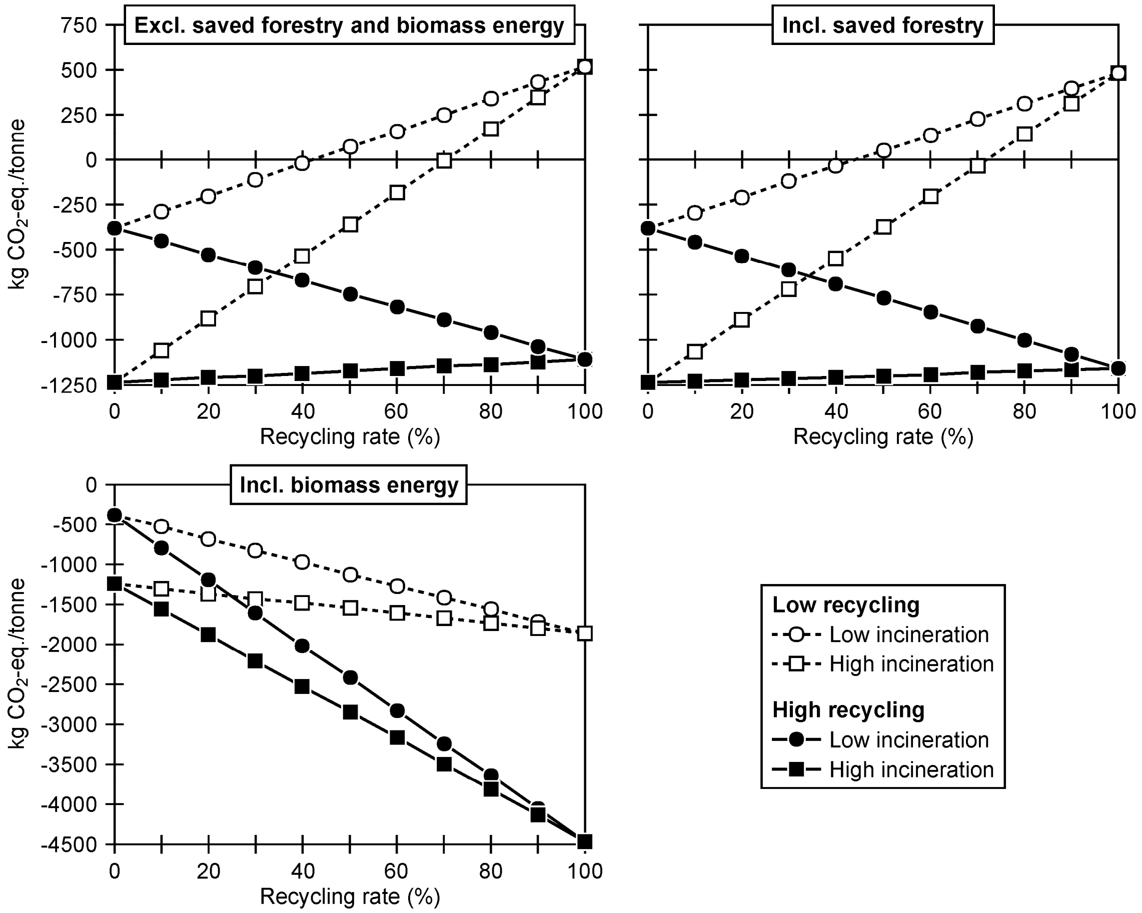

Figure 3: ***Global warming impact potentials as a function of the recycling rate for four combinations of technology levels and for three system boundaries (corrected from Merrild et al. I).***

2.5 Selection of impact categories

The selection of impact categories, and consequently impact category indicators, is related to the purpose of the life cycle assessment. The chosen impact categories should reflect a comprehensive set of environmental issues related to the studied system and should take the goal and scope into consideration (ISO, 2006b).

The selection of impact assessment method influences the selection of impact category indicators as the impact assessment methods per se employs different characterization models, impact categories and impact category indicators. For example, EDIP97 includes characterization models for the impact categories acidification, eutrophication, global warming, ozone depletion, photochemical ozone formation, human toxicity (for emissions to air, water and soil), ecotoxicity (for emissions to air, water and soil) as well as a number of waste and resource categories, while CML2001 recommends inclusion of acidification, eutrophication, global warming, ozone layer depletion, photochemical oxidation, human toxicity, ecotoxicity (fresh water aquatic, marine aquatic and terrestrial) and abiotic depletion (Wenzel et al., 1997; Guinée J.B. et al., 2001; Stranddorf et al., 2005).

Dreyer et al. (2003) studied three life-cycle impact assessment methods through a case study of water-based UV-lacquer and concluded that the two methods using midpoint indicators (EDIP97 and CML2001) were comparable for many of the impact categories. However, for the toxicity-related impact categories, the indicator results as well as the patterns of main contributors were different. The comparison with the third method, which uses end-point indicators (Eco-indicator 99), indicated that the results may go in opposite directions if different assessment methods are applied. In relation to waste management Moberg et al. (2005) concluded that the ranking between recycling, incineration and landfilling in the ecotoxicological impact category depended on the characterisation and weighting method used.

When choosing a set of environmental impact indicators to report potential environmental impacts, it is important to keep in mind that leaving some indicators out might lead to decisions that do not necessarily favour the overall environmentally best treatment option. For example, by focusing only on global warming, the system might be sub-optimized if there are other impacts, which results in large environmental impacts compared with the global warming impact potential.

3 Previous studies

Several case studies applying life cycle assessment to address different aspects related to waste management have been conducted. Here, the studies have been grouped into two main groups: studies focussing on treatment alternatives for specific waste fractions and studies focussing on assessing integrated waste management systems. The results from a number of studies within these two groups are presented here. The results for the global warming impact indicator in relation to other environmental impact category indicators are also examined. Only results for the two treatment options recycling and incineration are included.

3.1 Waste fraction studies

Some life cycle assessment studies, and a small number of reviews, regarding the six recyclable waste fractions paper, cardboard, glass, plastic and metals (including steel and aluminium) were examined. The results for each material fraction and general conclusions for material recycling are presented in the following six sections.

3.1.1 Paper

Based on the number of publications, the most studied recyclable fraction seems to be paper. A review of life cycle assessment studies covering alternative treatment options for managing paper waste shortlisted nine studies and concluded that recycling was environmentally a better option than incineration for the majority of the scenarios (Villanueva and Wenzel, 2007). This conclusion was assessed to be robust for the energy-related impacts (energy use/generation, global warming, acidification, nutrient enrichment and photochemical ozone formation), while no general conclusions could be drawn for the other impact categories (resource consumption, toxicity, waste generation and wastewater generation). In a study performed by Schmidt et al. (2007) increased recycling and increased incineration of paper were compared. The results showed that for the impact categories global warming and acidification increased recycling was preferable, while for eutrophication and photochemical smog increased incineration was preferable. Dahlbo et al. (2007) concluded that energy recovery (gasification and co-combustion as well as incineration) was environmentally better than recycling for newspaper if the produced energy replaced fossil fuel, otherwise recycling outperformed energy recovery. The results for the study were presented for three assessment methods applying end-point indicators and it is thus not possible to examine the behaviour of the global warming impact category (or climate change) compared with any other midpoint impact categories for this study.

The results from these studies show the complexity of assessing the environmental impacts of recycling and incineration for the paper fraction. For example, the results in Schmidt et al. (2007), which showed opposite results for global warming and acidification compared with eutrophication and photochemical smog, are not in agreement with the conclusion from Villanueva and Wenzel (2007), which concluded that recycling is environmentally better in all energy-related impact categories. The differences are, as mentioned in section 2, due to many reasons, such as selection of datasets and selection of system boundaries.

