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Carbon footprint of recycling systems

A comparative assessment of bring- and co-mingled kerbside collection and sorting of household recyclable materials

Master of Science Thesis

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Division of Physical Resource Theory
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Bins for co-mingled recycling, MSW and organic waste

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Abstract

Recyclable materials from household waste are in Sweden at present collected primarily in a bring system with recycling sites where people can leave sorted packaging materials. In other European countries such as the United Kingdom, recyclables are instead increasingly collected kerbside in a co-mingled fraction and sorted in a materials recovery facility (MRF).

This study compares the two collection systems with respect to total energy and global warming potential (GWP). Halmstad municipality is the chosen geographical boundary and the functional unit is the weight of the recyclable material produced by one person living in Halmstad during one year (kg/(capita*year)).

Both collection systems are modelled and analysed with the GaBi 4 LCA software. An increase in collection levels is modelled for the co-mingled system due to its higher level of service. Recycled materials are assumed to replace virgin materials. Non-recycled materials are sent to a combined heat and power incineration plant.

The results show similar performance for GWP for both collection systems and about 15 % better performance for the bring system for total primary energy use. Analysis shows that the results are highly dependent on the reject level in the MRF and the choice of electricity production for the total system.

Preface

This thesis constitutes the final part of my degrees in Master of Science in Engineering in Automation and Mechatronics and Master of Science in Industrial Ecology at Chalmers University of Technology in Göteborg, Sweden. It was performed at IVL Swedish Environmental Research Institute in Göteborg in the spring of 2009.

During this project I have received great help and support from many people. I would especially want to thank my supervisor Tomas Ekvall at IVL who has answered my many strange questions with great patience; Per Ålund at HEM who gave me the possibility to do this thesis; Kristian Jelse at IVL who has provided lots and lots of help with the modelling in GaBi and Johan Rundstedt at Petterssons Miljöåkeri who has been helpful in many ways.

A special thanks also to everyone at IVL, who have all been great to work with. And last but not least I would like to thank Malin and Tiger for their great support.

Göteborg, June 2009

David Palm

Abbreviations and nomenclature

CF	Carbon Footprint
CH_4	Methane
CHP	Combined Heat- and Power plant
CO_2	Carbon Dioxide
Ex	Extraction
FTI	Förpacknings- och Tidningsinsamlingen (FTI AB)
FU	Final Use
GWP	Global Warming Potential
HEM	Halmstad Energi och Miljö AB
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
N_2O	Nitrous Oxide "Laughing Gas"
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
KC	Kerbside Collection
RC	Recycling Centre (Återvinningscentral)
RS	Recycling Site (Återvinningsstation)
SEPA	Swedish Environmental Protection Agency

Bring collection

In a bring collection system people sort and transport their recyclables to a bring station (recycling site) near their home and dispose of it in various containers. The containers are then emptied either at a regular interval or at the request of level guards built into the containers.

Co-mingled recyclables

Different recyclable materials that are collected without household sorting. This can be done both in single stream where all the household recyclables are in one fraction or in dual stream where for example glass or paper is collected separately.

Förpacknings- och Tidningsinsamlingen (FTI)

FTI is the company chosen by the producers of packaging to handle collection and recycling in Sweden. They operate roughly 7500 recycling sites located all over Sweden where consumers can drop off sorted recyclables. Glass is not fully incorporated in FTI but this has no practical implications on this study.

Kerbside collection

In a kerbside collection system recyclables are collected either sorted or co-mingled at the kerb along with, or as a complement to, regular MSW collection.

Recycling

Throughout this report ‘recycling’ refers to ‘material recycling’. Energy recycling is referred to as ‘incineration with energy recovery’.

Table of contents

1. Introduction

The introduction chapter states the goal of the thesis and a short introduction to carbon footprint as part of life cycle assessment (LCA). It also includes a short presentation of the software used for the modelling and a readers guide for the report.

1.1 Goal

The goal of this thesis is to investigate which of the ‘bring system’ and the ‘kerbside collection of a co-mingled fraction’ is the environmentally preferred collection and processing method of recyclables in the municipality of Halmstad. Focus of this thesis lies on global warming.

The goal is also to investigate if it is possible to include small electronics in kerbside collection to increase the recycling of electronics.

1.2 Carbon Footprint as part of Life Cycle Assessment

A carbon footprint (CF) is a simplified LCA that only considers global warming related emissions. This chapter will provide a short guide to what life cycle assessment (LCA) is and what it can be used for. This description of LCA is based on the introductory chapter of ‘The Hitchhikers Guide to LCA’ by Baumann and Tillman [1].

A LCA can be said to investigate the environmental aspects related to a product during its lifetime, all the way from cradle to grave. It can also be limited to only part of the life cycle, for example from cradle to gate. LCA is documented in the ISO 14040-14043 standards.

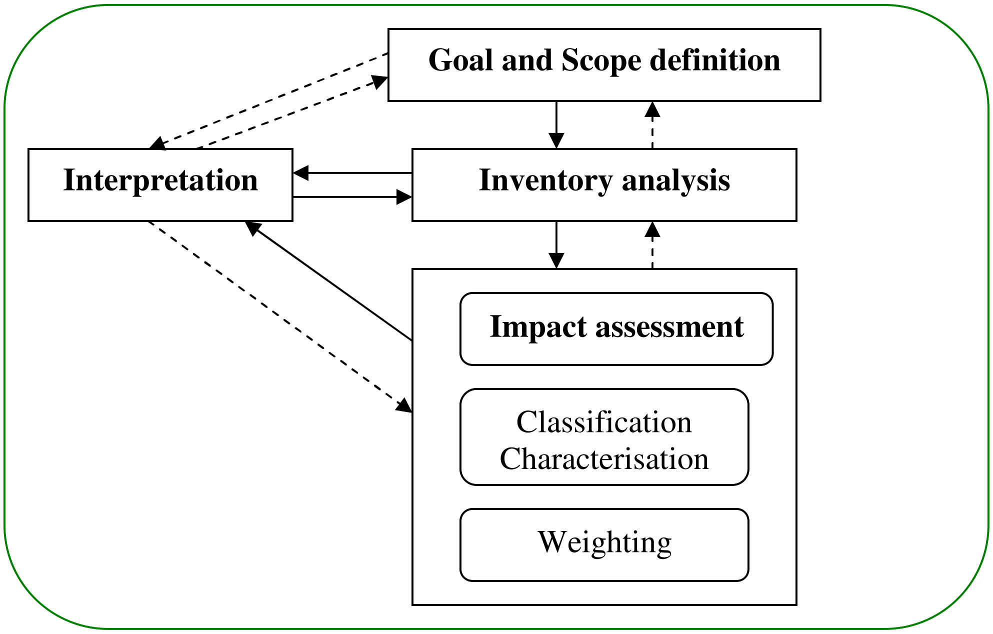

Figure 1.2 The LCA procedure (from Baumann and Tillman)

LCA is composed of a number of steps, which begin with the goal and scope definition as in Figure 1.2. This part states what question or questions to be answered; why the study is performed and for whom it is performed. It also states a functional unit, which will remain constant during the study so that all other figures can relate to this. A typical question could be: "How does this product affect global warming?" and a typical functional unit can be "litres produced beverage".

The next step is Inventory Analysis. In this step a flow model of the system is created and data for all relevant inputs and outputs are collected and calculated. This gives an inventory of the various materials, substances and energy flows that affects the product within the studied boundaries.

The final part in a life cycle assessment is the Impact Assessment. It consists of Classification, Characterisation and (optionally) Weighting. Classification means that the inventory parameters are sorted according to their environmental impact category. For example carbon dioxide is sorted under Global Warming Potential. In the characterisation, the emissions relative contribution to each type of environmental impact is calculated. Here for example carbon dioxide is aggregated together with methane and nitrous oxide into one figure for global warming potential.

1.3 Gabi Software

The model for this carbon footprint has been created with GaBi 4.3 Software for product sustainability from P E International. It is a tool for life cycle modelling. Gabi provides a structure for large datasets and a click-n-drag interface for model building. It can with the click of a button balance the studied system and also assist in aggregation of results [2].

GaBi is a widely used software with users like for example ABB, IVL, Tokyo University and Volvo [3].

1.4 Readers Guide

Following this introductory chapter is a background chapter that provides some information on why this thesis is performed, some technical information and a description of the bigger picture of which this thesis constitutes one part.

Chapter three consists of the scope of the performed CF and the data, method and assumptions related to the life cycle inventory.

Results from the life cycle inventory analysis are presented in chapter four whereas chapter five contains analysis of the results with regards to dominance, sensitivity and variance.

Chapter six and seven provides a discussion on the results and some suggestions on future work.

2. Background

This thesis is performed on behalf of Halmstad Energi och Miljö AB or HEM (Halmstad Energy and Environment). There are a number of reasons and events that lead to this thesis. The chapter 'Producer responsibility' describes why we recycle in Sweden and how this is regulated today, the chapter 'material recovery facilities' gives a short description on the technology used in the investigated system and 'the bigger picture' describe the project which this thesis is a part of.

2.1 Producer responsibility

Sweden was one of the early adopters of separating out recyclables from other waste. Already in 1993 the Swedish government proposed the law of producer responsibility, which says that producers of paper and packaging are responsible for collecting and recycling their products [4]. Newsprint and glass had been collected for some years before that. The basic principle behind the producer responsibility is the Polluter Pays Principle (PPP). Today much of the collection of recyclables is done by bring banks where households can leave their recyclables. This system, which is run by the company for collection of packaging and newsprint, FTI, might be subject to some kind of change. New EU legislation says that there should, before 2015, be available collection systems for paper, glass, metals and plastics [5]. This can be interpreted as a shift from only collecting packaging materials to include non packaging materials in collection, which would require some kind of change in the current Swedish system.

The Swedish government describes how a collection system should preferably be constructed in proposition 2002/03:117 paragraph 7.5.2 [6] (author's translation):

"It should become easier for the consumers to take part in the recycling of packaging and paper. This could be done by improved service for the consumer. The collection system provided by the producer should be adapted to the local conditions and preferably be done by kerbside collection where appropriate. […] It is of major importance that the consumers can easily take part in the system."

2.2 Materials Recovery Facilities

A materials recovery facility or a MRF (pronounced 'murf') is often a very large facility for sorting a co-mingled stream of recyclables into its respective fractions. MRFs can be more or less automated with the general concept that the larger the facility the more automated it is. Traditional MRFs are small and almost entirely consist of manual sorting stations where operators are stationed next to a picking line thus doing the sorting. In newer

MRFs most of the work is done by different mechanical equipment such as sifts, screens, air classifiers and various optical sorting equipment and many conveyors.

Different MRFs can handle different content in the co-mingled stream. Most MRFs run today do not accept glass as a fraction since it can negatively affect the quality produced of the other fractions, mainly paper. The Greenwich MRF, which the model in this thesis is based on, can handle plastic containers, metal containers, newspapers and magazines, cardboard and corrugated board and glass. This means that no sorting of the dry recyclables need to be done by the households other than separation from non recyclable waste.

2.3 The bigger picture

IVL completed a study in late January 2009 that investigated the possibilities for using Material Recycling Facilities in Sweden. This study focused on the quality attainable when collecting co-mingled recyclable materials which is separated in a MRF [7]. It included study visits at MRFs in both the UK and in Norway. Although this report was not able to provide a clear picture of the quality of the recycled materials it is possible that new technology can provide a better solution for handling recyclables than the bring system used in Sweden today.

This created an interest at Halmstad Energi och Miljö AB (HEM), a municipal waste management company and at several companies within the Stena sphere (Stena Recycling AB, Stena Miljöteknik AB, Stena Metall AB, Envac Centralsug AB) to look into how a kerbside co-mingled collection of recyclables in combination with a MRF would function in the municipality of Halmstad.

Cost calculations, both societal and corporate will be done by Åsa Stenmarck at IVL, while this thesis will provide information on the environmental issues related to this as well as a comparison with the present system.

At the start up of this project the company responsible for collecting used electronics and batteries in Sweden, Elkretsen, contacted HEM with a wish to examine if a new collection system could provide a simple system also for collecting small electronics. This in combination with the result found by the Swedish Environmental Protection Agency that small electronics often was found in recycling material [8] made it clear that also the collection of small electronics should be considered. This will however be limited to the discussion chapter.

