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Preface

This report covers the project "Materialåtervinning och klimatnytta – inventering och rekommendation av data" (The Climate Benefit of Material Recycling – Data Inventory and Recommendation), which started in November 2013 and will be complete in May 2015. The project is funded by the Nordic Council of Ministers, Återvinningsindustrierna, Stiftelsen Gästrikeregionens miljö, Norsk Industri and Norsk Returmetallforening. In addition to its primary focus on global warming potentials, the project identifies other environmental impact categories suitable for further study.

Summary

This project emanates from a perceived need for environmental data that can be used for communication in the recycling industry active in Norway, Denmark and Sweden. Its purpose is to compare emissions of greenhouse gases from material recycling and virgin material production, thus involving both material supply and recycling systems in the analysis. The method for estimating emissions and potential climate impact is based on life cycle assessment (LCA). The literature review is based on peer-reviewed journal articles, reports from authorities and industry associations, and inputs from stakeholders involved in the project. These stakeholders formed a reference group that supported the process in various ways throughout the project.

The results presented in this report can be used as indications of the average climate performance of selected and typical material recycling routes in Norway, Denmark and Sweden. They are intended to be used by companies, industry associations and policy makers in the communication of the present performance in this sector. The results should not, however, be used to draw conclusions beyond the scope of the study. There are five types of limitations that are of particular importance to define the role of the results in a wider perspective, and which are highlighted in this report:

- The retrospective approach of the project relates to the present state of the systems and is not suited to answering questions about any future potential to reduce the climate impact through increased material recycling or support upcoming investments or strategies.
- Working with averaged data, the results can be used to indicate the general performance of material recycling in Norway, Denmark and Sweden. This means that the data will typically not be appropriate for a specific context or scenario, due to divergence in energy systems, and in processes and how they are managed.
- Greenhouse gas emissions and potential climate benefits together form only one part of the environmental performance of recycling systems. It is necessary to take other indicators into account, such as resource depletion, eutrophication and toxicity, in order to get the complete picture. This could, in turn, lead to other priorities.

- Our approach is based on the assumption that the materials collected for recycling can replace virgin materials, though with certain losses, and the results are representative for current practices. The existence of alloys, composites, contaminations and other impurities imply limitations in the actual amounts that can be recycled, today and in the future.
- There is always uncertainty in LCA data because of variations between data sources. This is due to the immaturity of processes and how they are managed, and the methods used to measure or calculate data.

Taking these issues into account, the data proposed in this report should be used with care. With relation to both material supply and recycling systems, two perspectives are examined to analyse the climate benefit of current material recycling:

1. Choice of material: What is the expected climate benefit when using recycled material in new products?
2. Choice of recycling method: What is the expected climate benefit for waste being directed to recycling?

The first perspective is based on emissions data for secondary production (material recycling) and primary (virgin) production. The proposed averages show that emissions from secondary production are lower for all materials, implying that both the difference and the percent variance between secondary and primary production are negative (Table S1).

Table S1. Greenhouse gas emissions from secondary and primary production, and comparisons between secondary and primary production. The unit used is kg CO_2-equivalent/kg material, and the material output is assumed equal to the amount of treated waste (after losses), except for organic waste

Material	Secondary production (kg CO_2-eq./kg)	Primary production (kg CO_2-eq./kg)	Difference: secondary – primary (kg CO_2-eq./kg)	Ratio: primary/ secondary	Percent variance: secondary vs. primary
Glass	0.5	0.9	-0.4	1.7	-41%
Aluminium	0.4	11.0	-10.6	28	-96%
Steel	0.3	2.4	-2.1	7.5	-87%
Plastics	1.3	2.1	-0.8	1.6	-37%
Paper and cardboard	0.7	1.1	-0.4	1.6	-37%
Organic waste (composting)*	0.05	0.07	-0.02	1.4	-27%
Organic waste (digestion)*	0.01	0.09	-0.07	7.4	-87%

* For organic waste, it is the nutrient contents and the organic material that is recycled, and in the case of digestion, some of the energy is recovered through the production of biogas.

The second perspective, comparing the choice of recycling method, requires an expanded system approach. For relevant materials in this project a recycling alternative and an incineration alternative are compared. Emissions from the treatment of equal amounts of waste and supply of energy are considered. To make the alternatives functionally equivalent, incineration with energy recovery is combined with primary production, while material recycling (secondary production) is combined with a separate energy supply. The proposed averages show that emissions from the recycling alternative are lower for all materials, implying that both the difference and the percent variance between the recycling and the incineration alternatives are negative (Table S2).

Table S2. Greenhouse gas emissions from recycling (secondary production and separate energy supply) and incineration (incineration and primary production), and comparisons between recycling and incineration. The unit used is kg CO_2-equivalent/kg material, and the material output is assumed equal to the amount of treated waste (after losses), except for organic waste

Material	Recycling: secondary + energy (kg CO_2-eq./kg)	Incineration: incineration + primary (kg CO_2-eq./kg)	Difference: recycling – incineration (kg CO_2-eq./kg)	Ratio: incineration/ recycling	Percent variance: recycling vs. incineration
Plastics	2.2	4.9	-2.7	2.2	-55%
Paper and cardboard	1.1	1.2	-0.1	1.1	-6%
Organic waste (composting)*	0.11	0.14	-0.03	1.3	-21%
Organic waste (digestion)*	0.07	0.16	-0.09	2.2	-54%

* For organic waste, it is the nutrient contents and the organic material that is recycled, and in the case of digestion, some of the energy is recovered through the production of biogas.

The results can be used by companies and industry associations to communicate the general climate benefits in annual reports and similar publications, and on web pages. They may also be used by public authorities and contribute to discussions on a societal level, as long as their average and historic nature is recognised. The results cannot, however, be used to compare specific recycling routes or firms, and they should not be used to support large scale decisions regarding future development of the systems.

Review Statement

Reviewer: Lars-Gunnar Lindfors, IVL Swedish Environmental Research Institute, Stockholm

Introduction

The reviewer was given the task to review the study report “Climate Benefits of Material Recycling – Inventory of Average Greenhouse Gas Emissions for Denmark, Norway and Sweden”.

The purpose of the study was to compare recycling vs. virgin production of selected materials in terms of emissions of greenhouse gases in a life-cycle perspective, with the intention that the results presented in the report may be used as indications of the average climate performance of selected and typical material recycling routes in Norway, Denmark and Sweden. The method for estimating emissions and potential climate impact was based on life cycle assessment (LCA), and the data sources were published LCA studies found in peer-reviewed journals, reports from authorities and industry associations, and inputs from stakeholders involved in the project.

A draft report was sent to the reviewer on 17th November, 2014 and discussed with two of the authors, Karl Hillman and Ola Eriksson, at a meeting in Gävle on 26th November, 2014. The main critical comments by the reviewer were that the limitations associated with the results must be more highlighted, and that the study only addressed greenhouse gases despite the fact that information on other emission types were available. The second draft report was sent to the reviewer on 28th December, 2014. All critical comments made during the review process were addressed in a satisfactory manner in this final draft report.

General Comments

Reuse of LCA data for purposes somewhat different than those of the original studies is a difficult task. The quality of the data to use must be well known in details which are not always reported in published studies. The authors use a clearly reported set of critera for the selection of relevant data. System boundaries and assumptions are well justified. Possible uncertainties and limitations associated with the reported quantitative results are discussed in a full and transparent manner. Clear recommendations for a restricted use of the quantitative results are given, which compensates for the fact that the quantitative uncertainties associated with the results are unknown to some extent.

Some information on other types of emissions than greenhouse gases are added to report. This enhance the value of the information given in the report, which otherwise would have been rather limited.

Conclusions

The reviewer finds the chosen methodology and its execution to be of high quality. The quantitative results are uncertain, but this is reported in a transparent manner by the authors. The conclusions and recommendations for restricted use are well balanced.

Stockholm, 14th January, 2015

Lars-Gunnar Lindfors

1. Introduction

This project emanates from discussions with recycling companies active in Sweden and their industry association, The Swedish Recycling Industries' Association (Återvinningsindustrierna, ÅI). The discussion was partly fed by a pre-study performed at the University of Gävle in 2012, which pointed out that current figures used in Sweden for estimation or calculation of the environmental benefit of material recycling suffered from a number of shortcomings related to the underlying methodology (Hillman, 2013). Accordingly, the intention was to review and assess available studies to come up with a set of data that could be proposed for communicating the greenhouse gas performance of current recycling services, to be used by industry, organisations, and policy-makers.

During the application process more actors with similar interests were involved, such as the Federation of Norwegian Industries (Norsk Industri), the Norwegian Association of Metal Recyclers (Norsk Returmetallforening), the Nordic Waste Group of the Nordic Council of Ministers, and DTU Environment at the Technical University of Denmark.

The project not only contributes to improving the climate data for a number of materials, which can be used by companies and industry associations in Norway, Denmark and Sweden. It also provides insight for policy makers and firms that are commonly informed of, and affected by assessment results, so that they can interpret these in relation to the purpose and underlying assumptions of the assessment. The context of environmental assessments is that assessments influence, and are influenced by, firm strategy and policy, and that firm strategy and policy influence each other using environmental information (see Hillman, 2008).