3.1.2 Cardboard

Only few studies comparing recycling and incineration of cardboard waste were identified in the scientific literature. Holmgren and Henning (2005) compared recycling and incineration of cardboard, along with a number of other fractions, using energy use as the only impact category in the assessment. The comparison showed that increased incineration of cardboard was preferable to increased recycling as more energy would be saved. A review showed that for 15 identified scenarios comparing recycling and incineration of cardboard, five showed preference for recycling and eight for incineration when comparing on the basis of global warming (Waste & Resources Action Programme, 2006). Similar results were found for the impact category groups resource consumption, other energy-related impacts and waste, which also showed varied results. Conversely, the impact category energy consumption showed a unanimous preference for recycling, which is in disagreement with that found in Holmgren and Henning (2005). Only three scenarios included toxicity impact indicators and seven scenarios included waste water. In these two impact categories recycling was environmentally preferable in the majority of cases.

The review of literature does not shed light on whether recycling is environmentally preferable to incineration for cardboard as there was disagreement in the results, both between scenarios and between impact category indicators.

3.1.3 Glass

For glass there seems to be a general agreement in the studies that recycling is preferable to incineration. Holmgren and Henning (2005) reached this conclusion based on energy consumption. In the comparison performed by Edwards and Schelling (1999), the conclusion is drawn from many more impact categories, units of polluted air, units of polluted water, global warming, reserves depletion, acid deposition, fossil fuel use, renewable energy use, total energy use and solid waste production, which all show preference for recycling.

3.1.4 Plastic

Results in Holmgren and Henning (2005) as well as in Arena et al. (2003) showed that recycling of plastic was preferable to incineration. Holmgren and Henning (2005) based their conclusion on energy use, while Arena et al. (2003) based their conclusion on the impact indicators energetic resource consumption, water emissions, solid waste production, air emissions, water consumption and greenhouse effect, which all showed the same tendency. Finnveden et al. (2005) concluded that recycling of plastic in general is favourable to incineration in regard to overall energy use, greenhouse gas emissions and for the total weighted results. The study also showed that recycling may be favourable with respect to toxicological impacts. However, if the recycled plastic replaced impregnated wood instead of virgin plastic, recycling of plastics was found to be less favourable with respect to the overall energy use and greenhouse gas emissions. This is in line with the conclusions in the study by Mølgaard (1995) which concluded that recycling of plastic is environmentally sound if it is possible to separate the plastic into its generic plastic types, which in turn makes it possible to produce recycled plastic with properties comparable to virgin plastic. If separation is not possible, incineration would be sounder. The impact categories included in the study were global warming, acidification, nutrient enrichment (nitrogen), nutrient enrichment (phosphor), photochemical ozone formation, solid waste, stratospheric ozone depletion and resource consumption. Frees (2002) measured the degree of contamination of the used plastic packages by residues and concluded that if the chemical oxygen demand content was medium to high, recovery would probably not be suitable compared with incineration.

The results indicate that the choice of impact indicator when comparing plastic recycling and incineration is of minor importance for the conclusions, providing the recycled plastic substitutes virgin plastic.

3.1.5 Metals

Beigl and Salhofer (2004) concluded that metal recycling leads to benefits in the impact categories acidification and net energy use, but that there was no significant difference between recycling and thermal treatment in the impact category global warming. Even though it is not clearly stated, the small differences in the global warming category seems to be mainly due to differences arising from emissions during collection and transport, as ferrous metals are assumed to be sorted out from the residual waste before thermal treatment in the no-recycling scenario. Holmgren and Henning (2005) concluded that recycling was environmentally superior to incineration based on the energy use. Life cycle assessment comparing recycling and incineration of the metal fractions steel and aluminium are uncommon in the scientific literature. This is most likely because recycling of metals saves extensive amounts of energy as well as scarce resources, while there is also a perception that incineration is an irrational waste treatment option for this waste fraction. However, as the technologies for extraction of metals from incineration residues develop, the balance between the two waste treatment options might change.

3.1.6 General results for recycling compared with incineration

To summarize, the conclusions of the studies show a clear trend of recycling being preferable to incineration for the material fractions glass and metals; in other words, the material fractions that save fairly substantial amounts of energy and resources when recycled instead of being produced from virgin raw material and at the same time do not contribute to any energy production at the incineration plant.

The three other material fractions, i.e. paper, cardboard and plastic, are of a two-fold nature as these can be utilized for material recycling and also have a value as a fuel. This is reflected in the results for the material fractions paper and cardboard. For these results it is more difficult to generalize whether recycling or incineration is environmentally preferable as the results from the studies go both ways. This is not only a consequence of the materials' two-fold nature but also the fact that studies often apply very different assumptions for incineration plants in relation to emission levels and energy recovery rates; different system boundaries as well as different data for the background energy systems also have an influence. Even though plastic can be seen as a valuable fuel, it is based on fossil raw materials, in contrast to the other two materials. This is reflected in the results which showed that recycling of plastic was preferable to incineration, under the precondition that the recycled material is of such a high quality that it can be assumed to replace virgin plastic. If this were not the case, incineration would be preferable to recycling.

However, as the number of studies for many of the materials is limited and the systems modelled differ, it is difficult to draw general conclusions across studies, both within the material fractions and between material fractions. In a decision-making context it is thus important to be aware of the limitations related to examining past assessments that do not correspond to the particular system for which the decision is to be made.

When examining the studies in regards to the global warming indicator (for some studies greenhouse gases or climate change) compared with other impact category indicators, the results suggest that global warming is not always representative for the overall environmental performance. The studies where multiple environmental indicators were included showed that the results can go in opposite directions for the different impact category indicators. For example, the results in Beigl and Salhofer (2004) showed that there was no significant difference between the treatment options in the global warming impact category, but that there were clear benefits in the acidification and nutrient enrichment categories when recycling metals. Another example is the study of Schmidt et al. (2007) where the results showed that increased recycling of paper would be preferable if focusing on the impact categories global warming and acidification, while increased incineration would be preferable if eutrophication and photochemical smog were in focus. This suggests that including only the global warming indicator in the decision might not support the overall environmentally best solution. Nevertheless, performing life cycle assessment for all materials within the same waste management system could reveal whether global warming can be used as an indicator for some materials and whether it is global warming that is the determining factor.

3.2 Integrated waste management system studies

Life cycle assessment has been applied to integrated waste management systems a number of times over the past 15–20 years. As for the material fraction studies, it is also difficult to draw general conclusions from previous integrated system studies as these are seldom comparable. There are large differences in the structure of the waste management within the different systems and thus it is unsuitable to compare the studies. The system boundaries applied, assumptions made in regards to energy etc. are not always well described and this also inhibits the comparability. Thus it is irrelevant to describe the results for each study in detail and the following section instead focuses on how the results for the indicator global warming have been used in comparison with other environmental impact indicators included in the studies.

Table 1 presents the impact category indicators included in a range of studies. Both the number of included impact categories and the impact categories included vary greatly between the studies. The studies can be grouped into five groups in regard to which impact indicators are included in the assessment as well as on which impact indicators the conclusions are based.

The first group includes studies that only use global warming in the assessment (see, e.g. Thorneloe et al. (2002); Liamsanguan and Gheewala (2008); Zhao et al. (2009)). This kind of study can evidently not be used for the assessment of the representativeness of global warming and is thus not further discussed here.

The second group of studies covers those that included global warming and energy use as the two impact categories. The results presented in Chester et al. (2008) showed the same trend for the two impact categories, whereas the results in Mohareb et al. (2008) showed that the scenarios were rated differently in the two impact categories.

The third group of studies includes multiple impact indicators in the presentation of the results, but uses global warming as the main criterion when concluding which scenario would be environmentally preferable. Luoranen et al. (2009) concluded that one of the modelled scenarios would be better than the others based on the assumption that global warming was the main criterion. The chosen scenario was also the one with the lowest environmental impact in the impact categories photochemical ozone creation, human toxicity, acidification and abiotic depletion, while it was ranked lower in the impact categories ozone layer depletion and eutrophication. In Beigl and Salhofer (2004) global warming was also used as the primary criterion for ranking. Even though it was not explicitly stated, the reason for this could be that the results showed savings for the impact categories acidification and net energy use in all the modelled scenarios, while global warming often showed a load.