3. Carbon footprint

The carbon footprint is the main part of this thesis and covers both the current bring system and the co-mingled kerbside collection system. The method for collection of data includes a literature study, conversations with representatives from the waste industry as well as the recycling industry.

The CF has been performed with GaBi Software version 4.3 from PE International.

3.1 Scope

The scope of this study is defined in the functional unit, the chosen impact category and the system boundary and delimitations.

3.1.1 Functional Unit

The functional unit chosen for this comparative CF is the weight of the recyclable material produced by one person living in Halmstad during one year (kg/ capita*year).

It is important to note that this is not equal to the amount of recyclable material collected for material recycling but includes also the part following the MSW to incineration.

3.1.2 Impact categories

The carbon footprint performed in this thesis includes global warming related emissions and energy use and only emissions of carbon dioxide, methane and nitrous oxide are calculated. Therefore global warming potential is the only impact category examined.

3.1.3 System boundaries and delimitations

- The system is geographically limited to recyclables “produced” from households in the municipality of Halmstad.

- It is limited to waste generated in one year.

- The system considered begins at the creation of recyclable waste in the household and ends where the recycled material has replaced virgin material.

- Production of vehicles, buildings, roads, containers, garbage bins etc is not included.

- Combined heat and power incineration plants, glassworks, paper mills, steelworks, aluminium works and manufacturers of plastics are handled by system expansion.

- As stated above, the study is limited to only consider emissions contributing to global warming and primary energy.

3.2 The model

The model consists of a flowchart for the bring system, a flowchart for the co-mingled system and several sub charts including CHP-plant, MRF and recycling processes. The model is constructed with logic functions and parameters so that it can easily be changed for a number of factors including choice of electricity, collected amounts of materials etc.

Simplified versions of the bring- and the co-mingled flowcharts can be seen in Figures 3.1 and 3.2. The systems investigated includes also incineration of recyclables left in the municipal solid waste. The full flowcharts are available in Appendix A.

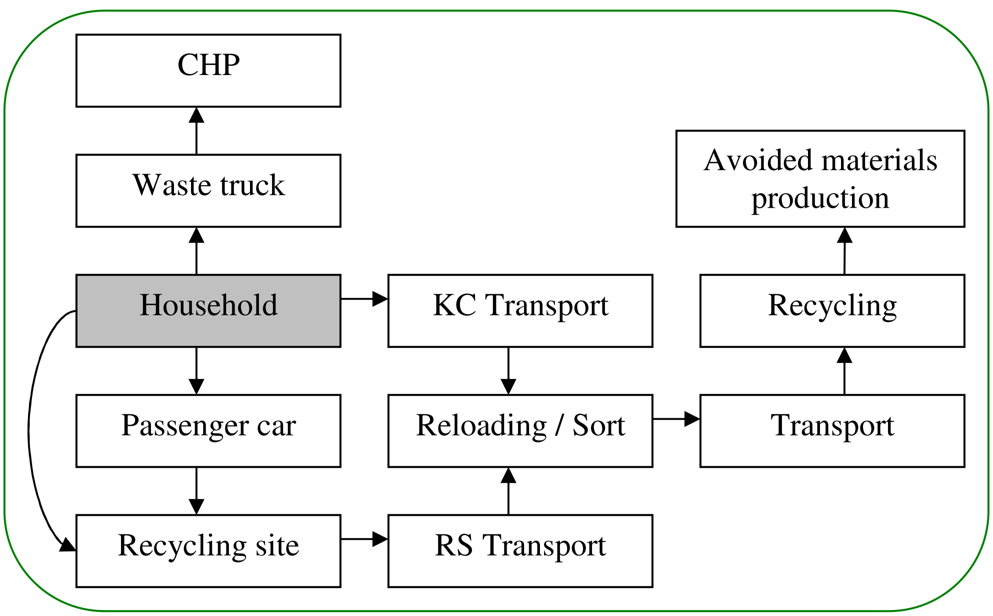

Figure 3.1 Simplified flowchart of the Bring collection system.

In the bring system the recyclable waste is created in the household. It is then transported either with a truck to incineration with the MSW, to a recycling site (sometimes with a car) and then to a reloading point by truck or with sorted kerbside collection directly to a reloading point. From the reloading point it is transported to recyclers where it can replace virgin material.

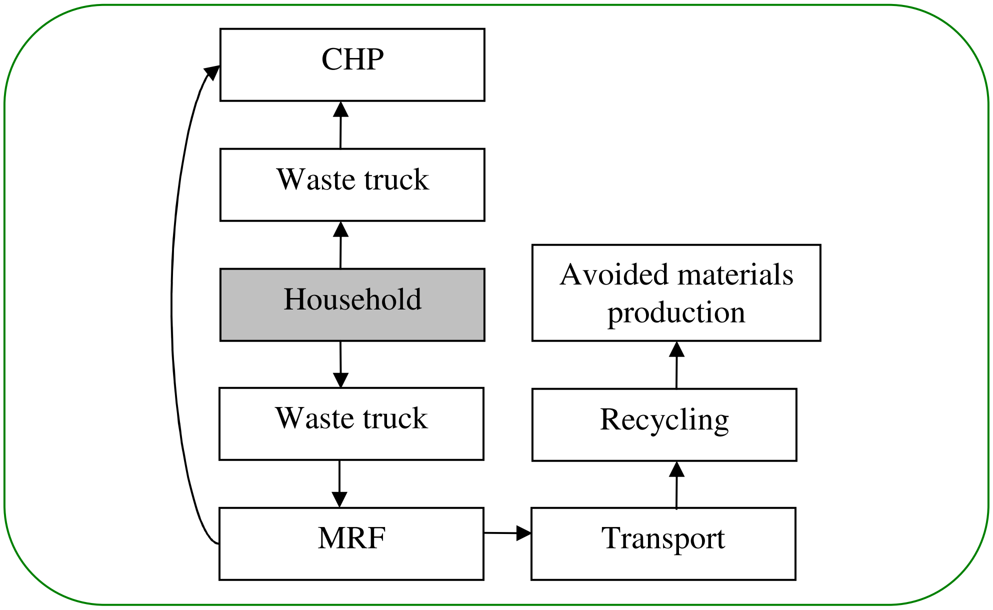

Figure 3.2 Simplified flowchart of the Co-mingled collection system.

In the co-mingled system the recyclable waste is created in the household. It is then transported either with a truck to incineration with the MSW or co-mingled with a truck to a MRF. Some recyclables will not be properly sorted in the MRF and are together with contaminants sent to incineration. Sorted recyclables are sent to recyclers to replace virgin material.

As a simplification, all recycled materials are assumed to replace virgin materials. Also specific recyclers have been used to calculate distances although not all recycling processes are specific for these recyclers. One should be aware that this simplification will benefit the collection system with the largest amounts of recycled material.

Flows not related to global warming have not been included in the model. For characterisation of emissions the CML method from December 2007 is used. This is included in GaBi.

3.2.1 Energy

Electricity used in processes is assumed to be long term marginal electricity from natural gas. The processes on production of plastics are however based on European electricity mix since power and fuels are aggregated in the emissions data available for this study.

The energy production in the combined heat and power waste incineration plant is assumed to replace long term marginal electricity from natural gas and heat from biomass. This according to Pilz *et al.* (2008) [9] and Sahlin *et al.* (2003) [10] respectively.

3.2.2 Materials Recovery Facility (MRF)

The MRF in this model is mainly based on the Greenwich MRF currently in operation in London, UK. The one difference is that the MRF modelled should be able to handle also laminated cardboard packaging (e.g. milk cartons).

The MRF has capacity for 100 000 tonnes annually and have an utilisation rate of close to 100 %.

Consumption of fuels, mostly diesel, is taken from an energy audit of the kerbside recycling services in Camden, which uses the Greenwich MRF, performed by Phil Metcalfe at ADAS. The MRF uses approximately 1.83 litres of fuel oil and 30 kWh electricity per tonne mixed waste [11]. The expansion to handle laminated cardboard is assumed to have little effect on the MRF energy consumption. The emissions from fuel are calculated based on diesel emissions for CO_2 and CH4 from Ekvall *et al.* [12].

The material flows within the MRF have not been modelled in detail because of lack of information on the different parts and their respective performance. Furthermore, only above mentioned total figures have an effect on the energy and emission results of this study. A simplified flowchart of the Greenwich MRF can be found in the report by Stenmarck and Sundqvist [13] and further information can be found in the interactive tour and video available on Veolia Environmental Services website [14].

The MRF is assumed to be located in the city of Halmstad at an equal distance to collection systems in relation to incineration, reloading and sorting points used today.

In the Greenwich MRF, the reject rate is 3-11 % [15]. This figure does not include rejects that occur in the recycling processes where the sorted material is used.

The reject level in the modelled MRF is assumed to be 10 % and is for simplicity only assumed to consist of the studied recyclable materials although it to some extent consists of other waste.

3.2.3.1 Non packaging material

One of the things a MRF needs to be able to handle is recyclable non packaging material. Office paper is probably the most common non packaging material. It is easily treated as a part of the newsprint fraction. Other materials are mainly small amounts of metal and plastics. Since the size of these materials is constrained equally as the packaging size is constrained by the bin or sack, they will not likely affect the MRF performance to a noticeable extent. An example to back this assumption is the Leipzig MRF in the ‘Gelbe tonne plus’ programme where similar non packaging plastic and metal materials are collected together with packaging materials already today [16].

A report from the Swedish Environmental Protection Agency (SEPA) on collection based on materials instead of packaging showed that most people already sort in this way and that when informed that they for a test period should sort based on material actually reduced the collected level of non packaging recyclable material [17]. The effects of including non packaging materials are therefore assumed to be small or none at al.

Based on this the small amounts of non packaging materials have not been included in the model but could easily be added.

3.2.3 Halmstad statistics

Population statistics on Halmstad is taken from Halmstad municipality website [18] and can be viewed in Table 3.1.

Table 3.1 Population statistics on Halmstad municipality

Statistic	Absolute	Relative
Population 2008	90 241	100 %
- Urban	60 242	66.8 %
- Rural	29 999	33.2 %
No of Households	43 581	100 %
- Apartments	22 323	51.2 %
- Small houses	21 258	48.8 %

Table 3.2 states the number of households that has sorted kerbside collection and recycling site (bring) collection [19]. Table 3.2 also states, based on approximately 2.07 people per household (population divided by number of households), the number of people that have sorted kerbside- or bring collection respectively. The number of people with sorted kerbside is likely somewhat lower than the calculated figure since it consists mostly of apartment households, which generally have fewer residents per household. This will in turn lower the amount of recyclables per person collected in sorted kerbside collection and increase the amount of recyclables per person collected at recycling sites.

Table 3.2 Collection statistics for Halmstad municipality

Statistic	Absolute	Relative
No of Households	43 581	100 %
- Sorted kerbside	12 000	27.5 %
- Recycling site	31 581	72.5 %
Population 2008	90 241	100 %
- Sorted kerbside	24 848	27.5 %
- Recycling site	64 879	72.5 %

Collected amounts of recyclables in Halmstad can be viewed in Table 3.3. Collected amounts and the ratio for bring- and kerbside collection respectively are from HEM [19]. The collected amount does not correspond to the statistics provided by FTI for most materials [20]. The major difference is for newsprint and plastics where figures from HEM are noticeably higher. The figures from HEM have been used since they are taken directly from the weighing stations.

The amount of the different materials within these groups is not available for Halmstad and has been calculated based on national averages. Note that figures may not add up due to rounding errors. The statistics for glass includes glass from business as well as households. More information on the materials can be found under their respective heading in the material chapter.

Table 3.3 Recyclables collected in Halmstad in 2008 [tonnes]

Material type	Weight [tonnes]	Recycling Site	Kerbside
Metal Packaging [21]	151	103	48
- Aluminium	14.4		
- Steel	136.7		
Plastic Packaging [22]	168	106	62
- HD PE	114.2		
- PP	43.7		
- PET	10.1		
Newsprint	4563	2697	866
Paper packaging	1075	797	278
Glass	1989	1437	552
Total	7946	5140	2806

3.2.4 Collected amounts with co-mingled collection

In the Subsection 3.2.3 'Halmstad statistics' the amount of recyclables collected in Halmstad today was specified. With a kerbside collection of all

recyclables these figures are likely to increase. Two major factors that influence whether or not people recycle are:
- How complicated it is and
- How far they need to go to do it [23][24].