The purpose of the project is to compare material recycling (for organic waste, biological treatment is the recycling method) with virgin material production, in certain cases in combination with waste incineration. Two perspectives are examined in order to analyse the climate benefit of current material recycling:

1. Choice of material: What is the expected climate benefit when using recycled material in new products?
2. Choice of recycling method: What is the expected climate benefit for waste being directed to recycling?

Our aim is to present a set of general data needed for communicating the potential climate benefit of material recycling from an industry perspective in Sweden, Norway and Denmark. The project mainly comprises of a discussion of industry purposes and needs, and an inventory of literature – data and assumptions – that assess material recycling from a life cycle perspective. A selection of climate data for a number of materials is made, which live up to industry needs and state-of-the-art methodological claims. Furthermore, though not quantified, it is documented to what extent the selected literature considers other environmental impact categories, providing scope for further analysis. The results will be presented so that the data can be used by companies and industry associations, and so that the method can be used for future updates of the work. Obviously there are many possible receivers of information from the project, such as customers, authorities, politicians and society in general, while it is likely that the project results also will be used as a base for company-internal decisions.

It is important that the limitations of this kind of study are clearly understood by the receivers and users of the results. These are further described throughout the report, and will help to put this study in perspective and highlight that it is just a part of a bigger picture concerning the environmental benefit of material recycling.

- The retrospective and attributional methodology for life cycle assessment (LCA) agreed within the project indicates the present status of the systems and is not suited to answering questions about any future potential to reduce the climate impact through increased material recycling, nor therefore to support decisions regarding specific investments or strategies
- To get a complete picture of the environmental performance of recycling systems, environmental indicators other than greenhouse gas emissions and potential climate benefits need to be taken into account. An expected advantage of material recycling is the reduced need for finite resources, and previous studies show potential reductions in various environmental impact categories (see e.g. Michaud *et al.*, 2010). In addition, energy use indicators may be useful to capture the inherent properties of processes and systems.
- Our approach is to focus on a number of materials that are collected for treatment and assume that they can replace virgin raw materials. In reality this is not always the case, due to the existence of alloys, composites, contaminations and other impurities in relation to recycled materials. Recycled material cannot always replace virgin

material on a one-to-one-basis, and this differs between materials and products.[1] Accordingly, the results are primarily representative of the materials currently going to recycling and not for all materials used in society.

- By defining averages for a region comprising of Norway, Denmark and Sweden, we primarily get an indication of the general performance of material recycling in this region. However, general inventory data for recycling processes cannot be considered to adequately describe a specific context or scenario. In most cases, the data will not be appropriate for a specific context, due to divergence in systems, processes and how they are managed.
- For several reasons there is always uncertainty in LCA data, due to variations between sources and how raw data is obtained.

It should be clarified that, as suggested in the pre-study (Hillman, 2013), the problem addressed by the present project is about properly selecting data and the use of consistent and transparent methodology to calculate environmental performance. As pointed out by some stakeholders, there may be a lack of good quality data for some materials and processes. It is beyond the scope of this project, however, to investigate such processes in order to obtain new data. What can be done is to identify the lack of data, and take steps towards supplementation.

[1] This can be taken into account as losses, as described where relevant in this report.

2. Methodology

Methods for collecting general information and data are described in sections 2.1 and 2.2. Then the methodology used to generate data in the studied literature – environmental life cycle assessment (LCA) – is introduced in section 2.3, and the system boundaries specific to the project are described in section 2.4.

2.1 Collaborative stakeholder cooperation

At the start-up meeting on 12th November 2013 the pre-study from 2012 and its recommendations were presented, followed by the present project proposal. The purpose of the meeting was to discuss a number of crucial issues and choices with the stakeholders, which were identified with help from the funding organisations. The discussion continued during the following weeks and its outcomes were summarised and distributed to collect more input from the stakeholders regarding their purposes and needs, and to collect relevant materials and treatments to include in the project.

After the collection of studies and data, the discussions were taken up again during June to September 2014. Methodological issues and information on selected studies was circulated and discussed at a video meeting on 27th August and a workshop meeting on 25th September, 2014. These discussions further clarified a common view of the studied systems and the stakeholders' purposes. The people participating at the three meetings are referred to as "the Reference Group", and are listed in Appendix 3. It consisted of representatives from Återvinningsindustrierna and several of its member companies, Norsk Industri and Norsk Returmetallforening, and the Nordic Waste Group.

2.2 Literature review

Several starting points contributed to the search for literature, such as the pre-study (Hillman 2013), projects and reports recommended by the stakeholders and the available research network, and scientific publication databases. Accordingly, the literature review is based on: 1) peer-reviewed journal articles in relation to LCA or greenhouse gas accounting of waste, 2) reports from authorities and industry associations, or reports performed by analysts engaged by such bodies, and 3) inputs from stakeholders involved in the project. In addition, inputs from two earlier review studies were included, in which some project participants have been involved. One of these considers the Danish situation (Wenzel & Brogaard, 2011) while the other one has an international approach (Brogaard *et al.*, 2014). Finally, further snowball searches, where original sources published in Danish, Norwegian, Swedish, English, German and French were traced.[2] Due to the time limitations of the project, the search was primarily directed at studies covering multiple fractions.

The literature search resulted in an internal list of publications that were considered for the collection of data. Edited lists of these studies are presented in Section 3.3 (Selected studies) and Appendix 1 (Rejected studies).[3] For studies from the two Danish reviews, we refer to Wenzel & Brogaard (2011) and Brogaard *et al.* (2014).

The publications were examined with respect to what kind of contribution they can make, such as method, data, and/or further sources. The primary guiding principles for the selection of studies and data used in the project are that they should be publicly available in reports or journal articles published within the last 10 years, that the data can be traced to its origin, and that the data can be assumed relevant for the situation in Norway, Denmark and Sweden. All material proposed by the stakeholders were considered; in many cases this meant that they were used to identify original sources of data that could be used for further analysis.

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[2] These languages were considered the most available for the stakeholders interested in the study, and they were also reasonably accessible to the researchers.

[3] For convenience, studies of informal character and/or not considered useful to the readers of this report were removed from the list.

2.3 Life Cycle Assessment (LCA)

The discussion at the start-up meeting can be summed up as a strong recommendation to use methodology and data that is easily understandable – almost intuitive – with regard to system boundaries and assumptions. A key message was that results should not confuse the receiver, but simply describe the environmental benefit of recycling. This implies that so-called retrospective attributional (or accounting) life cycle assessment be the methodology used in the project (JRC, 2011). To be fully correct, and consistent with the methodology, it is the potential amount of emissions from, and the difference in emissions between, material recycling and other existing alternatives that can be calculated. In this report, this difference is termed "the environmental benefit" or "the climate benefit" of material recycling compared to some stated alternative. This means that the benefit can be used to indicate the difference in emissions in recent years. The methodology, however, does not allow for the benefit calculated to be used to state that a certain amount of emissions was (or will be) avoided during a certain period of time as the result of material recycling.

Attributional (or accounting) LCA is more in line with the intended communication formats, and with environmental reporting using e.g. the Greenhouse Gas Protocol, which is an international voluntary standard for the calculation and reporting of greenhouse gas emissions. The results can be used for comparing the present performance of various alternatives, but a disadvantage with attributional LCA is that it cannot result in data representing consequences of decisions, such as the choice between a material recycling and an incineration investment at a certain point in time.

In the project proposal, global warming is suggested as the main focus of the project, while other environmental impact categories should not be quantified. In the start-up phase some stakeholders have questioned this, as trends might change at short notice and they would like to be prepared for questions concerning other kinds of environmental issues, such as toxicity, resource depletion and energy use. The outcome of the discussion was that it should be possible to use the project results as a base for quantifying other impact categories as well, which this report does by listing which studies included more than global warmning.

2.4 System boundaries

2.4.1 Included materials

The starting point for the data collection is that materials from all kinds of sources should be encompassed, including both household and industrial waste. In Appendix 2 a provisional list of materials is presented, based on all suggestions collected from the stakeholders. Some proposed waste categories consist of a mix of different materials and are not easily fitted into the project. Discussions with the reference group resulted in the focus of the project being on pure material fractions (see Discussion) and so-called "closed loop recycling".[4] This means that the recycled material is assumed to be used in similar products after it has been recycled. Due to their nature (e.g. paper fibre) some materials will degrade over time, and it can therefore be problematic to maintain the same quality unless new virgin material is added. Another option is that of being down-cycled to a less demanding product. For the comparisons made here it is assumed that recycled material replaces virgin production of similar type and quality.[5]

The provisional list provided a guide to the collection of studies and data but, as expected, the final list of included materials is much shorter. The reason for this is that the quality of the available studies and data suggests that some fractions are combined and considered to be the same material, while others are omitted. More details on how the materials were identified and selected are presented in Section 3, and how the selection was made for specific materials is part of the Results section (Section 5).