Example of studies in the fourth group are Banar et al. (2009) and Özeler et al., (2006) which are studies that concluded which scenario was preferable, even though the results showed dissimilar ranking for the different scenarios in the included indicators. Banar et al. (2009) based the conclusion on the normalized result for three assessments methods using end-point indicators. The characterized results for the scenario concluded to be the best, showed that the lowest impact in the three impact categories global warming, eutrophication, photochemical ozone formation, while for the other impact categories other scenarios performed better. The rating of the scenarios also differed between the impact categories in the study performed by Özeler et al. (2006). This study concluded that one of the scenarios was better than the others based on it exerting the lowest pressure in the impact categories non-renewable energy source exhausting, hazardous waste, acidification, eutrophication and human toxicity and the second lowest in the impact categories global warming and non-hazardous solid waste. In Rigamonti et al. (2009) the order of the scenarios was the same for all included impact categories; however, the cumulative energy demand and global warming are highlighted as these are the only two impact indicators mentioned in the paper's conclusion.

The fifth group represents studies that did not conclude which scenario was preferable due to the diversity in the ranking of scenarios in the impact categories. Emery et al. (2007) compared four waste management options, and the results showed that one of the scenarios performed the best in the impact categories eutrophication, greenhouse effect and ozone layer depletion, while another performed the best in the acidification category; a third performed the best in the resource depletion category. Eriksson et al. (2005) also showed that for most of the scenarios the ranking differed in the different environmental impact categories included and there seemed to be no correlation between the rankings. In Morris (2005) energy conserved, greenhouse gas emissions, acidification and eutrophication showed similar results for the waste management scenarios, while human toxicity rated the scenarios in a different order. Also in Kirkeby et al. (2006b) the comparison of scenarios showed different rating of the scenarios between the impact categories. For example, one of the scenarios performed better in the impact categories global warming, photochemical ozone formation, human toxicity water, human toxicity soil, while the other scenario performed better in acidification, nutrient enrichment, human toxicity air, ecotoxicity water chronic and ecotoxicity water acute. The results in Klang et al. (2008) showed one succession of the scenarios in the greenhouse effect category and another succession in the acidification and eutrophication categories. For the results in Villeneuve et al. (2009) there seemed to be a correlation between the greenhouse gas emissions and acidification as the scenarios were rated the same, while for the other impact categories the rating was more diverse.

Similarly to the material fractions studies, the results from the integrated system studies suggest that global warming is not always adequate for describing the environmental consequences of changes to the system. Here, too, the studies that included multiple environmental indicators showed that the results can go in opposite directions for the different impact category indicators. No general trend for which impact categories follow the same pattern can be seen from the results. This is partly due to inconsistency in the systems and most likely also partly due to the inconsistency between the methodologies applied.

Table 1: ***Environmental impact category indicators included in a selection of life cycle assessment studies performed on integrated waste management systems.***

Reference	Environmental indicators included
Banar et al. (2009)	Abiotic depletion, global warming, human toxicity, acidification, eutrophication, photochemical ozone formation
Beigl and Salhofer (2004)	Global warming potential, acidification, net energy use
Chester et al. (2008)	Energy consumption, greenhouse gas emissions
Emery et al. (2007)	Acidification, eutrophication, resource depletion, greenhouse effect, ozone layer depletion
Eriksson et al. (2005)	Global warming potential, acidification, eutrophication, consumption of primary energy carriers, emissions of NO_x, emissions of VOC and emissions of metals
Kirkeby et al. (2006b)	Global warming, acidification, photochemical ozone formation, nutrient enrichment, human toxicity (water, air, soil), ecotoxicity (water chronic, water acute, soil), ozone depletion, resource consumption (natural gas, crude oil, coal, lignite, water, aluminium, iron, manganese, primary energy)
Klang et al. (2008)	Greenhouse effect, acidification, eutrophication
Liamsanguan and Gheewala (2008)	Greenhouse gas emissions
Luoranen et al. (2009)	Photochemical ozone creation, ozone layer depletion, human toxicity, global warming, eutrophication, acidification, abiotic depletion
Mohareb et al. (2008)	Greenhouse gas emissions, energy consumption
Morris (2005)	Energy conservation, greenhouse gas emissions, acidification, eutrophication, human toxicity
Rigamonti et al. (2009)	Cumulative energy demand, global warming, acidification, human toxicity, photochemical ozone creation
Thorneloe et al. (2002)	Greenhouse gas emissions
Villeneuve et al. (2009)	Energy balance, energy recovery rate, recycling rate, greenhouse gas emissions, air acidification, hazardous waste landfilled, non-hazardous waste landfilled, dioxins and furans, travel distance
Zhao et al. (2009)	Greenhouse gas emissions
Özeler et al. (2006)	Non-renewable energy source exhausting, non-hazardous solid waste, hazardous waste, global warming, acidification, eutrophication, human toxicity

4 Case study

The examination of some previous studies showed inconsistencies in the conclusions about whether increased recycling is environmentally preferable to incineration for the different materials. Moreover, the studies showed inconsistencies in the correlation between the global warming indicator and other impact categories indicators. The differences between the studies entailed discrepancies in system boundaries, incineration technologies etc. and this made it difficult to draw general conclusions based on experience.

To avoid some of the discrepancies a case study was performed that examined the consequences of increasing the collection of recyclables in a waste management system for all the recyclable materials paper, cardboard, glass, plastic and metals at once. The case study area is the Municipality of Aarhus, which has nearly 300,000 citizens. It covers the City of Aarhus and its surrounding areas. The area has an incineration plant with a high energy recovery rate (approximately 21% of the lower heating value as electricity and 74% of the lower heating value as district heating) and effective air pollution control systems, including dioxin and NO_x abatement. The case study was performed in two steps: first the effects of increased recycling were studied on a material fraction basis in Merrild et al. (IV) and second the effects of several changes to the collection system in the integrated waste management system were examined in Larsen et al. (V). In the following sections the two sub-studies are introduced and the main assumptions and results are presented.

4.1 Environmental capacity for material fractions

Merrild et al. (IV) introduced the term environmental capacity to examine the benefits of recycling compared with incineration. The environmental capacity was defined as the difference between the environmental impacts from the residual waste treatment system (incl. collection of residual waste, incineration, transport of residual waste and substituted energy) and the environmental impacts from the material recycling (incl. recycling and substituted products), see Equation 1. I.e. it was the response to a change in the waste management system that was modelled, assuming that the initial handling of the materials was collection as residual waste and treatment through incineration. Thus the environmental capacity is the scope for environmental loads from separate collection, pre-treatment, and transport of source-separated materials when one tonne of material is recycled instead of being treated as residual waste in order for recycling not to become environmentally worse than incineration.

Equation 1:

$$Environmental\ capacity = (C + T + I - SE) - (R - SP)$$

◦ *C: Collection of recyclable material as residual waste*
◦ *T: Transportation of recyclable material as residual waste*
◦ *I: Incineration*
◦ *SE: Production of substituted energy*
◦ *R: Recycling*
◦ *SP: Production of substituted product*

Establishing the environmental capacity for the six material fractions paper, cardboard, glass, plastic, steel and aluminium was useful to investigate the performance of recycling compared with incineration for this particular case area. The environmental capacities for ten different scenarios were established for the four impact category indicators acidification, global warming, nutrient enrichment and photochemical ozone formation. For some materials two modelling scenarios were established to consider some assumptions which were believed to be critical to the outcome. These additional scenarios were expansion of the system boundary to include energy production from saved biomass for the materials paper and cardboard, and metal recycling from the incineration bottom ash for the materials steel and aluminium.

4.1.1 Results

The environmental capacities for each of the ten modelling scenarios are shown in Figure 4, both for a comparison with a high energy recovery rate incineration plant and an incineration plant with a lower energy recovery rate (21% electricity and 55% district heating). The high energy recovery incineration plant represents the actual plant in the case study area, while the low energy recovery plant was modelled to investigate the importance of the energy recovery rate for the outcome.