Mattson [25] writes:

"The present [bring] system may be seen as a constraint on consumers. A more productive method of approaching this issue may be to focus on the design of the collection system to make it easier to 'do the right thing'. If the systems which are developed are better suited to the lifestyles of the modern society, perhaps the burden on the consumer may in fact become smaller allowing much better participation rates to be achieved."

A more convenient and nearby collection system will therefore likely increase collection rates. A conservative approach for co-mingled collection as replacement for bring collection is that the collected amounts increase as when switching from bring collection to sorted kerbside collection. The increase would likely be even higher since in excess of reducing the distance to the recycling drop off point there is also added simplicity since all recyclable material go into one bin without the previous sorting.

3.2.4.1 Increased amounts

In a study by Dahlén *et al.* in 2006 [26] of six municipalities in southern Sweden, the municipalities with kerbside sorted collection collected twice the amount of plastics, metals and paper packaging as the municipalities where the bring system was used. The increased amounts for newsprint and glass were not as clear. This was largely to that fact that one or both of these materials were collected kerbside in all but one municipality.

The collected amounts per capita and recycling system is stated in Table 3.4. These figures are used for the calculation of the assumed collected amounts in a co-mingled system.

Table 3.4 Collected amounts per capita and collection system in 2008

Material type	Recycling site (Bring) [kg]	Kerbside sorted [kg]
Metal Packaging	1.58	1.93
Plastic Packaging	1.62	2.49
Newsprint	41.3	75.1
Paper packaging	12.2	11.2
Glass	22.0	22.2
Total	78.61	112.92

The assumed collected amount in a co-mingled kerbside collection is stated in Table 3.5. There is a 100 % increase for paper-, plastic- and metal packaging since this was the increase in the study made by Dahlén. It seems reasonable that the increases would be at least the same as when changing from bring to sorted kerbside collection. Regarding newsprint and glass they have both been assumed to increase with 10 %. This 10 % increase has not been shown in any previous study but since both newsprint and glass are fractions that are heavy to carry, it appears likely that they would increase when the distance to a drop off point is reduced.

Note that these increased amounts are calculated for the households without previous kerbside collection and thus with lower figures for all but paper packaging than if they would have been calculated overall. The increased amounts have been calculated as follows:

$$\text{Collected Weight} = (A_{RS} * I * P_{RS} + A_{KC} * P_{KC}) / P_{tot}$$

where
I = Increase factor (10 % = 1.1, 100 % = 2)
A_{RS} = Amount collected per capita in Bring system
A_{KC} = Amount collected per capita in Sorted Kerbside system
P_{RS} = Number of people with Bring system
P_{KC} = Number of people with Sorted Kerbside system
P_{tot} = Total number of people

Table 3.5 Amount of recyclables in co-mingled collection per capita

Material type	Collected Weight [kg]	Increase [kg]	Increase [%]
Metal Packaging	2.81	1.14	68.2
Plastic Packaging	3.04	1.17	63.1
Newsprint	53.6	3.0	5.9
Paper packaging	20.7	8.8	74.1
Glass	23.6	1.6	7.2
Total	103.8	15.7	17.9

The calculated figures in Table 3.5 have then been used for all households which results in increases for the average collection rate.

3.2.4.2 Available amounts in residual waste

The composition of current residual household waste has been investigated to find out whether or not the increase in Table 3.5 is possible. The statistics for 2008 provided by FTI [20] gives a collection rate for metal packaging of 67 %; for plastic packaging 60 % and for paper packaging 74 % respectively. This can be interpreted as that the suggested increase in collection is more than what is available. The statistics from FTI does however only state the collected amount in relation to the amount put on the market by the companies connected to REPA and successively to FTI. To get a view of the total available amount of recyclable materials a household waste composition study for Halmstad in 2008 is analysed [27].

The study in Halmstad consisted of three samples of which two where from apartment buildings and one was from small houses. The three samples have been aggregated into one. It has also been compared with two national studies from 2005 [28] and 2008 [29] performed by Avfall Sverige.

The amount of recyclables left in the MSW per capita is presented in Table 3.6. The second column is a factor used to correct the weight for humidity. This factor is multiplied with the weight of the material in the residual waste to get the dry weight of the material. This factor is taken from the 2005 study where one can also find additional information on how the studies are performed. Note that the weights in the first column are the adjusted dry weights.

Absolute figures have been calculated on the weight of MSW produced per capita in Halmstad during 2007 [30]. The percentage figures are percentages of sample weight and do not add up to 100 % since fractions not relevant to this report have been excluded from the table. As shown in the last three columns of the table, the figures for Halmstad are roughly equal or lower than national averages.

Table 3.6 Recyclable material left in MSW

Material type	Halmstad Weight per capita[kg]	Humidity correction factor	Halmstad 2008 relative weight [%]	Sweden 2005 relative weight [%]	Sweden 2008 relative weight [%]
Metal Packaging	3.0	0.65	1.5	1.7	2.0
Plastic Packaging (rigid)	19.1 (5.6)	0.57	10.6 (3.1)	10.3 (3.3)	9.0 (3.0)
Newsprint	18.8	0.66	9.2	7.8	10.0
Paper packaging	15.6	0.55	8.9	8.5	10.0
Glass	6.2	0.95	2.0	2.3	2.0
Waste	318.4	-	-	-	-

Table 3.6 shows that the increase calculated for co-mingled collection is for all materials with the exception of paper packaging less than 50 % of the available amount.

3.2.5 Materials

The quality of extracted materials is hard to estimate both in a co-mingled and in a bring system. Figures reported by HEM/FTI are collected amounts. FTI figures on material recycling are the amounts sent to material recycling, i.e. not the actual recycling. There is at present no independent study on what amounts are actually recycled [31].

In this study it is assumed to be equal levels of reject at the recycler regardless of co-mingled or bring collection for most materials. The quality of outgoing materials from MRFs appears to be, according to Stenmarck and Sundqvist [32], equal to the quality from the Swedish bring system. This is supported by Terry Coleman at the British Environmental Protection Agency and Simon Aumonier at ERM, with the understanding that the collection system is well designed [33].

The data for recycling, avoided virgin production and incineration of materials are taken from two previous studies. One performed by Ekvall *et al.* for the Danish EPA and one by Finnveden *et al.* for the Swedish National Energy Administration. The processes taken from Finnveden are originally constructed from Swedish conditions. They are based on for example Hylte paper mill, Fiskeby board and the PE recycling in Arvika. Some processes have been adjusted to accurately represent the processes needed in this study.

Total primary energy used in the material models are not complete due to that some of the processes, e. g. plastics virgin production, are from aggregated data where this was not available.

A comparison of the GWP savings achieved in the processes in this thesis with other comparable studies is available in Appendix B. All GWP related values are considered to be reasonable and correct.

3.2.5.1 Glass

Glass is in the bring system collected in two fractions, namely white (transparent) and coloured (mainly green and brown). It is transported to Svensk Glasåtervinning (SGÅ) in Hammar where it is separated from contaminants by a number of sifts, air classifiers, magnets, eddy currents and manual sorting stations. The sorting uses roughly 16 kWh electricity per tonne glass according to Per Johansson at SGÅ [34].

In the co-mingled system, glass is not colour sorted.

The recycling and avoided virgin production of glass as well as incineration of packaging glass is based on processes used in Ekvall *et al.* (1998) [35].

The use of electricity from coal in the original processes has been replaced with electricity from natural gas. The process for green glass has been used for all coloured glass.

About 5 % of the glass received at SGÅ goes to landfill. Emissions from this reject have not been included.

A study made by GTS[1] for WRAP [36] showed, in a small scale test, that best available MRF technology can recover 78 % of the glass. This would give a reject of 22 % but since part of this is already included in the MRF residue, the 5 % glass processor reject have been used also for the co-mingled system.

3.2.5.2 Paper packaging

Paper packaging is transported to Stena Recycling in Halmstad where it is very roughly visually screened and then baled for transport to Fiskeby Board in Norrköping. Electricity use for baling is approximately 9.8 kWh per tonne according to Stefan Bengtsson at Stena Recycling [37].

All paper packaging is assumed to be mixed cardboard, which in turn consists of mostly cardboard and laminated cardboard. Cardboard replaces virgin cardboard. The PE-laminate from the laminated cardboard is incinerated. These processes and the process for cardboard incineration are taken from Finnveden *et al.* (2000) [38].

From the incoming paper packaging approximately 10 % is reject according to Magnus Johansson at Fiskeby Board [39]. The reject consists of both fibre and PE from the laminate and is incinerated in a process identical to the incineration of cardboard. The reject has a higher content of PE than the mixed cardboard, which means that the CO_2-emission from this incineration is slightly underestimated. Energy from the incineration processes is assumed to replace 10 % electricity from natural gas and 90 % heat from biomass. Emissions from collection in the original processes have been excluded from the recycling processes since they are handled separately in the model. Trees saved are assumed to remain in the forest.

3.2.5.3 Newsprint

The newsprint fraction consists mainly of newspapers but also of periodicals, magazines and office paper. It is taken to Stena Recycling for a quality sort where a screen removes cardboard and a line of pickers remove plastic bags and other non-paper material. Sorting uses about 9.8 kWh electricity per tonne. The model for this sorting was constructed with the help of Stefan Bengtsson at Stena Recycling [40]. The newsprint is then sent to Hyltebruk paper mill for recycling.

[1] Glass Technology Services Ltd

Processes for recycling, avoided virgin production and incineration are taken from Finnveden *et al.* (2000) [41]. Emissions from paper collection have been excluded from the recycling process since it is handled separately in the model. Trees saved are assumed to remain in the forest.

The reject from the current bring system is according to Tomas Stenlund [42] at Stora Enso Hylte about 1.5 %. Stenlund has previously stated that newsprint from MRFs can be used in the production but that it produces more reject [43]. He could not specify this any further. For safety a 3 % reject has been assumed for the MRF newsprint.

3.2.5.4 Metals

Aluminium and steel is in the bring system collected together. Around 9.5 % of the metal is aluminium and 90.5 % is steel [21]. It is transported to Deponej in Halmstad and separated with eddy currents and magnets. According to Deponej [44] they use approximately 10.71 kWh electricity and 0.71 litres of diesel per processed tonne metals.

The separation process in the MRF is similar to the one at Deponej.

Aluminium is transported to Stena Aluminium in Älmhult [45] where it is re-melted to replace virgin aluminium. The processes for recycling, virgin production and incineration of aluminium are all taken from Ekvall *et al.* (1998) [46].

Steel is transported to Fundia in Smedjebacken [45] where it is recycled into new steel. The processes for recycling, virgin production and incineration of steel are all taken from Ekvall *et al.* (1998) [47].

The use of electricity from coal in the original processes has been replaced with electricity from natural gas.

The reject from Deponej is 15 % of the incoming material [44]. About 3 % of this is non packaging metals such as bike rims and frying pans; about 5 % goes to incineration and 7 % goes to landfill. Emissions related to this reject are not included in the model. This reject is only included in the bring system. The sorting of metal is rather simple and fairly exact and since the processes are similar both for bring and MRF the end result is likely to be similar as well.

3.2.5.5 Plastics

All rigid plastics are collected together and transported to Stena Recycling where a rough visual inspection is performed before the material is baled and sent to Swerec in Lanna. Electricity use for baling is approximately 9.8 kWh per tonne according to Stefan Bengtsson at Stena Recycling [40].

The three most common plastics have been assigned to represent all plastics, namely High Density Polyethylene (HD-PE #2), Polypropylene (PP #5) and Polyethylene Terephthalate (PET #1). Low Density Polyethylene (LD-PE #4) was not collected in Halmstad during the period studied. It is however a major part of the plastics that can be recycled and has therefore been included in the PE-incineration as a potential for recycling. This means that in the recycling process there is 68 % HD-PE, 26 % PP and 6 % PET while in incineration of the plastics left in the MSW there is 87 % PE, 10 % PP and 2 % PET. These percentages are from the total recycling of plastics in 1999 as described in IVL report on plastics recycling in 2002 [22].

The HD-PE recycling and avoided virgin production is taken from Finnveden *et al.* (2000) [48] while the incineration process is from Ekvall *et al.* (1998) [49]. The incineration of 40 % rejected plastics is included in the recycling process. In the recycling and virgin production processes the emissions from collection of plastics have been removed since this is handled separately in the model. In the incineration process the use of electricity from coal in the original process has been replaced with electricity from natural gas.