2.4.2 Definition of amounts

We have used two kinds of studies as input to the project. Mostly they either compare material production (secondary vs. primary) or waste treatment (material recycling vs. incineration with energy recovery). In the case of organic waste, secondary production implies biological treatment, such as composting and anaerobic digestion.

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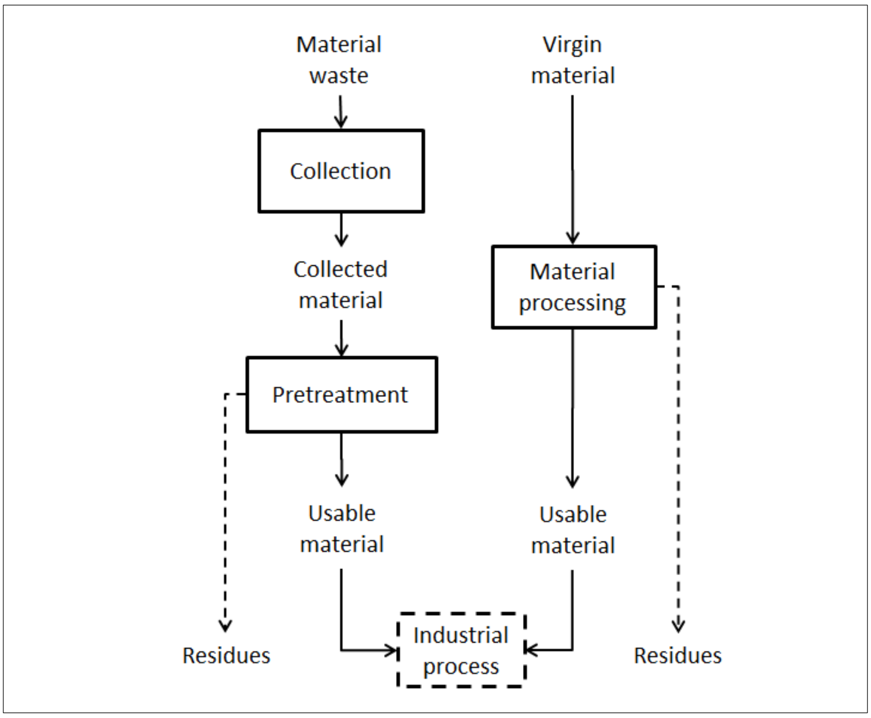
[4] Potentially, results for pure material can be used for calculations regarding mixed categories.

[5] The alternative is open loop recycling, which implies that recycled material is used for a new purpose after it has been recycled. For the purposes of analysis, this may call for comparisons between, for example, recycled plastics and other textiles for clothes, and recycled paper and plastics as a construction material.

There are commonly two types of functional units used in these two kinds of studies: 1 tonne of material output and 1 tonne of treated waste (after losses), respectively. Our general view, based on the selected studies and discussions with the reference group is that they are principally equivalent (except for organic waste). The amount of treated waste is considered to be what comes from pre-treatment and is sold for use in industrial processes. This is also the case with the output from primary and secondary production. In some cases, where the functional unit "1 tonne of collected waste" is used, the results are adjusted due to losses in the downstream processes, as documented in the respective studies.

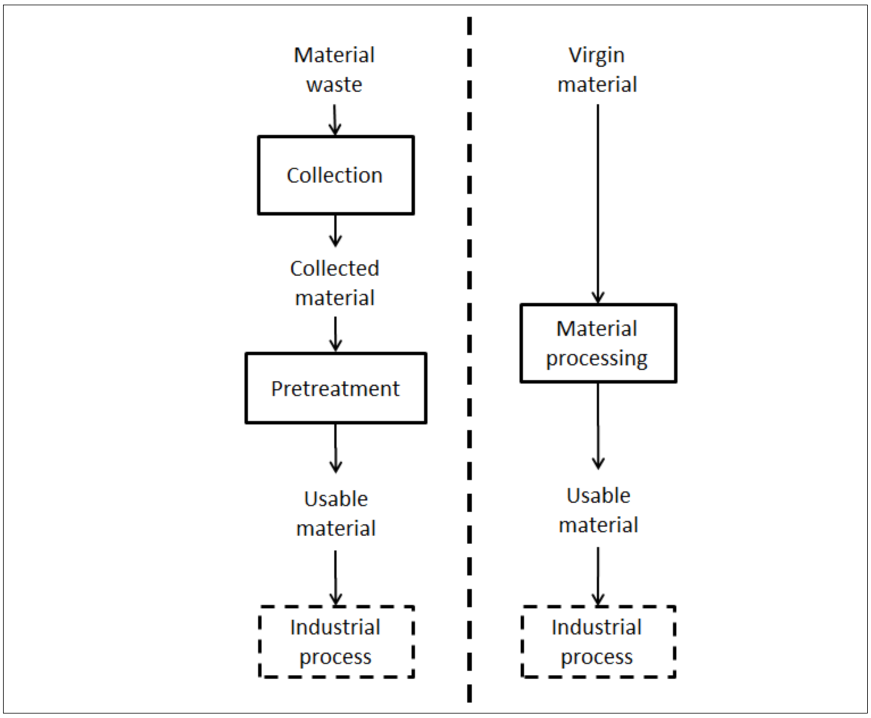
As illustrated in Figure 1, secondary and primary materials are often used in the same industrial processes, or even in pre-treatment. Here, "Material processing" refers to primary material production using virgin material (raw materials produced from natural resources) as input. Recycled material is equal to the output from secondary production, defined as "Usable material" in Figure 1, which is the amount of collected material minus losses in pre-treatment. Losses arise during sorting and pre-treatment due to impurities and possible material degradation.

Figure 1. Commonly, both material waste and virgin materials are used in the same industrial process



In some cases, secondary and primary production is actually separated, as illustrated in Figure 2. Also, in many studies, data for the separate material inputs are identified for the purpose of analysis. This sometimes involves considerations regarding how variations in the share of waste and virgin material affect the output and life cycle emissions for some material production. In this way, data for pure materials – waste or virgin – can be distinguished. Hence, combined use (Figure 1) can also be modelled in accordance with Figure 2, which illustrates the model used in relation to the choice of material in this report (Comparison 1). In this report, emissions from processes marked with continuous line boxes in Figure 2 are included in the analysis. For secondary production, this means that collection from the place where the waste is generated is included together with pre-treatment.

Figure 2. Cases where secondary and primary production are separated. Alternatively, a method for modelling the combined use of waste and virgin material. Emissions from processes marked with continuous line boxes are included in the analysis



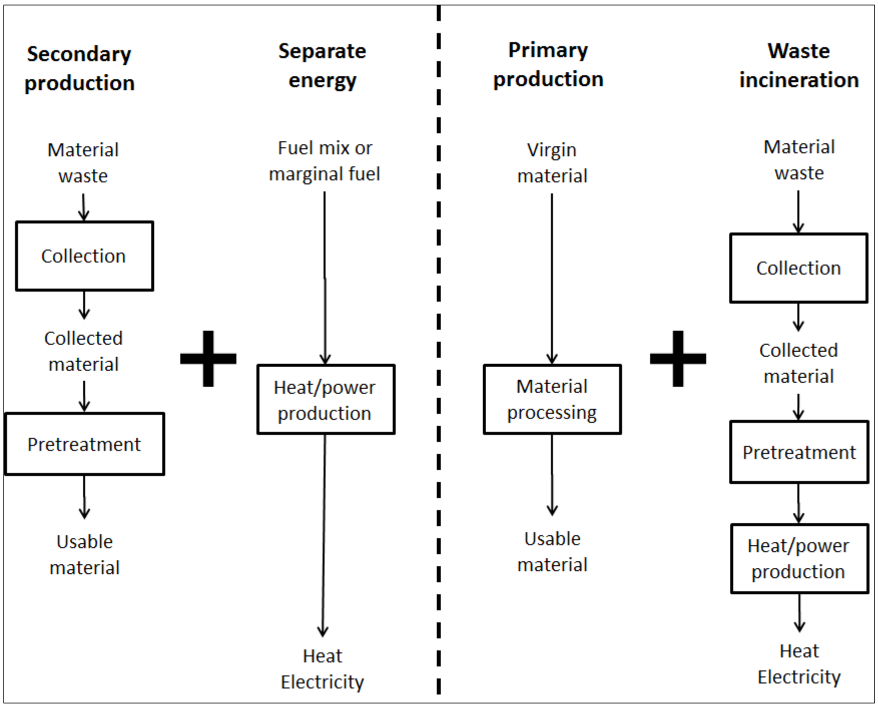
The second comparison between material recycling and other waste treatment calls for system expansion and is described below.

2.4.3 System expansion

When comparing waste treatment processes it is important that the alternatives are functionally equivalent. Considering the expected climate benefit of waste being directed to recycling (see Section 1), the comparison to be made is between material recycling and incineration with energy recovery, of which the latter typically involves the generation of heat and/or electricity. Thus, in order to make these alternatives comparable in the analysis, the recycling alternative has to be complemented with a separate production of heat and electricity. For the same reason, since there is no material produced, the incineration alternative has to be complemented with virgin material production.