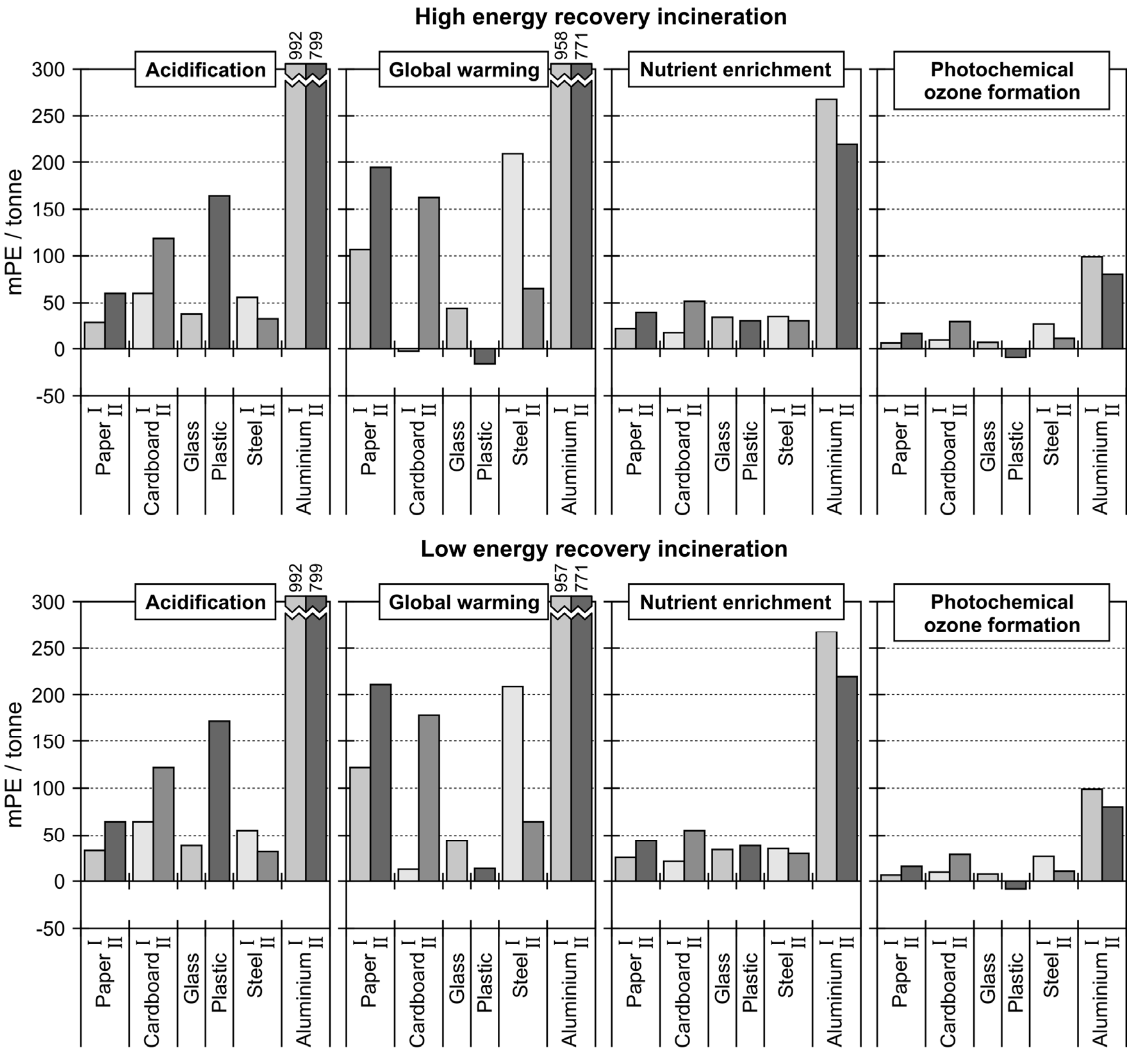

Figure 4: ***Environmental capacities for one tonne of material fraction (Merrild et al., IV).***

The modelling showed that there was an environmental capacity in all four impact categories for the material fractions glass, steel and aluminium regardless of the energy recovery rate at the incineration plant and regardless of the chosen system boundaries. As the lower heating values for theses material fractions are close to zero, or in some cases negative, the energy recovery rate at the incineration plant is of negligible importance for the results, thus there are insignificant differences between the high and low energy recovery rate incineration results. The changes due to recycling of 80% of steel and 20% of aluminium from the bottom ash did not invalidate the environmental capacity for these two materials.

For the paper fraction, the results also showed that there were environmental capacities in all four impact categories regardless of the energy recovery rate level and regardless of the system boundary. The datasets used for the recycling modelling were assessed as being in the better end of the scale with regard to environmental performance, which would be a realistic scenario in the case where the paper waste is of a high quality. Selecting another dataset representative of a more mixed quality paper fraction would most likely result in similar environmental capacities to those of the cardboard fraction modelling.

The results for the cardboard and plastic fractions were not as clear-cut as the results for the other fractions. In some cases, the modelling for these two materials resulted in numerically negative environmental capacities, suggesting that incineration might be preferable to recycling.

The cardboard modelling, which did not include energy production from saved biomass, resulted in a negative environmental capacity in the impact category global warming. The negative global warming value appeared because the gain from the energy produced at the incineration plant was larger than the savings from the recycling. The modelling with the lower energy recovery rate at the incineration plant changed the global warming savings from the incinerator to such a degree that the environmental capacity became positive. This suggests that even a small change to the energy recovery rate can change the outcome of the modelling in the global warming category for the cardboard fraction. The outcome of the modelling for cardboard is not only highly dependent on the energy recovery rate at the incineration plant but also on the system boundaries.

The results from the plastic modelling showed two negative environmental capacities, one in the global warming category and one in the photochemical ozone formation category, when the high energy recovery rate incineration modelling was applied. The global warming results showed a negative environmental capacity because the high energy recovery ratio at the incineration plant leads to higher fossil fuel energy savings than the recycling. Modelling with the lower energy recovery rate at the incineration overturned the result in this impact category, which suggests that the outcome in the global warming category, also for this material, is highly dependent on the energy recovery rate at the incineration plant. The reason for photochemical ozone formation being negative is also connected to the larger saving of fossil fuels in the case of treatment by incineration. The main cause of the impact in the photochemical ozone formation category was traced to the emission of methane and other volatile organic compounds during the extraction of coal and other fossil fuels. In contrast to the global warming category, the change of the energy recovery rate did not change the outcome in this impact category significantly enough to overturn the negative environmental capacity.

Comparing the results for the global warming indicator with those for the three other environmental impact indicators suggests that global warming could be a representative indicator to use in a decision-making context for all the materials except plastic. The reasoning behind this is that global warming was seemingly the only indicator affected in such a manner by the applied changes to the system boundaries and the energy recovery rate of the incinerator that the conclusion could change about whether recycling is preferable to incineration. Excluding plastic, which showed a negative environmental impact in more than one impact category, the other material fractions were assessed to have environmental capacities in the impact categories acidification, nutrient enrichment and photochemical ozone formation independently of which scenario was modelled. Furthermore, the examination of the results revealed that the incineration of the material fraction cardboard also results in impact savings for these three impact categories, but the savings would be smaller than those for the recycling. Thus this suggests that for these three impact categories there would always be an environmental benefit irrespective of whether the global warming indicator showed an environmental capacity. Therefore, the feasibility of using global warming depends on the aim of the decision, should it result in the largest overall benefit or is it acceptable to compromise on the other impact categories.