The PP recycling, avoided virgin production and incineration are all taken from Ekvall *et al.* (1998) [50]. The PET recycling, avoided virgin production and incineration are all taken from Ekvall *et al.* (1998). The use of electricity from coal in the original processes has been replaced with electricity from natural gas. Incineration of 40 % rejected plastics is handled in separate incineration processes.

The rejected plastics for incineration are a mix of all types of plastics and to some extent other materials but have for simplicity been assumed only to consist of the three studied plastics.

The incineration process for LD-PE is identical to that of HD-PE.

3.2.6 Transports

Transports have to a far extent been modelled on the actual transports taking place in the collection system in use at present. The transport for co-mingled recyclables has been adapted from the normal MSW collection. The passenger car transport to the recycling site is an estimation and the transports from reloading points to recycling facilities general transportation figures have been used. The last subchapter handles the transports not modelled.

The emissions of CO_2 and CH_4 from transports in MSW collection, collection of recyclable materials and kerbside collection of co-mingled recyclables are based on a medium sized truck in urban driving taken from Ekvall *et al.* (1998) [51]. This data is mainly based on EURO 1 and 2 trucks and may thereby be somewhat high for CH_4. Since most of these transports are more stop and go than normal urban driving they may however even be larger in reality and have therefore been found to be sufficiently accurate.

3.2.6.1 Municipal solid waste collection

Municipal solid waste (MSW) is in Halmstad to an almost full extent collected kerbside from wheeled bins at both small houses and apartments with a compressing waste truck. The data for collection of the recyclables that remain in the MSW to incineration is from HEM and Petterssons Miljöåkeri. HEM is responsible for collecting MSW in the city of Halmstad and Petterssons Miljöåkeri is responsible for the rural collection in the rest of the municipality. The figure used is the amount of diesel used per tonne collected waste. The relevant figures can be seen in Table 3.7. The data from Petterssons Miljöåkeri was for the period May 2008 to December 2008 and has been extrapolated to a full year.

Table 3.7 Fuel use for MSW collection during one year

Source of data i. e. collector	Amount of collected waste [tonnes]	Diesel used [l]	Diesel per tonne waste [l/tonne]
HEM [52]	23993	171114	7.13
Petterssons Miljöåkeri [53]	8520	70608	8.29
Combined	32513	241722	7.43

3.2.6.2 Passenger car

Transportation to the recycling site is based on a statistical survey done by SIFO [54] in 1998 stating that approximately 20 % of the trips to the recycling site was done by car and not combined with any other journey. There is unfortunately no information on the average distance to a recycling site in Sweden but following Hunhammar [55] in 'Transport av insamlade förpackningar och annat avfall' (Transport of collected packaging and other waste) a distance of 1 km seems like a good approximation.

Hunhammar also assumes one trip every other week giving 25 trips per year. A study made by Bäckman *et al.* (2001) [56] assumed only 12 trips per year. Since the amount of collected recyclables have more than doubled since the study by Bäckman *et al.* was performed, 25 trips seem more reasonable although it implies a higher figure. The above mentioned survey also stated that 40 % drive to the recycling site in combination with another trip. Not including these trips implies a lower figure. Based on this the assumption made is that 20 % of households drive a total distance of 2 km 25 times per year. This gives a total distance travelled by car:

Distance = H*n*r*d/R =

31581*25*0.2*2/90241 = 3.50 km/capita*year

where
H = Number of households using the bring system
n = Number of recycling trips per year
r = Percentage of sole recycling trips
d = Total distance to and from recycling site
R = Number of residents in the municipality of Halmstad

Emissions are calculated on the passenger transport and emissions from diesel and gasoline found in Finnveden (2000) [57].

3.2.6.3 Collection of recyclable materials

There are currently 72 recycling sites in Halmstad. Collection is performed by two different entrepreneurs.

Collection of newsprint and paper packaging from the recycling sites (bring sites) is done by Petterssons Miljöåkeri. Collection of glass, plastics and metal packaging from the recycling sites is done by EliaExpress. The amount of fuel used per tonne collected material is stated in Table 3.8.

The kerbside collection of sorted recyclables is done by HEM. Data on the kerbside collection can also be viewed in Table 3.8.

Table 3.8 Litres of diesel used per tonne recyclables collected

Material type	Bring collection [Litres/tonne]	Kerbside sorted collection [Litres/tonne]
Metal Packaging	36.0	69.2
(rigid) Plastic Packaging	21.4	53.5
Newsprint	5.5	4.6
Paper packaging	25.0	15.9
Glass	3.0	11.4

3.2.6.5 Kerbside collection of co-mingled recyclables

The collection of co-mingled recyclables is similar to the collection of municipal solid waste in Halmstad. These transports are constrained by volume rather than weight and since the co-mingled recyclables have a lower density than MSW more transportation is needed per tonne. One could theoretically compress the co-mingled recyclables to density close to the MSW but this dramatically complicates sorting and reduces material quality. Neil Arlett at Greenstar UK [58] estimates that the recommended maximum compressed density is roughly one third of compressed MSW and the amount diesel needed for collection has therefore been multiplied by three. The relative density figure is supported by a density of 150 kg/m^3 for Co-mingled recyclables according to Titech [59] compared to a density for MSW of 400 kg/m^3 according to Per Ålund at HEM [19]. These figures give a slightly lower density factor of 2.66, which compensates extra trips to drop off recyclables. Both Per Ålund and Johan Rundstedt [53] at Petterssons Miljöåkeri agree with the approximation of tripled diesel use. A density factor of three gives a fuel consumption of 22.29 L diesel per tonne.

Transport of reject from the MRF to the CHP is calculated as a 'Truck-trailer 34-40 tonnes' from the Gabi Lean Database with a load factor of 50 % and a distance of 7.5 km, which is the distance from Kistinge industrial area to the CHP plant in the Kristinehed industrial area [60].

3.2.6.6 Reloading point to recycling facility

The transport from reloading point or MRF to recycling facility is of minor importance since it is assumed to be roughly the same in both scenarios. For this transport the 'Truck-trailer 34-40 tonnes' from the GaBi Lean Database has been used. It is assumed to have a load factor of 85 % of maximum 27 tonnes load.

Distances from Halmstad to: Hyltebruk (Newsprint) 48 km, Fiskeby board (Cardboard) in Norrköping 347 km, Swerec (Plastics) in Bredaryd 91 km, Stena (Aluminium) in Älmhult 130 km, Fundia (Steel) in Smedjebacken 510 km and Glasbanken (Glass) in Hammar 325 km. All have been calculated with ViaMichelin [60].

3.2.6.8 Transports not modelled

Transports with rejects from recycling facilities have not been calculated for the processes where disposal of rejects are not included in the process. These are mainly apparent in plastics recycling and should have a negligible effect on this model.

Since the MRF is assumed to be located in Halmstad there is no transport modelled for bulk transport from reloading point to the MRF. If another municipality would have been modelled this transport would need to be included both for the co-mingled and the bring collection systems for most materials.

3.2.7 Data gaps

There is a lack of knowledge of what other materials than the intended recyclables that are actually collected both today and in a co-mingled system. In this thesis rejects have been assumed to consist of similar or equal materials that are recycled.

Data on energy use and emissions from sorting and pre-recycling handling of plastics at the recycler have not been included. They are not assumed to be negligible but should not affect the result to a major extent.

Data on emissions for reloading of glass before shipment to recycler are not included. They are assumed negligible.

4. Results

The results have been divided into two parts. The first part includes the benefits of recycling when virgin material is replaced. The second part only considers the collection system performance. The latter includes sorting in the MRF to make the two systems comparable. A scenario where all recyclable material goes to incineration with the normal MSW collection has been included as a reference.

Results from the life cycle inventory analysis (LCI), the characterised results as well as the energy results are all presented. The full recycling system gives the co-mingled collection system a slightly lower global warming potential (GWP), but when only collection and sorting is included, the bring collecting system has about half the GWP of the co-mingled system.

All results are in relation to the study's functional unit: the weight of the recyclable material produced by one person living in Halmstad during one year (kg / capita*year).

4.1 Total System performance

The main result from the system performance is that the bring- and co-mingled kerbside collection systems have very similar global warming potential. Table 4.1 shows a comparison of the two systems results with regards to life cycle inventory and CML GWP_{100}. The no-recycling scenario is also included in Table 4.1. Values are in kilograms per capita in Halmstad. The result is also visualised in Figure 4.1.

Table 4.1 Results for total system performance [kg / capita*year]

System	Life Cycle Inventory		Global Warming Potential (CML2007)
	CO_2	CH_4	
Bring	21	0.034	22
Co-mingled	20	0.045	21
No recycling	58	0.037	59

The global warming potential for both the bring and the co-mingled collection systems are very similar. The difference is 1 kg of CO_2-equivalents, which is a difference of about 5 %. It is clear that both these systems contribute far less to global warming than the energy recovery scenario.

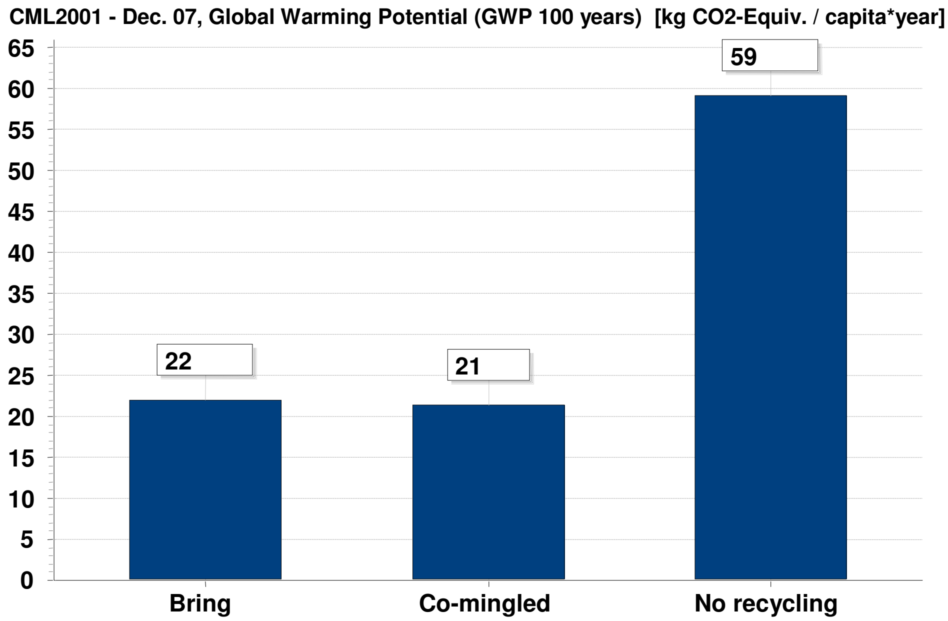

Figure 4.1 Global warming potential in kg CO_2-equivalents per capita and year for complete collection systems.

The total primary energy for the systems gives a somewhat different picture than the global warming potential. As can be seen in Figure 4.2, the primary energy needed for the bring system is 250 MJ or 13 % less than the co-mingled system. This is mainly due to two parameters that differ between the systems, namely recycling of newsprint and the co-mingled collection truck, which accounts for about 100 MJ each in favour of the bring system. The total primary energy is negative because recyclables have not been included as an energy source.