The system boundaries for the two alternatives are illustrated in Figure 3. The schema has to be somewhat adjusted when comparing biological treatment that involves the production of biogas, fertiliser and organic material. Emissions from the processes marked with continuous line boxes are included in the analysis. For the recycling alternative this means that collection, pre-treatment and heat/power production are included. For the incineration alternative, collection, pre-treatment, heat/power production, and primary material production are included.

Figure 3. Illustration of material recycling and incineration with heat recovery. Emissions from processes marked with continuous line boxes are included in the analysis



In some studies the virgin resources saved due to material recycling – the primary example being wood – are assumed to create a climate benefit as they can be used for other purposes such as heat/electricity production, in turn replacing fossil fuels to a certain extent. Such effects are not taken into account in this project (see Section 3.1).

2.4.4 Impact assessment

The primary environmental impact category used in the project is the potential contribution to global warming, as indicated by emissions of greenhouse gases measured in carbon dioxide equivalent (CO_2-eq.). Emissions of other greenhouse gases are then weighted in accordance with their relative contribution to global warming compared to carbon dioxide. The weighting factors used in the invented studies are mainly the Global Warming Potentials (GWP) published by the Intergovernmental Panel on Climate Change (IPCC) in 2004 and 2007. There are as yet no studies published using the new IPCC factors from 2013 that were found to be of use for the project. Other impact categories are not analysed in the project, but the inclusion of additional environmental impact categories in the selected studies are indicated in Tables 2–4 (Section 3.3).

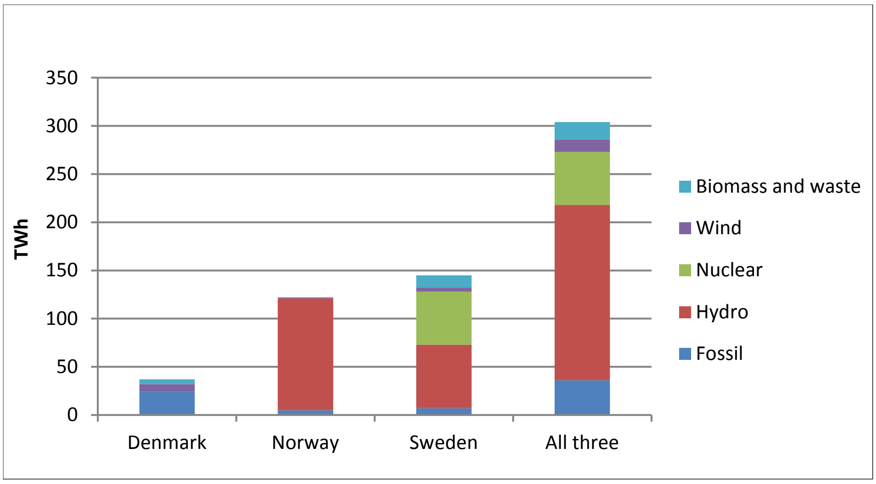
3. Investigation context

3.1 General assumptions

There are a number of data choices that are central in life cycle assessments of waste treatment alternatives. Firstly, different technologies used in the processes pre-treatment, recycling and virgin material production imply differences in energy efficiency, emissions and the ratio between usable and recycled material. Secondly, the types and distances of transports affect the emissions from those parts of the life cycle. Finally, the type of heat and electricity used for the processes of pre-treatment, recycling and virgin material production may have a large impact on the results. Also for complementary systems this may be crucial, for example when recycling is complemented with separate production of heat and electricity.

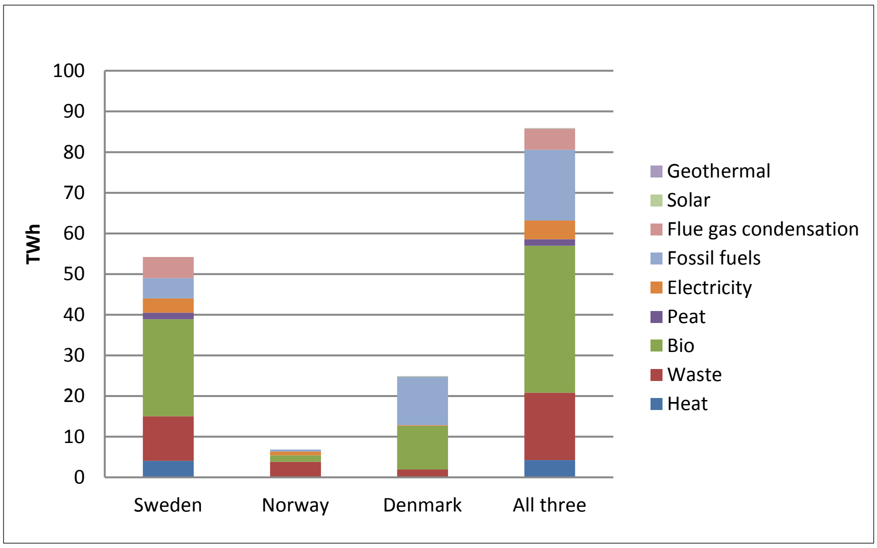
The general principle would be to use similar assumptions on technology level, heat mix, and electricity mix, respectively, for all studied processes. Hence, the starting point in this project is to use data that is representative for the average of the three countries, potentially with the exception of processes only located in specific countries outside the Nordic countries. This principle was supported by the reference group throughout the project, and it implies that the project should end up with results that are similar for the three countries involved. Firstly, for electricity production, it may be feasible to consider a general market, though Denmark, Norway and Sweden have very divergent production profiles (Figure 4). The average share of fossil fuels, crucial for the GHG emissions, varies slightly between the years and was just above 10% in 2012.

Figure 4. Electricity production (TWh) in 2012, in the three participating countries, with energy sources indicated colours (Source: Energistyrelsen Danmark, 2014; Statistisk Sentralbyrå Norge, 2013; Svensk Energi, 2014)



Secondly, for heat production, markets are more affected by the availability of regional resources and environmental performance is dependent on specific conditions. In some cases, a heat market may not be available. Nevertheless, for the purpose of presenting general data on climate benefits, the use of average data based on district heating production in the three countries (see Figure 5) can be justified. Here, the average share of fossil fuels was about 20% in 2012.

Figure 5. Energy sources used for district heating production in 2012 in the three participating countries (Sources: Svensk Fjärrvärme, 2013; Norges vassdrags- og energidirektorat, 2013; Energistyrelsen Danmark, 2014)



Regarding transport, whether data should be based on actual market relations or theoretical assumptions is open for discussion. In practice, however, we will mainly base the calculations on the best data available, while documenting any essential information about the data. When it comes to avoiding the use of virgin materials, it is difficult to find a general principle for the resulting potential influence on emissions. Oil not used for plastics production and trees not used for paper or wood production can be assumed left unused or, alternatively, used for some other specified purposes. Such assumptions can be based on agreed principles, or on how markets are affected (see e.g. Eriksson *et al.*, 2007). There are also other examples, such as raw materials for metal and glass, which can be considered in the same manner. The September 2014 workshop decided not to use unused resources for, e.g. heat/electricity, as it is not consistent with the methodology used (attributional LCA) and results may appear far-fetched and speculative when used in external communication.

3.2 Other impact categories

As mentioned in the Introduction (Section 1), focusing on greenhouse gases and climate change implies that a complete picture of the environmental performance of recycling systems is not obtained in this project. On a general level, there are correlations between carbon footprint and other environmental impact categories, though with significant exceptions such as toxicity (Laurent *et al.*, 2012). In the case of material recycling, other expected advantages are the reduced need for finite resources and primary energy, and in some cases reduced contributions to eutrophication and toxicity.

Though the search for studies emphasises climate related data, a number of the investigated studies have a wider scope comprising also other indicators. It is expected that the studies involving other impact categories include also global warming with few exceptions, which means that the number of studies not found is limited.[6] Four of the selected studies considered some kind of energy use indicator, while one involved a few other impact categories. In particular, analysing results

[6] One notable exception is a study on metals. The study by EMEP/EEA (2013) compare virgin vs. renewables, which is one of the best studies on metals, but which sadly only considers toxic emissions.

for various energy use indicators requires additional research, as there is no standardised methodology. Typically, studies are not fully clear on how energy use is calculated, while it is decisive for the results (Arvidsson *et al.* 2012, Modahl *et al.* 2013). The problem is not relevant for standard impact categories in LCA, such as eutrophication and acidification. These are typically treated in the same way as global warming, which means that the methodological quality is generally the same. Still, data quality may differ, calling for separate analyses.

The studies that include impact categories other than global warming potential are marked with colours in Tables 2–4 (selected studies) and in Appendix 1 (rejected studies). Red indicates that indicators for energy and/or water use are included, while green indicates the inclusion of one or several LCA impact categories.

3.3 Selected studies

The investigated studies are published since the 1990s, while the selection process aimed for studies published during 2003–2013. In this section the main features of the selected studies are presented. Several sources could not be used for this project for one or several reasons explained below. First of all, some studies did not contain any data, but only methodological or qualitative results. These were obviously not included in the analysis. All other investigated studies were either included and listed in Tables 2–4, or not included and listed in Appendix 1 together with the reason for refusal. All reasons for refusal are listed in Table 1.