The comparison between the environmental capacities for each material also revealed that the environmental capacity for the global warming indicator in six of the modelling scenarios was larger than the environmental capacities for the other impact category indicators. This was the case for the two paper scenarios, one of the cardboard scenarios, the glass scenario and the two steel scenarios. For the remaining cardboard scenario and for the plastic scenario, the environmental capacities for the acidification indicator and nutrient enrichment indicator were larger, and for the aluminium scenarios the environmental capacities were larger for the acidification indicator. Only in the two cases where the environmental capacity in the global warming category was negative did the global warming indicator appear to be the smallest. This suggests that, in most cases, global warming is not the limiting impact indicator when comparing the environmental capacity with the environmental impact from collection, pre-treatment and transport. This is relevant in the perspective of recyclable materials as the transport distances of the recyclable materials is often unknown and in most cases can be expected to be longer than the transport distance of residual waste to the incineration plant. Merrild et al. (IV) showed that the environmental impact from collection and pre-treatment was much smaller than the environmental capacities. The results also showed that for different means of transport, with different environmental impact per tonne*km, it was most commonly not global warming that was the limiting indicator. For example, photochemical ozone formation was the limiting indicator in most cases when the environmental capacities were compared with transport by truck while nutrient enrichment was the limiting indicator in most cases when the environmental capacities were compared with transport by small bulk carrier. Global warming was the limiting indicator in only one scenario, in addition to the two scenarios where negative global warming capacities appeared.

4.2 The integrated waste management system

Larsen et al. (V) studied the environmental consequences of changes to the current waste management system in the case study area. In the existing system kerbside collection of residual waste was mandatory for all households; additionally, there were well-functioning collection systems for source-separated paper and glass, which resulted in relatively high recycling rates for these two materials, 72% and 52% respectively. Source-separated paper and glass were mainly collected in a bring scheme with centrally placed drop-off containers, and to a lesser extent at recycling centres. In addition to this, approximately 40% of the paper waste was collected in a kerbside collection scheme, primarily from apartment blocks. The development in the European legislation to require establishment of collection schemes for plastic and metal fractions too prompted the investigation of how changes to the waste management system would affect the system's environmental performance.

Building on the current system, five possible future scenarios were modelled including different combinations for collection of recyclables through kerbside collection, drop-off containers or recycling centres. The waste fractions considered in the scenarios were paper, glass, packaging waste in terms of plastic, steel and aluminium as well as residual waste.

The five scenarios were:

- *Kerbside collection only*
- *Kerbside collection limited to two bins*
- *Voluntary participation in kerbside collection*
- *Drop-off containers only*
- *Recycling centres only*

4.2.1 Results

The changes to the collection schemes resulted in a range of recycling rates for the different scenarios. The then average recycling rate of 25% was estimated to increase to 31% in the scenario *only kerbside collection* or to decrease to 20% in the scenario *only recycling centres*.

The outcome of the modelling for each of the five scenarios in the six environmental impact categories global warming, acidification, nutrient enrichment, photochemical ozone formation, human toxicity and persistent toxicity are shown in Figure 5. Stratospheric ozone depletion was not included in the study, as emissions contributing to this impact category do not appear when studying waste materials commonly appearing in the household waste. The results are presented as weighted averages from the three types of dwelling area suburban single family houses, suburban apartment blocks and apartment blocks in the city centre, which were the three dwelling types the case study area was divided into in the modelling. A negative value means that the environmental impact decreased and a positive value that the impact increased in the particular scenario compared with the environmental impact in the current system. The graphs on the left in the figure show the contributions from collection and transport as one stage and waste treatment as one stage; the graphs on the right show the net environmental impact. The waste treatment stage included all the process downstream of collection, i.e. also the savings from the substituted goods.

The results showed a tendency of better environmental performance related to higher recycling rates for four of the six impact categories: global warming, acidification, nutrient enrichment and persistent toxicity. This suggests that by moving waste from incineration to recycling the environmental impacts can be decreased. However, in relation to the recycling rates the results showed inconsistency in the ranking of the scenarios *kerbside collection limited to two bins, voluntary participation in kerbside collection* and *only drop-off containers* in the impact categories global warming and persistent toxicity. Even though the recycling rate was higher for the scenario *kerbside collection limited to two bins,* the results showed a smaller saving in environmental impact in these two impact categories. This suggests that the size of the benefit was not only related to the recycling rate achieved in the scenario but also to which materials were assumed to be recycled. The inconsistency was predominantly traced to the difference in the amount of paper recycled in the scenarios. The chosen dataset for recycling of paper seems to favour incineration of paper over recycling in these two impact categories. The main contribution to the impact stemmed from the treatment stage in these four impact categories.

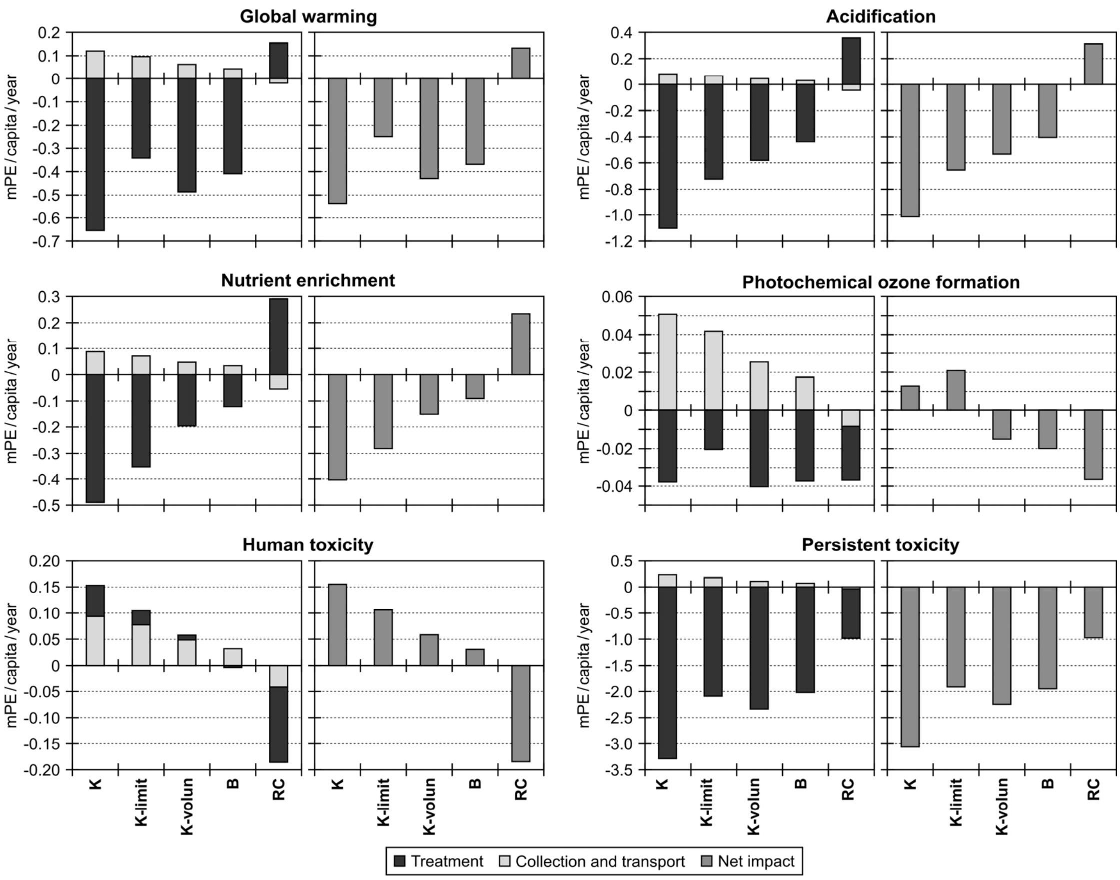

Figure 5: ***Changes in environmental impact for the scenarios compared with the current system (K: Only kerbside collection, K-limit: Kerbside collection limited to two bins, K-volun: Voluntary participation in kerbside collection, B: Only drop-off containers, RC: Only recycling centres) (Larsen et al., V).***

The impact categories photochemical ozone formation and human toxicity showed tendencies opposite those of the other four impact categories: the environmental impacts increased with the recycling rate. The photochemical ozone formation category showed the same inconsistency between the results and the recycling rate as did the global warming and persistent toxicity categories. The contribution from the treatment stage was relatively low in these two categories, meaning that changes in the contribution from the collection and transport stage dominated the overall result. The increased impact was particularly an effect of increased waste transport caused by recycling. The scenario with the lowest recycling rate, *only recycling centres*, and thus also the smallest amount of transport, gave the largest savings.