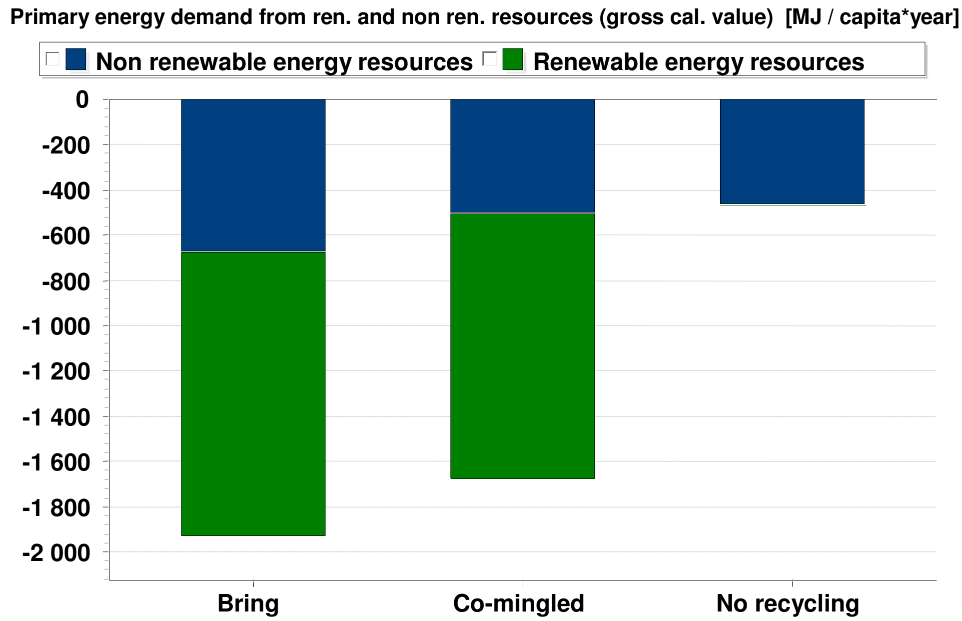

Figure 4.2 Primary energy demand in gross calorific value for complete collection systems. Divided into renewable and non renewable energy sources. Recyclables have not been included as an energy source.

4.2 Collection system performance

The collection system performance is in this case measured as the performance of the system when long distance transfer, material recycling and incineration with energy recovery have been excluded. Left in the system are collection, sorting, MSW-transport and transport of reject from the MRF. The results are presented both in Table 4.2 and Figure 4.3.

Table 4.2 Results for collection system performance [kg / capita*year]

System	Life Cycle Inventory		Global Warming Potential (CML2007)
	CO_2	CH_4	
Bring	5.0	0.0059	5.2
Co-mingled	9.7	0.0110	10
No recycling	3.4	0.0043	3.5

The difference in collection system performance between bring and co-mingled collection are rather clear. The co-mingled collection system has nearly twice the GWP of the bring system. The most efficient collection system is when the recyclable materials are collected in the MSW.

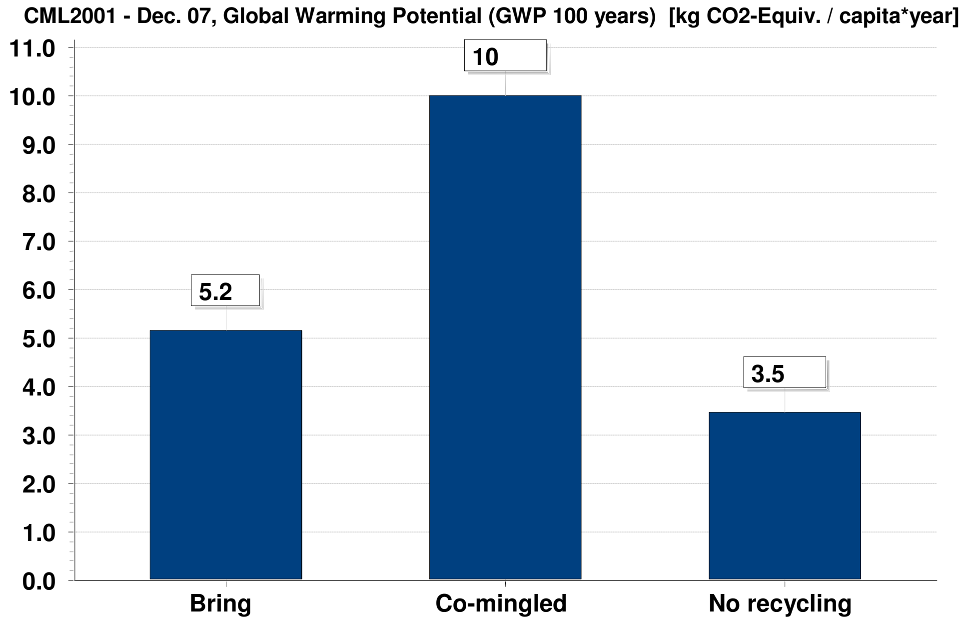

Figure 4.3 Global warming potential in kg CO_2 equivalents per capita and year for collection systems (includes sorting in both bring and co-mingled systems).

The collection performance can also be viewed in energy terms. This is shown in Figure 4.4. The energy in the collection systems consists only of non renewable energy sources. Around 35 MJ in the co-mingled system comes from the MRF itself. Recyclables have not been included as an energy source.

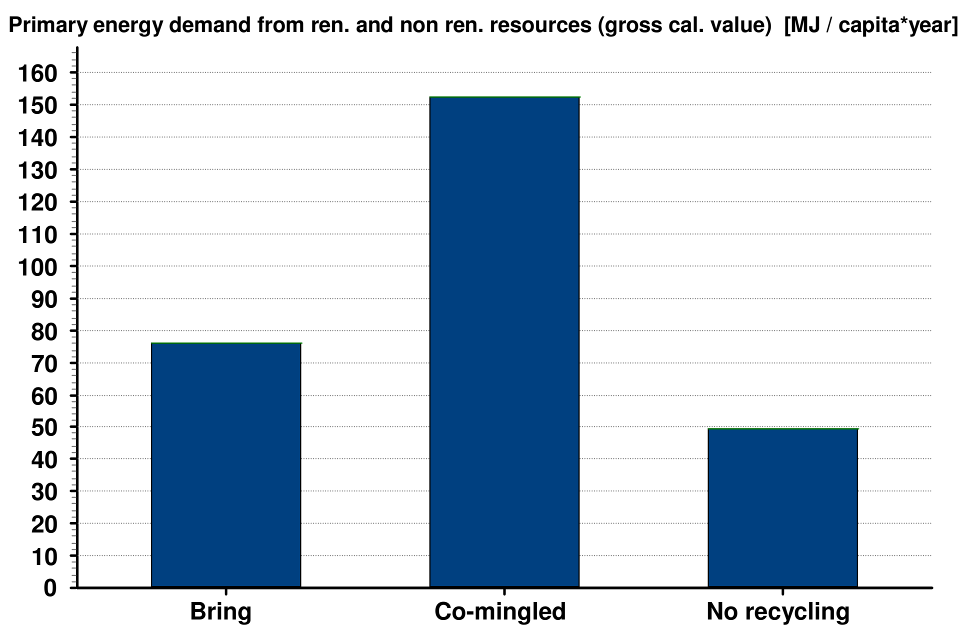

Figure 4.4 Energy demand for collection systems (includes sorting in both bring and co-mingled systems). Energy is from non renewable sources. Recyclables have not been included as an energy source.

5. Analysis of results

The results for total system performance showed only a small difference between the two collection systems. To better be able to answer which system is preferable from a global warming perspective, a number of analyses need to be performed. First, a dominance analysis shows which part in the collection systems that has the greatest environmental impact.

Second, a sensitivity analysis which varies crucial data and assumptions to see how they affect the result. The factors chosen for the sensitivity analysis are the density factor for the co-mingled material which affects fuel consumption per collected tonne; the level of reject from the MRF which affects recycling levels and the car travel to recycling sites.

Third, a variance analysis test system wide changes to see how different modelling choices affect the result. The electricity in the model was chosen to be marginal natural gas based. In the variance analysis both marginal coal- and average Swedish electricity are examined. Collected amounts in the co-mingled system are also varied to examine the impact of the assumed increased amounts.

There are many different opinions on whether or not glass can be recycled after MRF sorting. Because of this, a scenario where glass is not recycled from the MRF and a scenario where glass is left as a separate bring collected fraction are also examined in the variance analysis. The last variance analysis is a scenario where biomass saved from producing heat in waste incineration replace coal as fuel in a power plant.

Finally in chapter 5.4 there is a short assessment of the data quality.

5.1 Dominance analysis

The largest contribution to global warming in both systems is by far the incineration of the recyclable material that is not collected for recycling. This amounts to 54 kg and 49kg CO_2-eq respectively for the bring and co-mingled systems. These figures are this high due to the large amount of plastics incinerated, which produces close to 60 kg of CO_2. The largest CO_2 reduction comes from the recycling of newsprint in both systems with -27 kg and -25 kg CO_2 saved. All other parts of the systems contribute less than 8 kg each.

The interesting figures from the parts with lower contribution are that in the bring system, collection transport is the fifth most contributing with 2.4 kg CO_2 while in the co-mingled system the collection transport is the third most contributing with 7.1 kg of CO_2. One can also note that the MRF sorting contributes with 1.8 kg of CO_2, which can be compared to the contribution from bring sorting of 0.25 kg CO_2.

Notable is also that energy conversion, which consists mainly of electricity production, contributes to a CO_2 saving of equal magnitude to avoided virgin production. Energy conversion has a larger CO_2 saving than avoided virgin production in the bring system, while it has a smaller saving in the co-mingled system. This coincides well with what one would expect since recycling levels are somewhat higher in the co-mingled system.

5.2 Sensitivity analysis

The benefits from recycling compared to virgin production and incineration are compared to other studies in Appendix B. They are also tested for the effects related to a change of electricity source in the variance analysis and are therefore not included in the sensitivity analysis. Focus is instead on the density factor for the co-mingled collection truck which is the transport with the highest GWP contribution and the level of reject in the MRF which affect the level of recycling in the co-mingled system.

5.2.1 Fuel consumption in co-mingled collection

The density factor is approximated to be three in the base case. This gives a diesel use of three times the diesel use for collection of MSW or three times 7.43 litres per tonne collected. This is a fairly rough estimate and with the same collection routes the factor would be slightly lower if instead using the figure 400 kg/m^3 from HEM for MSW density and the figure 150 kg/m^3 from Titech for co-mingled recyclables density. These figures give a density factor of 2.66 and a fuel consumption of 19.76 litres per tonne.

There are however, other factors that also affect the fuel used in collection. A lower density of the waste means that less weight is transported which would result in somewhat lower fuel consumption per kilometre. On the other hand the collection trucks would need to travel to the drop off point at the MRF more often than they would travel to the MSW incineration plant. A lower fuel consumption and extra drop off trips would both, in opposite ways, affect the amount of fuel used.

To investigate how this affects the system, the fuel consumption is varied from 19.76 to 24.74, which corresponds to a density factor of 2.66 and 3.33. The higher level is somewhat arbitrarily chosen to be the same deviation as to the lower level.

The result is that it changes the CO_2-emissions from the co-mingled system by 3-4 % in either direction. Figure 5.1 shows the result in three bars: one with a low fuel consumption of 19.76 litres per tonne; one with the base case fuel consumption of 22.29 litres per tonne and one with a high fuel consumption of 24.74 litres per tonne.

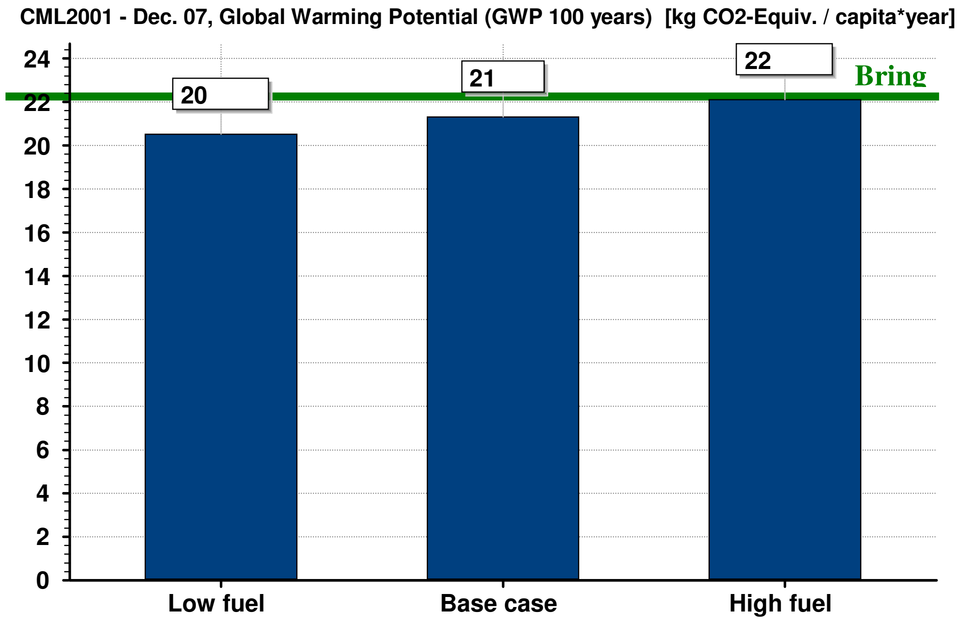

Figure 5.1 Emissions from co-mingled system with varied diesel consumption for the collection truck. The low fuel scenario use 19.76 litres per tonne; the base case use 22.29 litres per tonne and the high fuel scenario use 24.74 litres per tonne.