Table 1. All occurring reasons for not including studies, with further description/comment

Reason	Description/comment
Contains no data	Not included in the list of refused studies (Appendix 1)
Older than 10 years	Published before 2003
Only mixed fractions	Data for separate materials could not be discerned
Aggregated results*	No separate data for secondary and primary production
Diverging energy mix	Energy mix not comparable with the three studied countries
Only CO_2	Other greenhouse gases not considered
Diverging time perspective	Using e.g. BAT assumptions or scenarios
Refer to other sources	Then the other sources are investigated as well
Data origin unknown	
Language not available	The primary languages were Swedish, Norwegian, Danish and English, while some studies in German and French were not refused due to the language
Not available	The study could not be easily collected
Diverging functional unit	Using e.g. system perspectives where data for separate materials could not be discerned

* In some cases, when data is scarce, comparison results are used to support the data analysis. In such cases, this is documented (Section 5).

Concerning energy system assumptions, studies assuming for example US average electricity – produced from up to about two thirds fossil fuels (US Energy Information Administration, 2014) – are considered too divergent from the studied Nordic system. However, studies using Austrian, German and EU average electricity mixes are used in the analysis. Furthermore, results based on the assumed use of marginal electricity – typically from natural gas or coal – cannot be used in this project. In principle, some results may be recalculated using another energy system assumption, but this requires certain details from the studied publication. As the inclusion of this type of documentation is not the case for almost any of the investigated studies, such recalculations are not performed in the project.

3.3.1 Studies from Norway, Denmark and Sweden

The studies selected for use in the data analysis in chapter 5 are listed in Tables 2–4. However, data quality and other properties vary between fractions within studies, which imply that data for all fractions mentioned in the tables is not used as a basis for the calculations.

Table 2. Studies from Norway, Denmark and Sweden

No	Title	Authors	Year	Origin	Region	Fractions	Indicators	Energy	Localisations
1[a)]	Livsløpsanalyse for gjenvinning av plastemballasje fra norske husholdninger	Kari-Anne Lyng & Ingunn Saur Modahl	2011	Østfoldforskning, report prepared for Grønt Punkt Norge, Norway	Norway	Plastic packaging	Energy use (cumulative energy demand), GHG emissions	Norwegian heat Nordic electricity	Norwat, Germany, China
2	Klimaregnskap for avfallshåndtering	Hanne Lerche Raadal, Ingunn Saur Modahl & Kari-Anne Lyng	2010	Avfall Norge nr 5/2009, Norway	Norway	Glass packaging, metal packaging, paper, cardboard, plastic packaging, food waste, wood, household waste	GHG emissions	Norwegian heat Nordic electricity	Norway Norway and other countries (paper and cardboard recycling) Sweden (plastic recycling)
3[b)]	Miljømæssige forhold ved genanvendelse af papir og pap: opdatering af vidensgrundlaget	Frees, N., Søes Hansen, M., Mørck Ottosen, L., Tønning, K., Wenzel, H	2005	Instituttet for Produktudvikling, IPU and Teknologisk Institut Denmark, raport for Miljøstyrelsen, Denmark	Denmark	Office paper, corrugated board, newsprint	GHG emissions, acidification, photochemical ozone formation, eutrophication	Marginal (natural gas combined cycle)	Four sites in Denmark

a) indicates that indicators for energy and/or water use are included.
b) indicates the inclusion of one or several other LCA impact categories.

3.3.2 Studies from other European countries

Table 3. Studies from other European countries

No	Title	Authors	Year	Origin	Region	Fractions	Indicators	Energy	Localisations
4[a)]	Klimarelevanz ausgewählter Recycling-Prozesse in Österreich	Helmut Frischenschlager, Brigitte Karigl, Christoph Lampert, Werner Pölz, Ilse Schindler, Maria Tesar, Herbert Wiesenberger, Brigitte Winter	2010	Umweltbundesamt Endbericht, Austria	Austria	Aluminium, copper, iron/steel, glass, PET	GHG emissions, cumulated energy demand (CED)	Austrian	Austria
5[a)]	Paper and biomass for energy? The impact of paper recycling on energy and CO2 emissions	Jobien Laurijssen, Marc Marsidi, Annita Westenbroek, Ernst Worrell and Andre Faaij	2010	Resources, Conservation and Recycling (2010), volume 54, pages 1208–1218	The Netherlands	Fibres (newsprint)	GHG emissions, energy use	Biomass replacing fossil fuels Incineration to electricity	The Netherlands (hypothetical)
6	Resource savings and CO_2 reduction potential in waste management in Europe and the possible contribution to the CO_2 reduction target in 2020	Prognos AG, Ifeu GmbH, INFU TU Dortmund	2008	Same as author(s)	EU-27	Paper, PE/PP, PET, PS, PVC, glass, steel aluminium, copper, textiles, rubber, biowaste (composting), biowaste (anaerobic digestion), wood, solid fuel waste, mineral demolition waste	GHG emissions	EU mixes	EU-27 average
7[a)]	Report on the Environmental Benefits of Recycling	Sue Grimes, John Donaldson, Gabriel Cebrian Gomez	2008	Centre for Sustainable Production & Resource Efficiency (CSPRE), Imperial College London, Commissioned by the Bureau of International Recycling, Under the project leadership of Roger Brewster, Metal Interests Ltd., October 2008, Belgium	-	Aluminium, copper, ferrous, lead, nickel, tin, zinc, paper	GHG emissions, energy requirements	Benchmark based on technological excellence	Not applicable

a) indicates that indicators for energy and/or water use are included.

b) indicates the inclusion of one or several other LCA impact categories.

3.3.3 Studies from the United States of America

Table 4. Studies from the USA

No	Title	Authors	Year	Origin	Region	Fractions	Indicators	Energy	Localisations
8[b)]	Life Cycle Inventory of 100% Postconsumer HDPE and PET Recycled Resin from Postconsumer Containers and Packaging	Franklin Associates, a Division of ERG, USA	2011	Prepared for The Plastics Division Of The American Chemistry Council Inc., The Association Of Postconsumer Plastic Recyclers (APR), The National Association for PET Container Resources (NAPCOR), and The PET Resin Association (PETRA)	USA	HDPE, PET	Full LCI	US national average fuel consumption by electrical utilities	USA
9[b)]	Life Cycle Impact Assessment http://www.container-recycling.org/assets/pdfs/aluminum/LCA-2010-AluminumAssoc.pdf of Aluminum Beverage Cans	PE Americas: Nuno da Silva, Neil d'Souza, Marc Binder	2010	PE Americas, report prepared for Aluminum Association, Inc. Washington, D.C.	USA	Aluminium	Primary energy use (renewable and non-renewable), GHG emissions, acidification, eutrophication, photo-oxidant formation	Hydro: 69.4% Coal: 29.7% Natural gas: 0.6% Nuclear: 0.3%	North America
10[b)]	Life-Cycle Inventory Data Sets for Material Production of Aluminum, Glass, Paper, Plastic, and Steel in North America	RTI International, USA	2003	RTI International, report prepared for U.S. Environmental Protection Agency	North America	Steel, aluminium, paper (paper, board, cardboard), PE, PET, wood, glass, office paper, newsprint, corrugated board, steel	Full LCI	US electricity mix	US averages Europe (plastic, recalculated)

a) indicates that indicators for energy and/or water use are included.
b) indicates the inclusion of one or several other LCA impact categories ("Full LCI", Life Cycle Inventory, indicates that many impact categories are included).

4. Investigated materials

The following sub-section gives a short description of the primary characteristics and crucial process parameters for the different materials included in this study.

4.1 Paper and cardboard

This mixed category consists of newsprint/newspaper, graphical paper/office paper, cardboard and corrugated cardboard. Paper and board is produced from wooden fibre pulp. The pulp can be produced through either mechanical or chemical-mechanical pulping methods (IPPC, 2001).

The methods are mainly dependent on which fibre material is to be produced. Graphical paper consists of wood fibres, and it is used for writing and printing. The lignin that occurs naturally in the raw material is removed through chemical pulping to produce a high quality copy paper. Newsprint is used for newspapers and advertisement inserts and has a lower quality requirement compared to copy paper. It is produced from mechanical pulp, which means that the lignin is not removed. Cardboard and corrugated board is mainly produced from mechanical pulping, and has the lowest quality requirement as the thickness of the material makes up for the lower quality.

Every time a fibre product is recycled the fibre length will be shortened, it can therefore only be recycled a certain number of times. Mixing recycled paper with primary material is therefore often required to meet paper strength specifications (Christensen & Damgaard, 2010a). This is demonstrated when secondary fibre is used; the content of recycled paper varies greatly between the different fibre types, with values of 8.7% for graphical paper, to 87% for newspaper and 93% or higher for cardboard according to ERPC (2014).