No preferred overall ranking of the scenarios could be established based on these six environmental impact categories as the ranking changed between them. The results also showed that no scenario could be implemented without trade-offs, as all caused an increased load in at least one of the impact categories.

Comparison of the results for the global warming impact with the other environmental impact categories showed that it was for persistent toxicity only that the same ranking of the scenarios occurred. This means that focusing exclusively on the impact indicator global warming and implementing a scenario based on the global warming results would not necessarily result in the overall largest environmental benefit. However, although there was some inconsistency in the ranking between the impact categories global warming, acidification and nutrient enrichment, ranking the scenarios based on the global warming indicator would entail environmental benefits also in these other two impact categories as the net results showed savings or loads for the same scenarios in the three impact categories. This suggests that global warming would be a representative indicator for the three impact categories acidification, nutrient enrichment and persistent toxicity in this particular case study. The result indicated that global warming was not representative as an indicator for the photochemical ozone formation and human toxicity category results, as the results went in opposite directions for these categories.

The results for consumption of fossil fuels in terms of hard coal, natural gas and crude oil showed alternating reductions and increases for all scenarios, and thus no consistent ranking of the scenarios could be made from the fossil fuel consumption. The rankings showed the same inconsistency as the ranking in the categories global warming, persistent toxicity and photochemical ozone formation. The two major contributors to the hard coal result were recycling of paper and incineration of residual waste, which, however, seemed to cancel out each other; consequently, the differences in the net results seem small. For example the increased recycling of paper resulted in savings of approximately the same magnitude as the lost benefit from the decreased incineration of residual waste in the *only kerbside collection* scenario. Paper recycling was also the major contributor to results in the natural gas category, which was a reflection of the natural gas consumption of the specific paper process chosen in the modelling. Thus increased paper recycling resulted in increased natural gas consumption and vice versa. The outcome of the crude oil results was mainly a result of changes in the amount of packaging material recycled. Assuming that global warming is a representative indicator for the fossil resources use does not seem to be consistent with the results in the case study. In this case, prioritizing the scenarios on the basis of global warming would be representative only in relation to crude oil consumption, not for the hard coal or natural gas consumption. This is partly due to the fuels' different global warming impact potentials and partly because not all the fossil resource use is due to the resources being used as fuel, but also as raw materials e.g. in plastic production.

The results for the metal resources were, as expected, proportional to the recycling rate for metal packaging. This proportionality cannot be directly linked to the global warming impact as this impact category is also affected by other parts of the system, i.e. energy recovery at the incineration plant.

Acidification, nutrient enrichment and human toxicity, i.e. only three of the twelve environmental impact and resource consumption categories, showed results consistent with the recycling rate. The inconsistency between the recycling rates and the performance in the other impact categories suggests that using performance indicators such as recycling rates as the only success criterion would not always lead to the overall environmentally best performing system.

As can be seen in Figure 5, the difference between the suggested scenarios were relatively small, ranging from changes of approximately 0.01 to 3 mPE per capita per year for the environmental impact categories. Similarly, the changes were small in the resource consumption categories, ranging from approximately 0.001

to 0.5 mPR per capita per year. Enhanced recycling of household waste thus seems to be of minor importance compared with the overall environmental impact caused by one person in one year. However, these changes should be seen in the light of being changes applied to an already well-functioning and environmentally well-performing system. The changes should thus be compared with the effect of other changes in the waste management system before judging their significance.

5 Discussion

In this section the use of life cycle assessment in waste management and the representativeness of global warming as an indicator for environmental performance of waste management are discussed based on the previous knowledge and the case study. The use of life cycle assessment as decision aid tool is also discussed.

5.1 Life cycle assessment within waste management

Several life cycle assessment-based comparisons between recycling and incineration of some of the commonly appearing recyclable materials in household waste were examined. This examination showed that there was low consistency in the results between the different studies. Some studies concluded that recycling was environmentally preferable to incineration, while other studies concluded that incineration was preferable. In the past there has been a general belief that recycling is preferable to incineration, most likely as a result of the strong emphasis on the waste hierarchy in policy making. The comparison might thus show surprisingly diverse results for some of the material fractions. However, the recyclable materials can be grouped into two groups: the materials that have a significant heating value, and thus also have a value as a fuel, and the materials that do not. The diversity was found to be strongly connected to the energy content of the material fractions, and thus this diversity was larger for the first group than the second group. This diversity is to some degree connected to the energy performance of the incineration plant and also to the assumptions regarding marginal energy. The relation to the incineration plant's performance suggest that drawing general conclusions about whether recycling or incineration is preferable is not feasible, and that system-specific modelling has to be performed in each specific case. The system-specific modelling would eliminate the uncertainties connected to the energy performance of the incineration plant. The system-specific approach is also necessary regarding the crediting of district heating production. If the district heating is connected to an existing network, it will substitute district heating from other plants on the network, as was the case for the incineration plant in the case study area. However, if the network is extended or newly built, the district heating from incineration would substitute in-house heating devices (Wollny and Schmied, 2000). The discrepancies that appear due to the marginal electricity assumptions and assumptions regarding marginal technologies connected to recycling of material fractions, such as the recycling technologies and virgin production technologies, are more difficult to eradicate even though a system-specific approach is applied. This is due to electricity and recyclable materials being commodities distributed into systems affected by economic forces, e.g. investment policies and market forces. The marginal technologies for electricity production are often identified using static models, but dynamic modelling would give a more complete description of the consequences of using or delivering electricity as it takes into account effects on existing production facilities as well as investment in new production facilities (Ekvall et al., 2007). Establishing the marginal electricity technology due to electricity consumption and production at the incineration plant would require in depth energy systems analysis, which in itself is complicated and would entail a number of assumptions and uncertainties. Likewise, the identification of marginal consequences due to recycling would ideally be based on the price elasticity of supply and demand, but in practice this is difficult to obtain (Ekvall, 2000). Today, recyclable materials are traded on a world market and identifying the marginal technologies is thus a difficult task.

Another problem related to the material fraction based studies is that only few of the studies examine more than one recyclable material for the same system. The results from material fraction studies that are not performed for the same system cannot be compared with results from another material fraction study based on another system. For example, it would not be possible to judge whether efforts should be made to increase the recycling of cardboard or to increase the recycling of plastic as the outcome of this would be system specific. Comparison across material fractions might be of importance in a decision-making context, e.g. if the decision-makers need to prioritize the effort between materials.

The case study illustrated that comparing recycling and incineration on a material fraction basis for several materials within the same system can give an indication of whether it is worth recycling a specific material, and if there would be enough environmental capacity for the extra collection and transport assumed needed for recyclable materials. However, expansion of the case study to include the waste composition showed that deciding on whether to recycle a material fraction based only on a life cycle assessment made on a material fraction basis might not give the best solution for the integrated waste management system. Some of the material fractions appear in relatively large amounts in the household waste, e.g.

paper, whereas other material fractions appear in relatively limited amounts, e.g. aluminium. Thus it is important to know the waste's material fraction composition when assessing the potential benefits from recycling. This aspect underlines the importance of modelling waste management on a system basis, since the waste composition is likely to be different in different geographical areas as is dependent on, e.g. collection systems in place, type of dwellings and composition of the population.

Other important aspects, which can be captured only when a system approach is implemented, are the recycling rates and the consequences for the residual waste. Larsen et al (V) showed that the most significant parameter for the difference between the collection methods in the case study was the estimated recycling rates and hence the amount of source-separated recyclables. The collection method itself was of minor importance when the downstream effect of moving waste between recycling and incineration was taken into consideration. Larsen et al (V) also showed that for some of the impact categories the outcome was at least as dependent on the loss of benefits from the incineration plant as the gained benefits by increased recycling. This indicates that if only individual parts of the waste management system are studied, the system might be sub-optimized.