Comparing the high fuel consumption case with the bring system shows that the co-mingled system has 0.4 % higher CO_2-emissions.

5.2.2 Reject levels in the MRF

In the base case a reject level of 10 % is assumed for the MRF. The reject level can differ both depending on the MRF and on what is included in the reject. As previously stated, the Greenwich MRF has a reject between 3 % and 11 %. In the report by Stenmarck and Sundqvist [7] it is stated that the residue can be up to 15 %. The difference between reject and residue is not stated. The model is examined with reject levels of both 3 % and 15 % in order to see how the extreme values affect the result.

With a reject of 15 %, which is the right bar in Figure 5.2, the emissions from the co-mingled system are just over 1 kg, or 5 %, larger than the bring system. On the other hand, with a 3 % reject, which is the left bar in Figure 5.2, the emissions from the co-mingled system are close to 4.3 kg, or 19 %, lower than the bring system. This shows that the level of reject has a substantial effect on system performance.

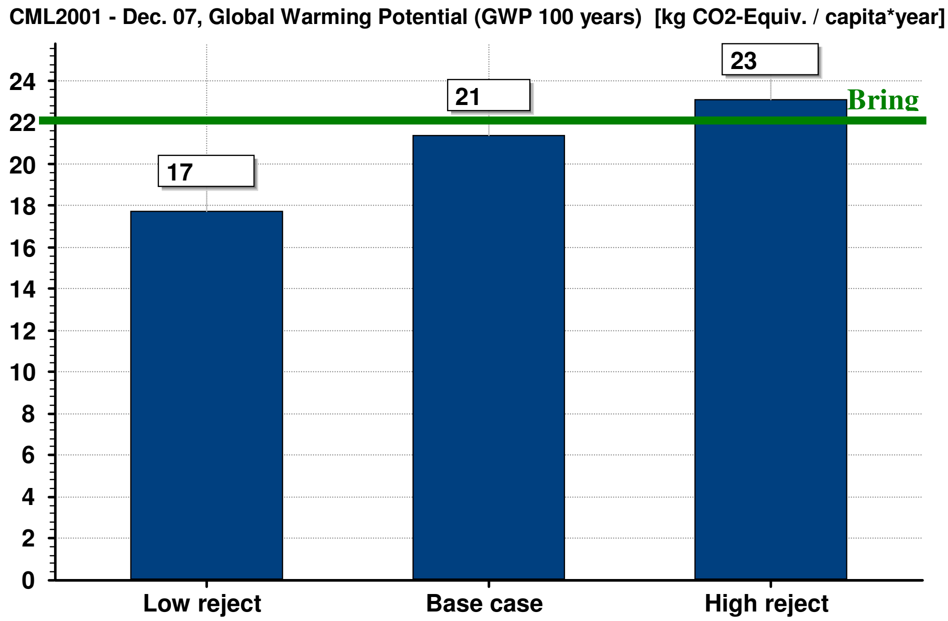

Figure 5.2 Emissions from the co-mingled system with varied reject from the MRF.

5.2.3 Car travel to recycling sites

The transport by car to the recycling site is based on reasonable assumptions but have little factual data for support. In the base case a roundtrip of 2 km and 25 trips per year is assumed for 20 % of the residents with bring collection. It is, based on the literature used, possible to argue both that the distance is longer and that the number of trips is fewer. The extreme values could be where the distance is the same and there is only one trip per month or that the distance is doubled and the trips remain every other week.

The system effect from changing the car transport to the recycling site is, as seen in Figure 5.3, less than 1 kg, which means that it has about the same influence on the result as the co-mingled transport. In all three cases the bring system has higher CO_2-emissions than the co-mingled system.

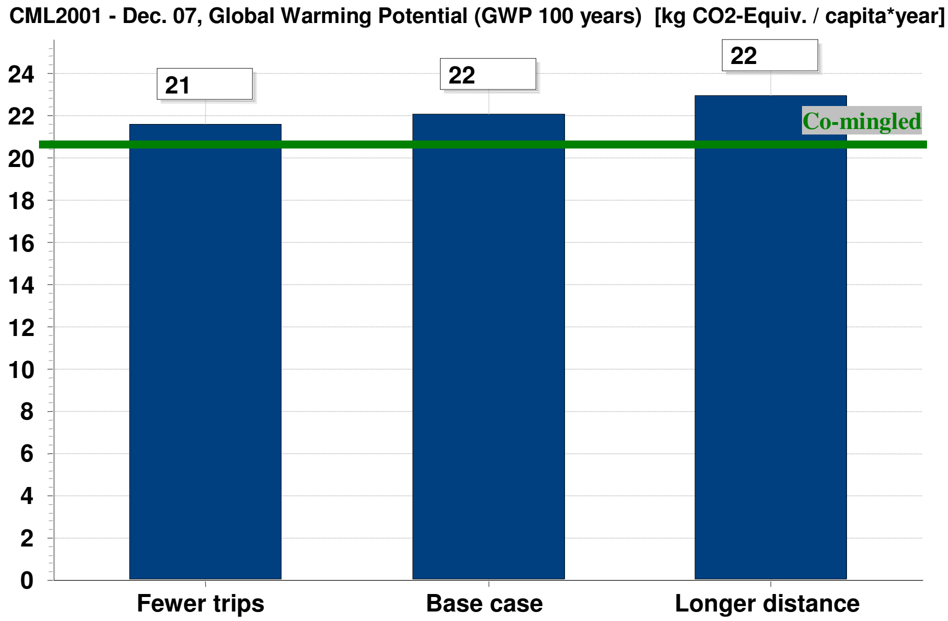

Figure 5.3 Emissions from bring system with varied car transport to recycling site. The fewer trips scenario has a distance of 2km and 12 trips per year; the base case has a distance of 2km and 25 trips per year while the longer distance scenario has a distance of 4km and 25 trips per year.

5.3 Variance analysis

The variance analysis focuses on four major possible alternate scenarios for the model: Different sources for electricity; changed collection amounts in the co-mingled collection; a special case for glass recycling in the co-mingled collection and a scenario where the biomass saved by incineration of waste and recycling of newsprint and paper packaging replaces coal for electricity production.

5.3.1 Electricity

In the base case all electricity is produced from natural gas. This because natural gas is likely to be the long term marginal electricity. It is possible to argue that the current marginal electricity, which is mostly coal, or the average Swedish electricity, which is mostly nuclear and hydro, are better suited for this study. The result for both collection systems is shown in Figure 5.4. The first two bars are the base case with natural gas (blue), the second two bars are with coal (black) and the third two bars are with the average Swedish electricity mix (green) for the two systems.

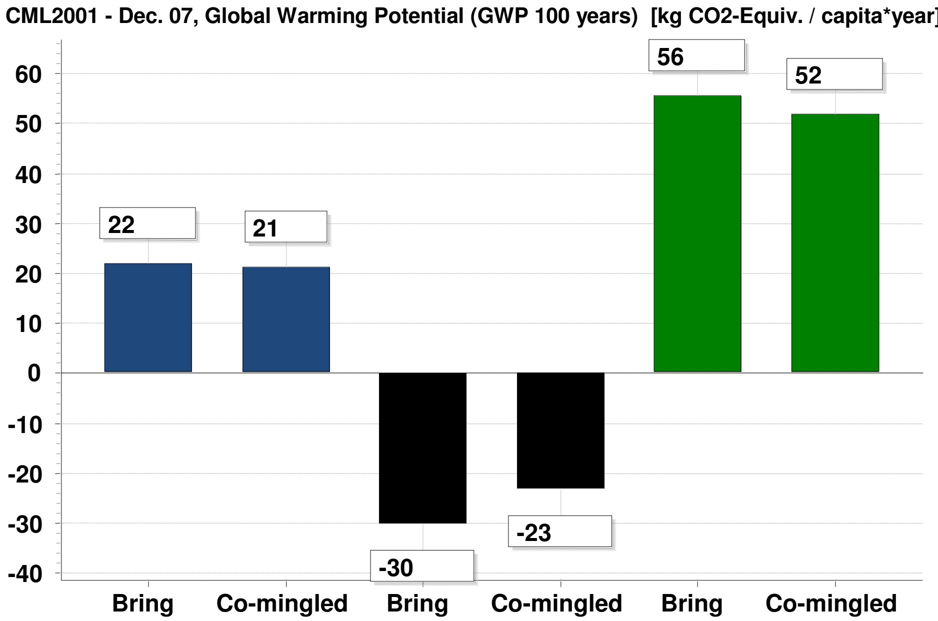

Figure 5.4 Emissions with electricity from natural gas (the first two blue bars), coal (the middle two black bars) and average Swedish electricity (the last two green bars).

It is clear that the choice of electricity has a large effect on the result. Since, in the modelled system, incineration with energy recovery saves more electricity than recycling, the more CO_2 produced in energy production, the more favourable incineration becomes. Recycling of newsprint could have been a possible exception from this since it saves substantial amounts of electricity. The recycling of newsprint is however similar in both systems, although somewhat higher in the bring system, which would account for this behaviour. This means that the bring system is favoured by electricity from coal and that the co-mingled system is favoured by the Swedish electricity mix. With coal based electricity the bring system performs 23 % better than the co-mingled system and with average Swedish electricity the co-mingled system performs 7 % better than the bring system.

5.3.2 Collected amounts in co-mingled recycling

The amounts of collected recyclables in the co-mingled system are primarily based on the study by Dahlén *et al.* made on a number of municipalities in southern Sweden. This study shows a likely increase of 100 % for plastics, metal and paper packaging but could not give any certain results for newsprint and glass since most municipalities collected these fractions kerbside. Newsprint and glass are because of this assumed to increase by 10 % since the simpler handling suggests somewhat higher levels.

Dahlén *et al.* also found that a separate collection of biodegradable waste can possibly increase the collection rates of dry recyclables. Since this is not done in Halmstad the increases might not be as high. It is also possible to argue that there would be an increase for the residents with sorted kerbside collection today since handling of recyclables becomes easier.

To test how this affects the system, levels are varied from a low increase case, where the increase for plastics, metal and paper packaging are reduced to 50 % and with no increase for newsprint and glass, to a high increase case where a 10 % increase for all materials occur for the residents that previously had sorted kerbside collection. Total collected amount in the co-mingled system is in the low increase case 93.6 kg; in the base case 103.8 kg and in the high increase case 106.9 kg.

Figure 5.5 shows the collection level significance on system performance. A lower increase makes the co-mingled collection emit 20 % more CO_2 than the bring collection system. A slight increase in collection for households with sorted kerbside collection has less significance but would give the co-mingled system about 8 % lower CO_2-emissions than the bring system compared with the base case 3 %.

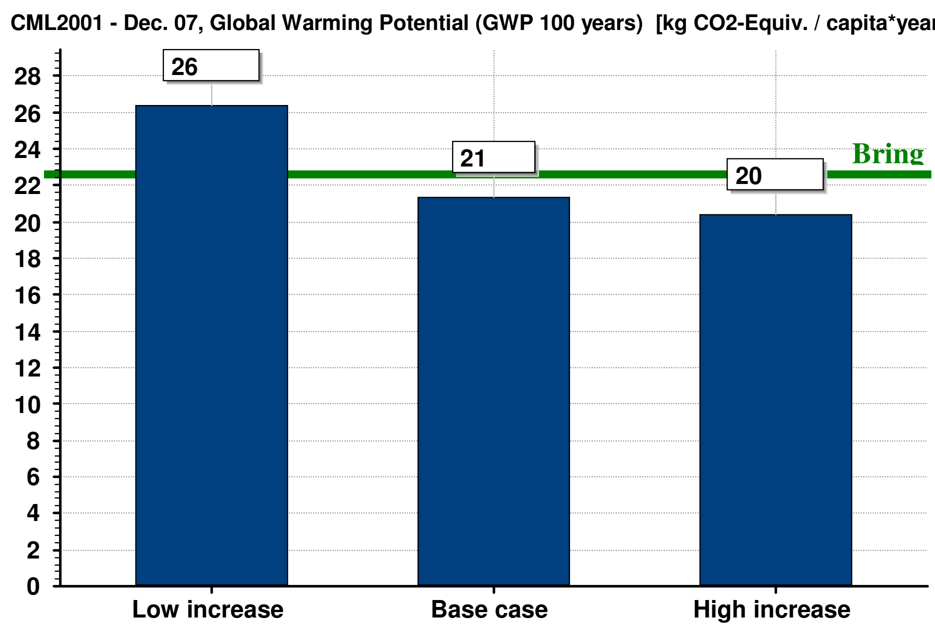

Figure 5.5 Emissions from co-mingled collection with different collection levels. A low increase gives a total amount of 93.6 kg collected recycling; the base case gives a total amount of 103.8 kg and the high increase gives a total amount of 106.9 kg.