4.2 Glass

Container glass for food and beverages is made of soda-lime glass and constitutes 50–60% of the total amount of glass produced globally (IPPC, 2013). Glass, which is produced at 1,500–1,600 °C, can be found in clear, green or brown finishes. Clear glass is produced from quartz sand with low amounts of iron oxides, whereas manganese, iron, nickel and cobalt oxides are added to the production of brown glass, and chromium, cobalt and vanadium oxides are added to green glass (Christensen & Damgaard, 2010b).

There are no limitations to the number of times glass can be recycled, the main consideration is that the glass is properly sorted (colour and purity) before re-melting. There are often one or more sorting steps before remanufacturing.

Since there are no scarcity of raw materials for glass production (quartz) the main reason for recycling is that the primary production is more energy intensive, and in addition primary production releases CO_2 from carbonates used in production, which can be up to 200 kg released per tonne of raw material (Eggleston *et al.*, 2006).

For the sake of glass quality, not more than 90% of the glass mass may be composed of recycled glass, the reason being that some virgin material must be added to ensure that the correct chemical composition is reached for the new product, as there will be some variation in the recovered glass input (IPPC, 2013). Since furnaces cannot tolerate the high temperatures required to manufacture glass from only virgin material, at least 20% of the glass mass should be composed of recycled glass. Energy demand is lower when using cullet compared with only virgin commodities. About 13% less energy is consumed for melting glass mass using 90% recycled material in comparison to when the proportion is only 20% (National Food Agency, 2011).

4.3 Plastics

Plastics can be classified as thermoplastics or thermosets. Thermoplastics can be shaped by heating and will maintain their shape after cooling, whereas the melting point of thermosets is high enough that they will burn before they melt, which makes them hard to recycle (Christensen and Fruergaard, 2010).

Primary plastics are produced from crude oil through the distillation of naphtha, and some plastics may also be produced from natural gas by cracking it into ethylene. Additional monomeric chemicals are added to give the material different properties, depending on the type of plastic produced (Plastics Europe, 2006).

Plastic recycling can be done either by feedstock recycling or mechanical recycling. Feedstock recycling breaks down the plastic to monomers, which can then be used in refineries and chemical production. Mechanical recycling includes shredding, cleaning, melting or granulation (Christensen and Fruergaard, 2010), and it produces quality products only when the materials are void of contaminants, sorted into a single type of polymer and sufficiently segregated according to the colour required for end use. There is requirement for a good sorting prior to remanufacturing, which means that it can make sense to focus on plastics that are either in large quantities or easy to separate such as Polyethylene (PE) and Polyethylene Terephthalate (PET).

There are also a number of plastics made from renewable resources such as starch, maize etc. and also biodegradable plastic but these are not included in this study.

4.4 Steel

The major technologies used for the production of steel are electric arc furnaces and oxygen blast furnaces. These technologies produce the same type of product but use different levels of energy consumption and therefore different emissions. An electric arc furnace can receive 100% scrap metals, while the basic oxygen furnace scrap is limited to 25–30% of the total amount of metal (Damgaard and Christensen, 2010). In both furnaces the final product can have alloying compound metals (e.g. chromium, nickel and tin) added to it to obtain the sought-after steel properties. Globally, it is estimated that the majority of post-consumer scrap is processed in electric arc furnaces (IISI, 2005), so this can be considered the representative technology in most cases, whereas most of the primary production takes places in oxygen blast furnaces.

4.5 Aluminium

There is a large difference between primary and secondary aluminium production. Primary aluminium is produced from bauxite that is processed via alumina oxide refining, followed by alumina smelting using electrolysis, after which is its refined to the finished product (Aluminium Association, 2010). The electrolysis step is the most energy demanding step, and is the main difference between the impact of primary and secondary production. In secondary production the aluminium waste is shredded, ferrous metal contaminants are sorted and removed, and the aluminium is de-coated before smelting and refining.

4.6 Organic waste

Direct recycling of organic waste is of course not possible, so the focus is therefore on recovery of the inherent energy, and nutrients and minerals in the waste, as well as the carbon source itself. The technology choices are whether to incinerate the material for energy recovery, or to anaerobically digest it for energy production followed by spreading on land to utilise the nutrients in new agricultural production. In the case of composting, the volumes and contents of organic material for spreading will be different, and energy is not recovered.

The savings will be direct processing emissions minus the avoided emissions from substituted energy as well as the conventional fertilisers being avoided. Finally a part of the organics that are land-applied will be sequestered in the soil matrix and work as a carbon sequestration. For an example of influencing factors in the accounting of organic waste management, see Boldrin *et al.* (2011).

4.7 Other metals

Besides aluminium and steel, other non-ferrous metals (e.g. lead, copper, brass, zinc and precious metals) can be recovered from waste materials. There is though very little data existing in literature on emissions associated with primary and secondary production.

The main source of data is the Ecoinvent database (Classen *et al.*, 2009) which covers all the mentioned metals for primary production and some for secondary production. But in the documentation it is also

stated that the quality of the data is such that if they play a determining role in a study they should not be used due to the associated uncertainty.

The uncertainty is due to a large degree to the fact that there is a huge variation in the age and quality of plants in Europe and abroad for processing these metals. It is therefore highly determinant where the actual processing takes place. EMEP/EEA (2013) and BREF (EC, 2014) gives an overview of some of these differences, and also gives suggested median values, but the focus is on non-greenhouse-gas emissions, and can therefore not be used in this case.

That said when looking at Classen *et al.* (2009) there are GHG savings seen for most metals covered, and from a resource perspective it clearly makes sense to recover the metals. It is found that, due to the lack of studies on recycling of these metals, the overall data quality is so poor that we cannot recommend any average factor.

5. Results

In this section, emissions data for a number of materials is analysed with respect to specific system boundaries, and averages are proposed (Sections 5.1–5.6). The materials for which data is considered useful and of adequate quality for the project were glass, aluminium, steel, plastic, paper and organic waste (see Section 3 for selection criteria). Data for secondary and primary production, and the calculated difference between them, are presented for all materials (cf. Figure 2). For plastic, paper and organic waste, incineration data is also included, and to be able to compare systems for material recycling and incineration, data for separate energy supply is added. This amount of energy supplied is the same as supplied from incineration (cf. Figure 3). Finally, the proposed averages for all materials analysed are presented and the collected results described (5.7).

Several studies refer to the significance of transports being low when considering climate impact. This is confirmed by e.g. the two Norwegian studies, in which transport emissions are reported in separate columns in the results tables (Raadal *et al.* 2010, Lyng & Modahl 2011). In other studies they are included, as well, but not that easily discerned.

5.1 Paper and cardboard

The selected studies on paper and cardboard production cover Norway, the Netherlands, EU-27 and the US (Table 5). Three studies give relevant numbers for primary production of paper and cardboard – i.e. the EU-27, the Norwegian, and the US studies – that together form the basis for the proposed average. The Dutch study presents figures for the separate processes that cannot be easily recalculated for Nordic conditions due to the study's energy assumptions.

The same three (non-Dutch) studies show quite divergent results for secondary production, ranging from 0.2 to 1.5 kg CO_2-equivalent/kg material. In the EU-27 study, which had the lowest number, our interpretation is that a certain amount of losses are used for energy supply, implying that a credit for avoided emissions is included. In the Norwegian study, the emissions for secondary paper production related to a

specific Norwegian site may be identified. The same study states that a substantial share of the paper and cardboard are recycled abroad. Thus, a higher share of fossil energy can be justified, and this is taken into account in the higher figures from Norway (cardboard) and the Netherlands (newsprint). Finally, the relevant studies for Norway and the Netherlands indicate numbers for secondary paper, newsprint and cardboard production of 0.5–0.9, which forms the basis for the proposed average of 0.7. As emission differences between studies are of the same size as differences between paper and cardboard, a general average for paper and cardboard is proposed. Finally, only the Norwegian study presents numbers for incineration and avoided heat production, in which case the figures for paper and cardboard are similar.

Table 5. Analysed data for paper in kg CO_2-equivalent/kg material. Data used for calculating the proposed average is marked by italics. NA indicates that data is not available

Material/ study no	Region	Secondary production (kg CO_2-eq./kg)	Primary production (kg CO_2-eq./kg)	Incineration (kg CO_2-eq./kg)	Separate energy (kg CO_2-eq./kg)	Recycling: secondary + energy (kg CO_2-eq./kg)	Incineration: incineration + primary (kg CO_2-eq./kg)
Paper							
No 2	Norway	*0.47*	*1.32*	0.065	0.41		
No 6	EU-27	0.19	*1.07*	NA	NA		
No 10	US	1.47	*1.07*	NA	NA		
Newsprint							
No 5	Netherlands	*0.8*	1.45*	NA	NA		
No 5	Netherlands	*0.8*	0.3*	NA	NA		
Cardboard							
No 2	Norway	*0.89*	*1.06*	0.07	0.41		
Proposed average (Paper and cardboard)		0.7	1.1	0.07	0.4	1.1	1.2

* The higher figure for primary production in the Dutch study is for mechanical pulp, while the lower is for chemical pulp.