As the results of a life cycle assessment comparing recycling and incineration are highly dependent on the system-specific circumstances, e.g. the energy recovery rate of the incineration plant, results from single case studies are suitable only for local decision-making. On a local level it is a strong system analysis tool that seems superior to the waste hierarchy as the results showed that recycling is not always environmentally preferable. Due to the system specificity, policy making on a national or international (European) level based on generalisation from life cycle assessment case studies seems unsuitable, unless the case studies can describe the diversity of the actual systems in a representative manner.

5.2 Global warming as an indicator for environmental performance

The advantage of being able to use only one indicator, e.g. global warming, in environmental assessment of waste management systems would possibly be that the results from the assessment would appear simpler and more readily available for the decision-makers. Presenting multi-indicator results that often show different ranking of the investigated scenarios makes the decision process complex and requires the decision-makers to weight the environmental impacts against each other. The global warming indicator will undoubtedly be an important part of future decision-making, but the question is how representative it is for the environmental performance of waste management systems.

There are some advantages of the global warming indicator compared with other indicators commonly applied in life cycle assessment:

- There is a high comparability for the global warming indicator across impact assessment methods as the categorization methods are based on the global warming potentials from the Intergovernmental Panel of Climate Change (IPCC, 2007b). This means that no matter which assessment method is chosen, the results should be the same for assessments of the same inventory data. Other impact categories are more difficult to compare across impact assessment methods as they apply different characterization methods. Jolliet et al. (2004) divided the impact categories into two groups. The first group is the impact categories where there is a good level of agreement on how to determine meaningful midpoint indicators. In addition to global warming, these impact categories are photooxidant formation, stratospheric ozone depletion, acidification and aquatic eutrophication. The other groups of impact categories are the toxicity categories, the natural resources and land use. For these, there are often different impact mechanisms included in the characterization. Environmental indicators can be strongly affected by uncertainty related to the characterisation of the inventory data. An example mentioned in Ekvall et al. (2007) is the problem that, in some cases, life cycle assessments aggregate substances of the same type into sum parameters, e.g. PAH, VOC and TOC. The environmental impact can vary greatly between different substances within these sum parameters and such aggregate measures thus reduce the ability of life cycle assessments to accurately model actual environmental impacts.
- The global warming indicator is assessed from a global point and could thus more easily be applied as a general impact assessment category. The other impact categories (excluding stratospheric ozone depletion, which does not seem relevant for the comparison of recycling and incineration of the chosen material fractions) are important on a regional or local scale, and as the geographical information is not included in the characterisation

of the impacts of emissions contributing to these categories, these might not correctly describe the consequences.

- The energy aspects are the most important parameter for the global warming results, process specific emissions due to incineration of materials and due to recycling of materials are of minor importance, and using general emission factors for different energy sources could thus be a good approximation for calculating the environmental impact for the global warming indicator for most of the materials. However, for the plastic fraction, specific emissions from incineration would also be required as this material fraction contains fossil carbon. For many of the other impact categories, waste specific, fuel specific and process specific data are of more importance, both in relation to emissions from waste treatment and in relation to emissions from energy production. General assessments based on emission factors would thus be much more difficult and possibly give more unreliable results for other impact categories.

The work performed in relation to this thesis showed that ranking scenarios solely on the basis of the global warming indicator results would most likely not give the overall most environmentally best performing waste management system. However, the results also showed that for some impact categories, in this case acidification, nutrient enrichment and persistent toxicity, a ranking based on the global warming indicator seemed to give a reasonably fair decision support as the trends for the other three environmental impact categories were the same as for global warming, i.e. the scenarios with net savings in the global warming category also showed net savings in the other categories. Based on the premises that it is not necessarily the optimal improvement that should be achieved, global warming could be used as an indicator for these impact categories. Acidification and nutrient enrichment are mainly linked to energy aspects and thus it seems fair to assume that global warming is representative for these two environmental impacts in other case studies too. But one should always be aware of the specific system assessed, as some recycling technologies might have emissions of specific substances that influence the outcome. For example, recycling of paper can sometimes entail emissions of nutrients to surrounding water bodies, which would result in impact in the eutrophication category. For the persistent toxicity category, the link to global warming seems more coincidental; the impact was found mainly to be related to the avoided extraction of virgin metal resources.

Therefore, assuming that there is generally a link between global warming and persistent toxicity seems erroneous.

Furthermore, global warming was seemingly not a representative indicator for the other impact categories included in the case study, namely photochemical ozone formation, human toxicity and resource consumption. These impact categories were affected by other parts of the system than the other impact categories. For example, the proportion of the impacts due to collection and transport were much larger in the photochemical ozone formation and human toxicity impact categories than in the other impact categories. Assessing the collection based on global warming might not be the most appropriate. Global warming does not differentiate greatly between different combustion engines, but other impact categories might show a larger difference, see, for example, calculations on diesel combustion in Larsen et al. (2009).

Several other impact indicators not included in the cases study, e.g. land use and landfilling requirements, could also be relevant in relation to waste management systems. Whether these other impact categories could somehow be linked to global warming would need a closer investigation, but it seems unlikely that categories that are not linked to fossil energy use would be well described by the use of the global warming indicator.

5.3 Life cycle assessment as a decision support tool

Although a multi-indicator life cycle assessment might give a more complete description of the environmental consequence than the use of merely a global warming indicator, there are still a number of aspects to consider when using life cycle assessment as a decision support tool.

Although a multi-indicator approach gives a more comprehensive description of the environmental impacts of changes to the waste management system, the results are based on modelling. System modelling is a simplification of the reality and the results reflect a number of assumptions (Finnveden et al., 2007). Using life cycle assessment as a decision support tool, it should be remembered that information is lost when modelling. Life cycle assessment models are typically linear steady-state models of physical flows, and in reality the environmental burdens of collection and recycling are likely to be a non-linear function of the collection rate (Ekvall et al., 2007). Modelling future systems gives rise to uncertainty, because the future is inherently uncertain (Björklund, 2002). Every time the system is expanded and new processes are involved it has to be taken into account that there are choices and uncertainties related to the processes involved. Expanding the system boundaries outside the municipal waste management system to include processes that are not under the control of the municipal waste administration, e.g. utilization of wood as renewable fuel and the consequences hereof, might be difficult for the municipal waste administration. It is, however, a necessary step in understanding the consequences of changing the collection system for recyclable material fractions as the processes outside the municipal waste management system have a large influence on the overall results.

The question of which waste management scenario should be implemented cannot be answered without ranking the impact categories with respect to importance and accepting trade-offs. For this, life cycle assessment offers no guidelines, instead it is a responsibility of the decision-makers to weight the impacts. In this process they should be aware of the fact that basing decisions on one indicator can sometimes be misleading.

Environmental performance is an important parameter in evaluation of waste management options, but in order to promote sustainable solutions economic and social aspects are also important. In contrast to life cycle assessment, the analyses of economic and social impacts are not standardised and this opens up for methodological uncertainties. Properly and fully integrating meaningful economic analysis into life cycle assessment requires the addition of a time dimension to the modelling as well as the ability to introduce and work with variables that are sometimes independent of the inventory flows (Norris, 2001). Various studies have combined life cycle assessment with some kind of economic assessment with the intention of achieving a more holistic result by including this second sustainability parameter, see, e.g. Beigl and Salhofer (2004); Morris (2005); Klang et al. (2008); Chester et al. (2008). The results for the economic studies are, as the environmental studies, highly system dependent and general conclusions are thus hard to draw. Differences in the vehicle fleet, collection schemes, fees etc. all influence the costs.

Larsen et al. (V) showed that the difference between the suggested collection scenarios was relatively small, both for the environmental and economic assessment results. The changes of the environmental impact from collection of household waste in the future scenarios ranged from -6% to +4% of the impact for the current system and the costs for the municipality varied from -2% to +4% compared with the current system. The result from the economic assessment does not seem to be of great help in the ranking of the scenarios, as the differences were small. However, it showed that as long as an incineration tax is applied in Denmark, treatment costs can be reduced by increased recycling. The economic assessment was based on historical data and as the results are sensitive to the fluctuating prices for recyclables on the world market, electricity prices etc. using these to model the future might not results in the most economical solution.