5.3.3 Glass

Glass is a somewhat special material to include in a MRF sorting. Glass has only recently been added to the co-mingled stream in most collection systems. Since it is a rather new part of the MRF technology there are few studies on what the glass can be recycled into. John Strand at FTI claims that MRF sorted glass cannot be recycled at all [61]; Titech does not recommend including glass in MRFs [62]; while Neil Arlett at Greenstar recycling claims to already today send glass to be recycled into new packaging from a Greenstar Recycling MRF [58].

Because of this two scenarios are investigated. In the first scenario glass goes into the MRF, but is not material recycled, which would represent a use as aggregate, and in the second scenario it is not included in the co-mingled stream but left as fraction with bring collection.

As seen in Figure 5.6, collecting the glass and using it as aggregate is not environmentally preferable with 22 % higher emissions than the bring system.

Keeping glass in the bring collection system while other materials are collected co-mingled instead gives a CO_2-emission that is 9 % lower than the full bring system. When comparing this to the fully co-mingled system with recycled glass, it is clear that it actually performs better without glass. This might seem strange, but is due to the higher recycled amount of glass already assumed for the bring system compared to the co-mingled system in combination with an efficient collection of glass in the bring system. Note that this result has an error in that some of the sorted kerbside collection of glass is done together with other materials, which likely has an effect on the result.

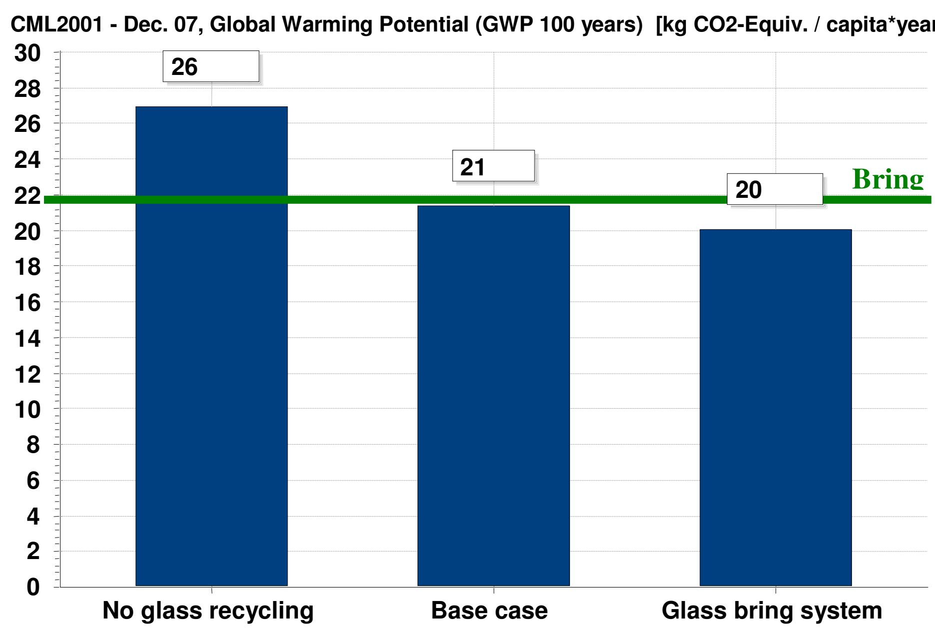

Figure 5.6 Emission with different glass scenarios in co-mingled collection. In the no glass recycling case glass is collected co-mingled and then landfilled; in the base case glass is collected co-mingled and recycled and in the glass bring system case, glass is collected separately in a bring collection.

5.3.4 Biomass replacing coal

When waste is incinerated and heat is produced, it is assumed to replace heat from biomass. The biomass saved, can in turn replace for example coal in a power plant. This favours a system where a lot of heat is produced and therefore the no recycling scenario is included in this analysis. To make this comparison fair biomass saved from recycling must also be included.

As seen in Figure 5.7, replacing coal with the saved biomass has a large impact on the result. Savings of CO_2 are substantially higher for all alternatives. The bring system, with its higher degree of incineration with energy recovery performs slightly over 4 % better than the co-mingled system. The relation to incineration is clear when comparing the 'no recycling' scenario which is far closer to the bring and co-mingled system than in the base case.

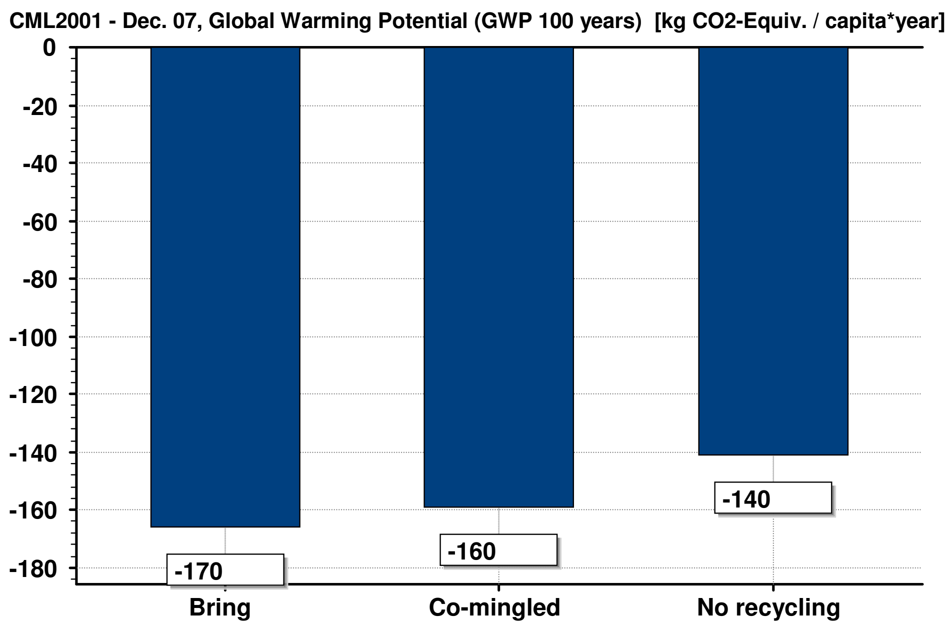

Figure 5.7 Emissions from collection systems when biomass saved with waste incineration and recycling, replace coal used in a power plant.

5.4 Data quality assessment

Data quality on recycling, avoided production and incineration processes are rather hard to estimate. The data are more than 10 years old but have been compared to other data as displayed in Appendix B and considered to be reasonable and adequate.

The data from Pettersons Miljöåkeri was estimated to an uncertainty of about 5 %. The data from HEM are collected in a similar way and likely have a similar uncertainty.

Data for sorting in the bring system are averages for the entire processes. Information on exactly what is included is not available which makes this data rather uncertain but due to its small effect on the results it is adequate.

Transports from drop-off points in the bring system and MRF in the co-mingled system to recycling facilities are rough estimates. They contribute little to both systems and have a negligible difference between systems.

Data on the MRF are not first hand information but since they are used in a similar study of the British collection system they should be accurate.

6. Discussion and conclusion

The system that ultimately will be the environmentally preferred system can not be answered with enough certainty from this thesis both due to uncertainties of the co-mingled system and also due to the lack of knowledge on how the current bring system actually performs. A full picture of the bring system performance is hard to get because of the many actors involved and that they have no obligation to publish environmental performance data.

A major problem for both the co-mingled- and the bring system is that published information on recycling levels actually are what can be best referred to as diverted levels and not actual recycling. This becomes clear when one compares data published by FTI and the Swedish environmental protection agency where it says that all collected newsprint is material recycled. If one instead asks the paper mills the reject from incoming material is generally 1.5 %. These kind of discrepancies in combination with the lack of transparency for some material flows create an uncertainty of what actually is actually recycled.

However, given the limitations and assumptions made in this thesis the environmental performance (with respect to global warming) of the co-mingled system for collecting recyclables is fairly equal to the current bring system. It is clear that the co-mingled collection system in it self contributes to global warming more than the bring system with about twice the emission of CO_2-eq, but also that this effect is counteracted by increases in collected and recycled amounts of material.

The results from the base case are highly dependent on some of the assumptions examined in the different analyses. Some of the scenarios are however not likely to occur. The increases in collected levels when switching to co-mingled kerbside collection are likely to be at least as high as when switching to sorted kerbside collection. A small increase for households with kerbside sorted collection is also likely since a co-mingled system requires less work to participate.

Reject levels in the MRF are in the base case chosen rather high. The conditions for a variation up to a 15 % reject level likely includes old MRFs that have been adapted to include more and more types of material. It can also be the effect of poorly designed collection systems, which leads to high levels of contamination. The Greenwich MRF has rejects levels up to 11 % with technology that are a couple of years old. A new plant, with new sorting equipment, is likely to perform better. With a proper, well designed collection system the amount of contamination should be kept at a minimum, thus lowering the reject levels.

The different electricity scenarios show a large impact on system performance. It is however clear that the less CO_2 emitted from electricity production, the more favourable the co-mingled system, with its higher recycling levels, becomes.

Coal based electricity is an unlikely scenario since assuming coal as marginal electricity is somewhat outdated both according to Elforsk [63] and a report to the European parliament by in 2009 [64]. Elforsk states that the CO_2-emissions from marginal electricity ranges from 400 to 750 gram CO_2 per kWh depending on energy demand and the EU-report states that it will be coming down to 350 gram CO_2 per kWh in the coming years. Both these are lower than the average ca 830 gram CO_2 per kWh for coal and are closer to the 380 gram CO_2 per kWh from natural gas based electricity. This is of course also relevant to consider for the result from using saved biomass to replace electricity from coal.

Whether or not glass can or should be included in the co-mingled collection is not clear. If it cannot be recycled into new glass, it should not be included. In this case it could preferably continue as a bring collected fraction. If instead some of it can be recycled into new glass, the question becomes more complex since not all glass from the bring collection is recycled into new glass either. The issue of including glass requires further study.

There are two simplifications in the model that have not been analysed and that affect the result. The first is that recycled material replaces virgin material to 100 %. This gives an advantage for the co-mingled system, again because of its higher recycling levels. The second is the composition of rejects. The content of most rejects are unknown. Especially for the MRF reject, it would be interesting to investigate what its actual content is. In the model it is assumed to be the collected materials with their respective ratios, but in reality it would be a mix of recyclable materials as well as other materials such as biodegradable waste. The reject in the Greenwich MRF increased when biodegradable waste was included as a separate fraction, which caused a higher contamination of the dry recyclables.

As a conclusion I would say that further study is needed. It is not clear which collection system is best from an environmental point of view. This primarily because of lack of information on both collection systems. The results from this thesis indicate that a co-mingled collection of recyclable materials performs similar to a bring collection system in the municipality of Halmstad with respect to global warming.

6.1 Small electronics

As for including small electronics in the collection, this can be done similar to other recyclables in the co-mingled stream and then removed at the MRF as it is done in Germany or in a plastic bag which is then removed from the stream directly by the collector. After discussions with Per Ålund at HEM, we found it a good solution to hang a plastic bag on the co-mingled recycling bin where small electronics and dry batteries could be placed. This would then be put in a separate compartment on the collection truck.

A special handling of small electronics and batteries is necessary when switching to material collection from packaging collection. As mentioned earlier, the trial with material collection in Eskilstuna done by the Swedish EPA showed that the amounts of small electronics increased in the metal fraction when including all metal [8]. A special bag directly on the recyclable bin can address this issue.

7. Suggestions for future work

There is need for a study on how the current Swedish collection system for dry recyclables performs. This thesis has not been able to fully examine how the materials (mainly plastics) flow through the system. There needs to be more transparency both on how the materials are recycled and on how much of the materials is actually recycled.