5.2 Glass

Four studies were selected for glass (Table 6). The Norwegian study indicates a small difference between secondary and primary production. One reason for this is that the data for primary production actually implies the use of 60% recycled raw material, which makes it less suitable for this project. With the exception of that study, only the Austrian study presents numbers for both secondary and primary production, while the other studies only present a comparison of the two production types. The larger differerence than in the EU-27 study, presented in the Austrian study, is then confirmed by a German study by Dehoust *et al.* (2010) that gives -0.47 CO_2-equivalent/kg materia.

Referring to greenhouse gas emissions from energy, Germany and Austria are more similar to the three studied countries than are the EU-27 average.[7] The average for secondary production is thus based on the Austrian study (supported by the German data for comparison), while the average for primary production is based on the Norwegian and Austrian studies.

Table 6. Analysed data for glass in kg CO_2-equivalent/kg material. Data used for calculating the proposed average is marked by italics. NA indicates that data is not available

Study no	Region	Secondary production (kg CO_2-eq./kg)	Primary production (kg CO_2-eq./kg)	Difference: secondary – primary (kg CO_2-eq./kg)
No 2	Norway	0.94	*0.90*	0.04
No 4	Austria	*0.54*	*0.92*	-0.39
No 6	EU-27	NA	NA	-0.18
Proposed average		0.5	0.9	-0.4

5.3 Plastics

For plastics, there are studies selected for Norway, Austria, the EU-27 and the US (Table 7). The figures for secondary and primary production vary considerably between types of plastic, but also between studies. For secondary production, there are large differences, even for the same types of plastic. Partly, this can be explained by assumptions related to

[7] The average EU-27 mix implies roughly 50% fossil fuels. In Austria, the share of fossil fuels is lower, between 20-30% (Frischenschlager *et al.*, 2010).

losses, which are typically assumed to be used to replace specific fossil fuels close to where the treatment is located.[8]

The Norwegian study from 2010 is based on specific data from treatment in Sweden, while the 2011 study is based on European average database data. These two studies assume that residues are used to replace production of heat/electricity at the place where the waste is treated, i.e. in Sweden and Germany/China, respectively.

The EU-27 study shows similar figures for all types of plastic, except PVC, which is slightly lower. The US study presents two figures, similar to each other, for the two types of plastic covered. The Austrian figures for secondary production of PET are considerably higher than the two other figures, and this divergence could not be explained on the basis of the documentation.

Removing this higher value from the Austrian study, avoiding the US studies, and selecting the Swedish treatment for Norway, the average for secondary production is the same as the only available figure for polyolefins, resulting in a value of 1.3 kg CO_2-equivalent/kg material for plastics in general. As emission differences between studies are of the same size as differences between various types of plastics, a general average is proposed.

For primary production the figures for polyolefins (PE and PP) and PVC are the lowest, while those for mixed plastic, PET and PS are higher. The average for primary production of plastics in general is based on the European studies, weighted according to the share of various plastic types.[9]

Three studies – the two for Norway and the one for the EU-27 – give similar figures for incineration of mixed plastics. The same studies present numbers for separate heat/electricity production, i.e. emissions that are avoided due to waste incineration. The Norwegian studies assume that the energy is used to replace Norwegian average heat. The EU-27 study recommends data based on replacing typical fuels in a cement kiln, while also presenting a number for replacing heat/electricity from natural gas and light fuel oil (in equal shares).

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8 In addition, there are some direct emissions from incineration of such losses.

9 The share of various types of plastic are taken from Prognos (2008), which indicate that about 60% is polyolefins (PE/PP) and the rest has an almost equal share of the rest (including "other polymers"). The share of PE/PP is of the same order of magnitude as in Lyng & Modahl (2011).

The figure closest to the average emissions from heat and electricity in the three studied countries is the Norwegian heat mix.[10] Thus, avoided emissions from separate energy supply are based on the Norwegian studies, while the emission figure for incineration is an average of all three studies.

Table 7. Analysed data for plastics in kg CO_2-equivalent/kg material. Data used for calculating the proposed average is marked by italics. NA indicates that data is not available

Material/ study no	Region	Secondary production (kg CO_2-eq./kg)	Primary production (kg CO_2-eq./kg)	Incineration (kg CO_2-eq./kg)	Separate energy (kg CO_2-eq./kg)	Recycling: secondary + energy (kg CO_2-eq./kg)	Incineration: incineration + primary (kg CO_2-eq./kg)
Polyolefins (PE/PP)							
No 8	USA	0.63	1.8	NA	NA		
No 6	EU-27	*1.3*	*1.5*	NA	NA		
PET							
No 4	Austria	2.69	*3.50*	NA	NA		
No 6	EU-27	*1.37*	*3.71*	NA	NA		
No 8	US	0.80	2.75	NA	NA		
PVC							
No 6	EU-27	*0.99*	*1.91*	NA	NA		
PS							
No 6	EU-27	*1.38*	*3.5*	NA	NA		
Mixed plastics							
No 1	Norway	1.88	*3*	*2.6*	*0.9*		
No 2	Norway	*1.33*	*2.81*	*2.89*	*0.88*		
No 6	EU-27	NA	NA	*2.89*	3.41		
Proposed average (plastics)		1.3	2.1	2.8	0.89	2.2	4.9

[10] Norwegian heat is based on about 15% fossil fuels, while heat and electricity mixes of the three studied countries involves about 20% and 10-15% fossil fuels, respectively.

5.4 Steel

The Austrian study has the clearest results for the different processes discussed here. The difference in emissions between secondary and primary production is dependent on which comparison is made (Table 8). The difference is larger if secondary production through an electric arc furnace is compared to primary production through a blast furnace. If secondary production is compared with primary production through variation of the scrap share in a blast furnace the difference is smaller. The proposed average for secondary production is just the Austrian figure for electric arc furnace. For primary production, it is the Austrian figure for blast furnace with 30% recycled material.

The other selected studies indicate results for secondary production lying in-between those values. It is suspected that these assume a mix of electric arc and blast furnace for secondary production.

Table 8. Analysed data for steel in kg CO_2-equivalent/kg material. Data used for calculating the proposed average is marked by italics. NA indicates that data is not available

Study no	Region	Secondary production (kg CO_2-eq./kg)	Primary production (kg CO_2-eq./kg)
No 2	Norway	0.11	1.56
No 4	Austria	1.89*	2.37
No 4	Austria	*0.32**	*2.37*
No 10	US	0.54	1.65
Proposed average		0.3	2.4

* The higher number for secondary production in the Austrian study is for blast furnace and the lower is for electric arc furnace.

5.5 Aluminium

The investigation resulted in three studies that were considered relevant for the project (Table 9). The EU-27 figures for secondary and primary production are a bit higher than the American figures, which in turn are higher than the Austrian ones. This can be explained by the fact that the energy mix assumed in the American study implies about 70% hydro power and 30% coal, which give smaller GHG emissions than the average EU-27 mix (see previous footnote). In Austria, the share of fossil fuels is even lower, between 20–30% (Frischenschlager *et al.*, 2010). The average for Norway, Denmark and Sweden is 10–15% (see Section 3.1). The Norwegian study does not separately elaborate on aluminium, but the underlying data for metal packaging indicate that the results for secondary production are similar to the American and Austrian studies, while the data

for primary production is close to the EU-27 study. The latter may be explained by the use of average European data from the Ecoinvent database.

The proposed value for secondary production of aluminium is the average of the US and Austrian figures, and for primary production it is the average of the US, Austrian and EU-27 figures. The recommendation for primary production is quite conservatively set, as discussed by McMillan and Keoleian (2009), who point out that most new primary capacity has been added in developing nations where the fossil share in the energy mix is higher. This emphasises the advantage of recycling the material.

Table 9. Analysed data for aluminium in kg CO_2-equivalent/kg material. Data used for calculating the proposed average is marked by italics. NA indicates that data is not available

Study no	Region	Secondary production (kg CO_2-eq./kg)	Primary production (kg CO_2-eq./kg)
No 4	Austria	*0.33*	*10.1*
No 6	EU-27	0.7	*11.8*
No 9	US & Canada	*0.46*	*11.1*
Proposed average		0.4	11.0

5.6 Organic waste

In this project, composting and anaerobic digestion are considered material recycling methods for organic waste. To be correct, the virgin material is not reproduced, which is different from the other materials analysed. Instead, it is the nutrient contents and the organic material that is recycled, and in the case of digestion, some of the energy is recovered through the production of biogas. The selected studies cover Norway and the EU-27 (Table 10), and the functional unit used here is the amount of organic waste treated. In this case, this amount is not equal to the amount of material produced.

The EU-27 study assumes that compost replaces primary "production and use of fertiliser and organic substance". Furthermore, it is assumed that 20% is used in agriculture after saturation, 40% for gardening or as substrate, and 40% as substrate for recultivation. In the Norwegian study 30% is assumed to replace peat and 60% are replacing fertiliser products. Both studies assumed that treatment functions as a sink for 24 and 20% of the carbon, respectively. This emission credit is larger in the EU-27 study, suggesting that the Norwegian data

is used as an estimate.[11] The carbon sink is subtracted from the figure for secondary production.