In addition to the costs for the municipality there are also costs and benefits for other stake holders in society, e.g. the waste collector and the citizens. These can be both of a monetary and non-monetary character, and all these costs should be included to represent the full effect the waste management decision has on the welfare of society, thus advocating sustainable decision-making. However, as the monetising of the non-monetary costs is difficult and very uncertain, calculating the full cost for waste management is a cumbersome task. Often, many of the effects, e.g. damage to the environment caused by greenhouse gas emissions, time consumption in the household or damage to human health caused by air emissions, are often not possible to monetise in a credible way, and thus the conclusions on society's costs and benefits are drawn from an incomplete basis.

The sustainability of a waste management system should ideally also be assessed in terms of the waste management system's social sustainability. den Boer et al. (2005) defines three social sustainability parameters: social acceptability, social equity and social function. Measuring of these, or other social sustainability parameters, is not common within waste management. This might be due to their intangibility as well as their inherent subjectivity. Any kind of measurement of this kind of parameter would include a valued judgement, e.g. when evaluating if a bring system in one part of the study area is socially equitable with a kerbside system in another part of the study area.

Even though economic and social aspects are important, the decision maker should be aware of the increased complexity and uncertainty the inclusion of these aspects can cause. Making a decision based on environmental aspects is a complex task in itself as it requires weighting of different environmental impacts towards each other. Including economic and social aspects would require that also these are weighted towards the environmental impacts and towards each other.

6 Conclusions

As the public awareness and political focus on greenhouse gas emissions and related environmental problems have increased, global warming has become an important priority criterion in decision making. As global warming is a priority criterion, this indicator should always be included in any decision-supporting assessment of the environmental impacts of waste management options. The aim of the study was to study how robust global warming is as an indicator for environmental performance within waste management and the work performed has shown that the global warming indicator should not stand alone.

In relation to the other impact categories included in the case study performed, and in previous studies, the representativeness of global warming as an indicator for the environmental performance of waste management systems seems relatively poor. Acidification and nutrient enrichment seem to be the only two impact categories that could be reasonably well represented by the global warming category. Even though these two impact indicators did not show the same rating of the modelled waste management scenarios as did the global warming indicator, they showed the same trend, i.e. savings appeared concurrently and loads appeared concurrently. However, one should always be aware of system specific circumstances that could bring about emissions that contribute to the load in these impact categories. This could be emissions due to characteristics in the chemical composition of the waste, e.g. fossil carbon content in the plastic, or due to emissions possibly prevailing in a certain process, e.g. emissions contributing to nutrient enrichment from paper and cardboard production. For the impact categories photochemical ozone formation, human toxicity, persistent toxicity and the resource consumption categories, global warming did not seem to be representative. Whereas global warming, acidification and nutrient enrichment were highly dependent on the energy aspects of the study, the results in these other impact categories were affected by other parts of the system. For example, the impacts in the categories photochemical ozone formation and human toxicity were mainly linked to emissions from the collection and transport phase. This indicates that the use of global warming as the only indicator for assessment of waste management strategies would not give a fair picture of the consequences of the changes to the system, and that as many indicators as possible should be included in the assessment. However, some indicators are relevant only in relation to specific waste fractions, e.g. stratospheric ozone depletion would be necessary to evaluate only in regard to material fractions containing ozone depleting substances.

Although there are several issues to be aware of when applying life cycle assessment to assess the environmental sustainability of waste management options, life cycle assessment is, nevertheless, a useful tool in the decision making process. Compared with designing the waste management system based on the waste hierarchy, the use of life cycle assessment can give a more nuanced picture of the environmental performance of different combinations of recycling and incineration. The case study showed that the impact for several of the environmental indicators did not change in parallel with the recycling rates in the scenarios. For example, inconsistencies appeared between the rating of the scenarios based on recycling rates and the rating of the scenarios based on global warming. Life cycle assessment is also a useful tool in relation to improving the understanding of which parts of the waste management system contribute with the highest loads and benefits as well as which parts of the waste management system are essential for the outcome.

To conclude whether recycling or incineration is preferable in relation to environmental performance seems straightforward for the material fractions glass and metal packaging, as incineration of these materials does not reveal any environmental benefits. Concluding in relation to the material fractions paper, cardboard and plastic is more complex due to the double nature of these material fractions, being valuable both as materials and as fuels. Since these material fractions can be valuable as fuels, the results of the life cycle assessment are highly dependent on several aspects related to energy, e.g. if biomass is a limited resource that would be used for energy purposes if not used as raw material, the energy recovery rate at the incineration plant, and assumptions in regards to marginal energy substitution. The work also showed that life cycle assessments of waste management can give good decision support only if performed on the specific system the decision would influence as the results are dependent on several system-specific aspects. These aspects, e.g. the influence of the waste composition in regards to material fraction composition, the recycling rates, the performance of the incineration plant, the influence of changes to the residual waste, can be captured only when modelling the specific system and when modelling the full system. The case study showed that a material fraction with a high environmental benefit from recycling, e.g. aluminium, on a system basis might not result in any significant benefits due to the low amount in the waste and the low recycling rates. The system modelling also resulted in relatively small changes to the environmental performance of the waste management system, and thus it might be more important to focus on other improvements of the waste management system, e.g. aspects related to bulky waste or hazardous waste or aspects related to the performance of the incinerator. The system specificity also indicates that using life cycle assessment for decision support is feasible at local level only and that policies can be made only for the same case study area as that modelled and this is something the decision-makers should be aware of when applying life cycle assessment.

7 Future work

The work has showed that modelling of changes to waste management systems on a system basis, and not only on material fraction basis, enabled several aspects to be included that could influence the conclusions regarding the environmental performance of different waste management options. These aspects were:

- The waste's material fraction composition and the recycling rates
- The energy recovery rate at the incineration plant
- System specificity

The waste's material fraction composition was found to be important in relation to prioritization of which material fractions should be recycled. This was clear in relation to the material fractions that on a material fraction basis showed large potential environmental savings but appeared only in small quantities in the waste, e.g. the metal fractions. The recycling rates turned out to be an important parameter in relation to the environmental performance of the system. However, knowledge is limited about waste composition and sorting efficiencies of different collection systems and material fractions. As these parameters are of importance for the outcome of the environmental assessment, it is recommendable that future life cycle assessments of a waste management system should include them. This would require further research into waste compositions in different geographical areas as well as investigations in relation to collection systems.

The energy recovery rate of the incineration in the investigated waste management system is normally known, but the subsequent effects of producing energy at the incineration plant are more complex to model. As the marginal district heating changes from incineration plant to incineration plant and as there is no consensus on what the marginal electricity production is for Danish conditions, the effect of substituting different district heating productions and the effect of substituting different electricity productions should be studied.

System specificity is of importance and thus time should be taken to identify system boundaries and consequences of changes to the specific system, not only within the waste management system but also downstream of it every time a new life cycle assessment is performed e.g. identification of marginal recycling technologies. Sometimes the marginal technology cannot be identified as the recyclable material enters a world market; however, then it would be useful to have a dataset that there was consensus about in the waste management field or in the life cycle assessment field. There are also decisions regarding the system that could be made on a more general basis. One example is whether saved biomass is utilized for energy purposes or left in the forest. Changes to any waste management system in Denmark that could influence this part of the system would most likely have the same effect; thus it could be fair to make a general theory and dataset on this issue. To reach consensus on aspects such as these, in-depth investigations of each of the aspects and the related cause-effect relationships are required.

As the changes in environmental performance were small for the modelled changes to the household waste system, it would be interesting to compare the magnitude of these with possible improvements to other fractions in residential waste, e.g. bulky waste and hazardous waste, or to possible improvements within the system, e.g. increased performance of the incineration plant. This could help to improve the decision-makers' focus on the most important improvement potentials and strengthen the basis for decisions.

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9 Appendices

Paper I:

Merrild H., A. Damgaard and T.H. Christensen, (2008). Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. *Resources, Conservation & Recycling*, 52(12), 1391-1398.

Paper II:

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