There should also preferably be a technical study on the best available MRF- and collection technology. There are three major questions that need to be answered:

- What quality can be achieved?
- What are the most important factors for high collection rates without the risk of compromising a high material quality?
- How is the MRF-technology affected by Swedish conditions?

Finally, a study on regional implications for a co-mingled system is needed. This thesis has only examined the effects for a medium populated area and the implications on a densely populated area like Stockholm or a scarcely populated area like Kiruna may be different.

Since this thesis has focused on GWP, one should preferably also include emissions contributing to other environmental impacts.

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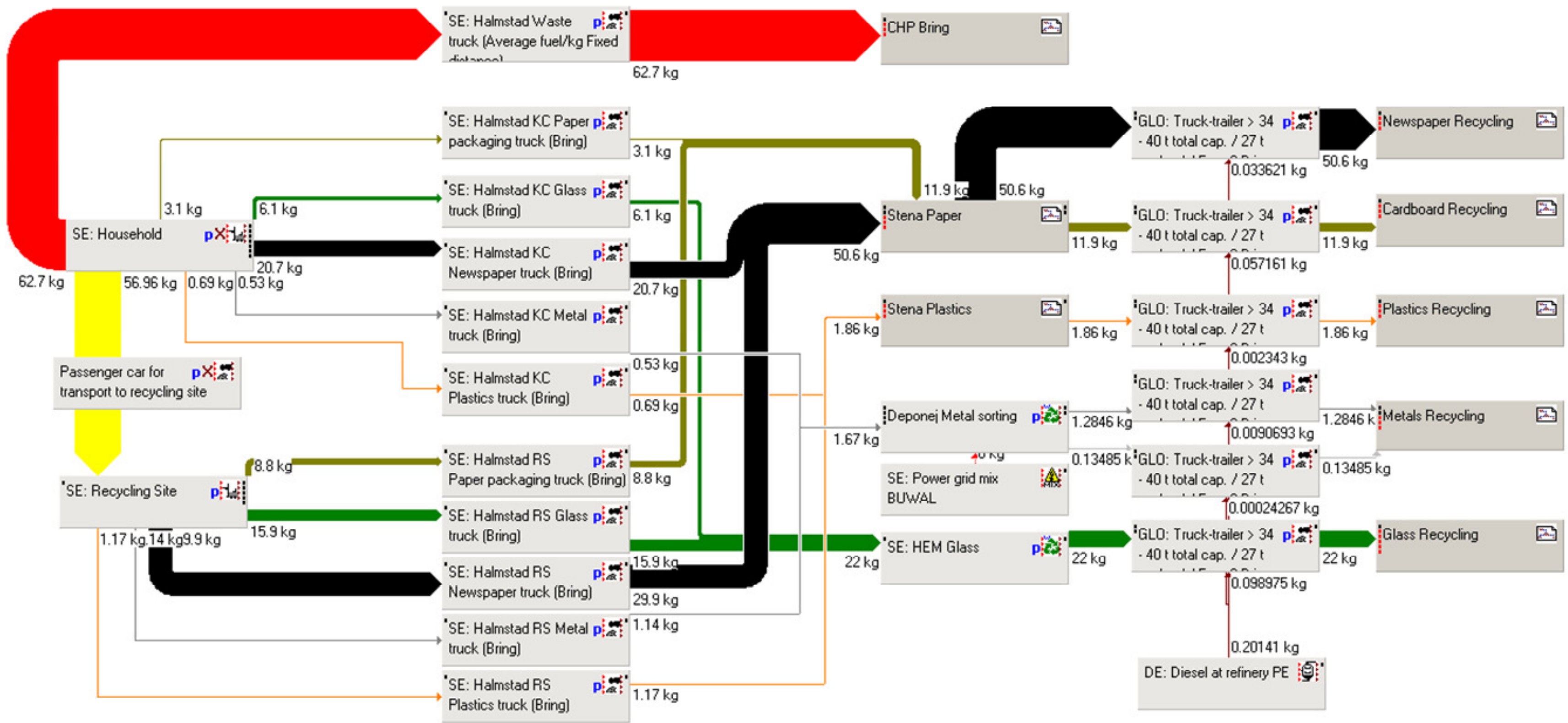
Appendix A: GaBi models

The two plans in this appendix constitute the main part of the model. The light grey boxes are processes and the darker grey boxes are sub plans. All flows are material flows except the bright red power flow to Deponej metal sorting. Material flow colours are explained in the colour legend in Table A1.

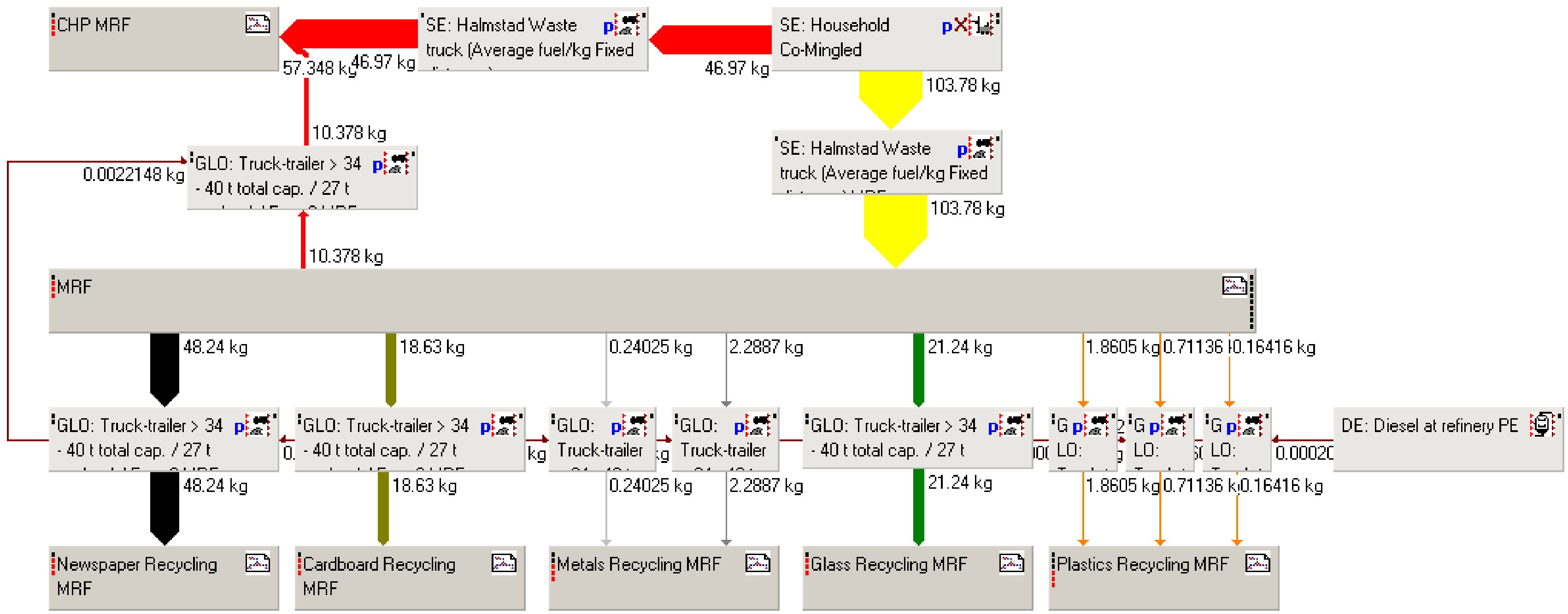
Table A1. Colour legend for models

Colour	Material
Bright red	Recyclables to incineration
Yellow	Mixed recyclables
Tan	Paper packaging
Green	Glass
Black	Newsprint
Dark grey	Metals and steel
Light grey	Aluminium
Orange	Plastics
Dark red	Diesel

A1. Bring system



A2. Co-mingled system



Appendix B: Material recycling compared with other studies

To check whether or not the environmental benefits of the processes used in this thesis where reasonable they where compared to benefits from other scientific publications. Since not all figures presented have the same system boundaries the figures from this thesis have been adapted to be comparable. There are still minor differences. This Appendix is only to show that the values are reasonable, not that modeling is exactly equal.

Figures marked as WRAP are from a major study made by Dr H. Wenzel at the Technical university of Denmark that compared results from 55 different state of the art life cycle assessments. It was done for the Waste and Resources Action Programme (WRAP) in the UK in 2006 [I]. This study includes international results and the mean value is presented.

Figures marked as CIT are from two studies performed by Chalmers Industriteknik Ekologik on behalf of Återvinningsindustrierna [II][III].

Figures marked as Finnveden are from a LCA made by Finnveden *et al.* on energy from solid waste [IV].

Figures marked as APEAL are from The Association of European Producers of Steel for Packaging [V]

All values are in kg CO2-ekv per kg recycled material.

B.1 Glass

The recycling of glass is compared with WRAP as seen in Table B.1. Compared with WRAP the difference is almost 55 % which is high. However, when examining the WRAP report further, five out of the eleven studies are very close to 0.32 which can be seen in the second part of Table B.1. All these are roughly comparable with this study. See the WRAP study for further information.

Table B.1 Glass CO2-ekv savings

Study	Benefit
This Thesis	0.27
WRAP	0.6
Difference in %	0 % (55 %)
- Sweden 1991	0.28
- EU 1997	0.23-0.6
- EU 2001	0.26-0.28
- USA 2002	0.32-0.33
- United Kingdom 2004	0.28-0.31

B.2 Paper Packaging

Paper packaging is compared to both Finnveden and WRAP. The figures from WRAP are to a large extent based on corrugated cardboard, to a less extent on paperboard and to no extent on laminated cardboard. WRAP also has the same environmental benefit for both paper and paper packaging which is unlikely to be the case in this study. This makes the comparison to Finnveden most correct since it is based on the actual recycling at Fiskeby board which handles part of the paper packaging recycling in Sweden today. The comparison can be seen in Table B.2.

Table B.2 Paper packaging CO2-ekv savings

Study	Benefit
This Thesis	0.15
Finnveden	0.148-0.457
WRAP	1.7
Difference in %	0 % (91 %)

B.3 Newsprint

Newsprint is compared with WRAP. The figure used in this thesis is based on natural gas for electricity production. To be able to compare it with WRAP it had to be adjusted to coal based electricity as seen in Table B.3. The original figure is bracketed. With this adjustment, the figures are similar.

Table B.3 Newsprint CO2-ekv savings

Study	Benefit
This Thesis	1.8 (0.51)
WRAP	1.7
Difference in %	6 %

B.4 Steel

Steel is compared with WRAP and APEAL in Table B.4. The figure is close to APEAL but has a significant difference to WRAP. When studied closer, the lower figures in the WRAP report did in most cases not include a 100 % recycling and / or calculated on recycled steel being replaced by recycled steel which lowers the figure.

Table B.4 Steel CO2-ekv savings

Study	Benefit
This Thesis	2.01
WRAP	0.94
APEAL	1.87
Difference in %	7 % - 53 %

B.5 Aluminium

Aluminium is compared to WRAP and CIT. In WRAP the variations in savings are large, most likely due to differences in electricity production. Table B.5 shows the comparison with the reasonable difference to CIT of 5 %.

Table B.5 Aluminium CO2-ekv savings

Study	Benefit
This Thesis	10.4
CIT	12.4
WRAP	10
Difference in %	4 % - 16 %

B.6 HD-PE

HD-PE is compared to CIT. One could also compare it with the overall plastics figure from WRAP since PE is the by far most common plastic. WRAP is therefore also included in Table B.6.

Table B.6 HD-PE CO2-ekv savings

Study	Benefit
This Thesis	1.67
CIT	1.8
WRAP (All plastics)	2
Difference in %	7 %

B.7 PP

To compare the value for PP a study by Frees used in the WRAP study was used since no other comparable study was found. The values are compared in Table B.7.

Table B.7 PP CO2-ekv savings

Study	Benefit
This Thesis	0.86
WRAP (Frees)	0.8
Difference in %	7 %

B.8 PET

PET is compared with Finnveden. Here the figure from Finnveden included incineration as the alternative instead of landfill. The test of this thesis value therefore included incineration. The value for recycling compared to landfill is in brackets.

Table B.8 PET CO2-ekv savings

Study	Benefit
This Thesis	4.4 (2.2)
Finnveden	4.7
Difference in %	6 %

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