In the EU-27 study, when biogas and biofertiliser is produced from anaerobic digestion, these are assumed to replace average EU electricity, an EU heat mix[12] (50% natural gas, 50% light fuel oil) and organic substance. In the Norwegian study, it is assumed that the 72% of the biogas that is not flared is used to replace the Norwegian heat mix,[13] while the digestate is used to replace fertiliser. This number given for separate energy may be used for the approximation of the climate benefit of biogas in the three countries.[14]

In reality, Denmark has some biogas used also for electricity production, and Sweden has a large share of biogas upgraded to be used in vehicles. The Norwegian study indicates that the benefit is higher when using the biogas for vehicle fuel and lower for electricity production, where Nordic averages are concerned. As in the case with compost, a credit for the carbon sink, based on the same assumption, is subtracted from the figure for secondary production.

The Norwegian study also presents numbers for incineration and the avoided use of Norwegian heat. The Norwegian study is recommended as a conservative estimate for all data on composting and anaerobic digestion.

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[11] Although other studies point to even lower figures (Bruun *et al.* 2006).

[12] Here, 20% of the heat is assumed to be used externally.

[13] There are also other assumptions used in the report, involving substitution of electricity and diesel.

[14] This should not be confused with the separate energy that is needed in the recycling case, when comparing with waste incineration (cf. Figure 3).

Table 10. Analysed data for organic waste in kg CO_2-equivalent/kg treated waste. Data used for the proposed average is marked by italics. NA indicates that data is not available

Material/ study no	Region	Secondary production (kg CO_2-eq./kg)	Primary production (kg CO_2-eq./kg)	Incineration (kg CO_2-eq./kg)	Separate energy (kg CO_2-eq./kg)	Recycling: secondary + energy (kg CO_2-eq./kg)	Incineration: incineration + primary (kg CO_2-eq./kg)
Composting							
No 6	EU-27	0.035	0.095	NA	NA		
No 2	Norway	*0.051*	*0.070*	*0.075*	*0.063*		
Proposed average (composting)		*0.05*	*0.07*	*0.08*	*0.06*	*0.11*	*0.14*
Anaerobic digestion							
No 6	EU-27	-0.008	0.14	NA	NA		
No 2	Norway	*0.012*	*0.086*	*0.075*	*0.063*		
Proposed average (anaerobic digestion)		*0.01*	*0.09*	*0.08*	*0.06*	*0.07*	*0.16*

5.7 Collected results

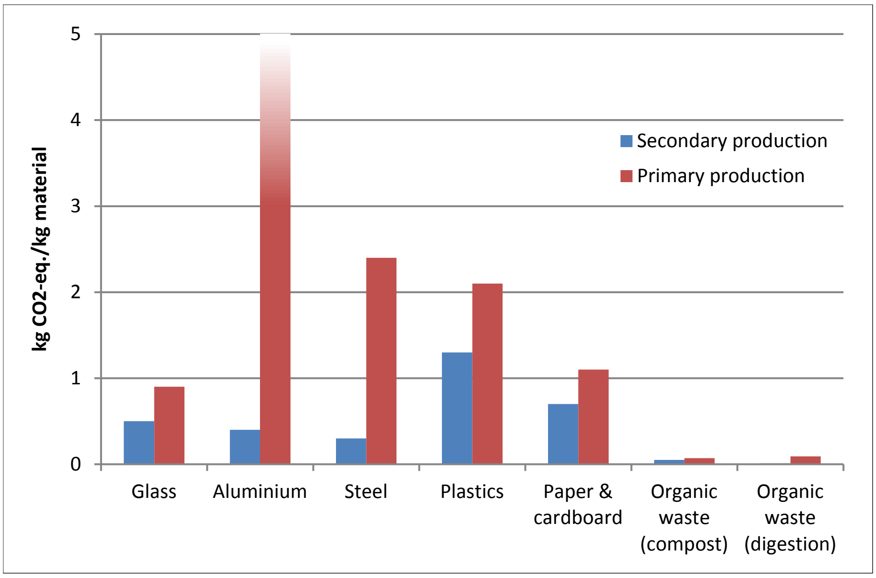
The proposed averages from Sections 5.1–5.6 are collated and illustrated below, and comparisons are made by calculating the difference (B-A), the ratio (A/B) and the percent variance (B-A/A) between the alternatives. The results of the first perspective of the project – the choice of material – are presented in Table 11 and Figure 6. The greenhouse gas emissions for secondary and primary production of each material are included.

The figure shows that the emissions from secondary production are lower than for primary production for all the materials analysed, and in many cases they are roughly halved. The difference, ratio and percent variance for each material (Table 11) can be interpreted as the climate benefit per kg of using recycled material instead of virgin material.

Table 11. Greenhouse gas emissions from secondary and primary production, and comparisons between secondary and primary production. The unit used is kg CO_2-equivalent/kg material, and the material output is assumed equal to the amount of treated waste (after losses), except for organic waste

Material	Secondary production (kg CO_2-eq./kg)	Primary production (kg CO_2-eq./kg)	Difference: secondary – primary (kg CO_2-eq./kg)	Ratio: primary/ secondary	Percent variance: secondary vs. Primary
Glass	0.5	0.9	-0.4	1.7	-41%
Aluminium	0.4	11.0	-10.6	28	-96%
Steel	0.3	2.4	-2.1	7.5	-87%
Plastics	1.3	2.1	-0.8	1.6	-37%
Paper and cardboard	0.7	1.1	-0.4	1.6	-37%
Organic waste (composting)	0.05	0.07	-0.02	1.4	-27%
Organic waste (digestion)	0.01	0.09	-0.07	7.4	-87%

Figure 6. Greenhouse gas emissions for secondary and primary production for all studied materials. Note that the result for primary production of aluminium is 11 kg CO_2-eq./kg material (outside the figure). Also, the basis for comparison for organic waste; 1 kg of treated waste, is not equal to the amount of material produced



The results of the second perspective of the project – the choice of recycling method – are presented in Table 12, and in Figure 7 (plastics and paper/cardboard) and Figure 8 (organic waste). The greenhouse gas emissions for secondary production complemented with separate energy supply – "the recycling alternative" – are compared here with "the incineration alternative", i.e. incineration with energy recovery complemented with primary production of materials.[15] Only the materials for which incineration is considered a realistic option are covered: plastics, paper and cardboard, and organic waste.

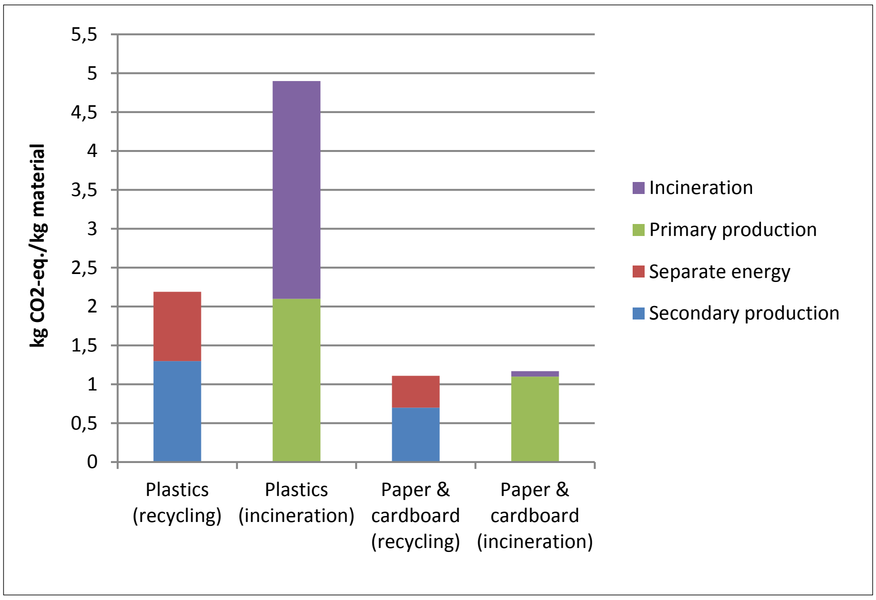
Figure 7 shows that the emissions are lower using the recycling alternative for both plastics and paper/cardboard, and for plastics they are roughly halved. The small difference for paper and cardboard is largely related to the assumed share of fossil energy.

Table 12. Greenhouse gas emissions from recycling (secondary production and separate energy) and incineration (incineration and primary production), and comparisons between recycling and incineration. The unit used is kg CO_2-equivalent/kg material, and the material output is assumed equal to the amount of treated waste (after losses), with the exception of organic waste

Material	Recycling: secondary + energy (kg CO_2-eq./kg)	Incineration: incineration + primary (kg CO_2-eq./kg)	Difference: recycling – incineration (kg CO_2-eq./kg)	Ratio: incineration/ recycling	Percent variance: recycling vs. incineration
Plastics	2.2	4.9	-2.7	2.2	-55%
Paper and cardboard	1.1	1.2	-0.1	1.1	-6%
Organic waste (composting)	0.11	0.14	-0.03	1.3	-21%
Organic waste (digestion)	0.07	0.16	-0.09	2.2	-54%

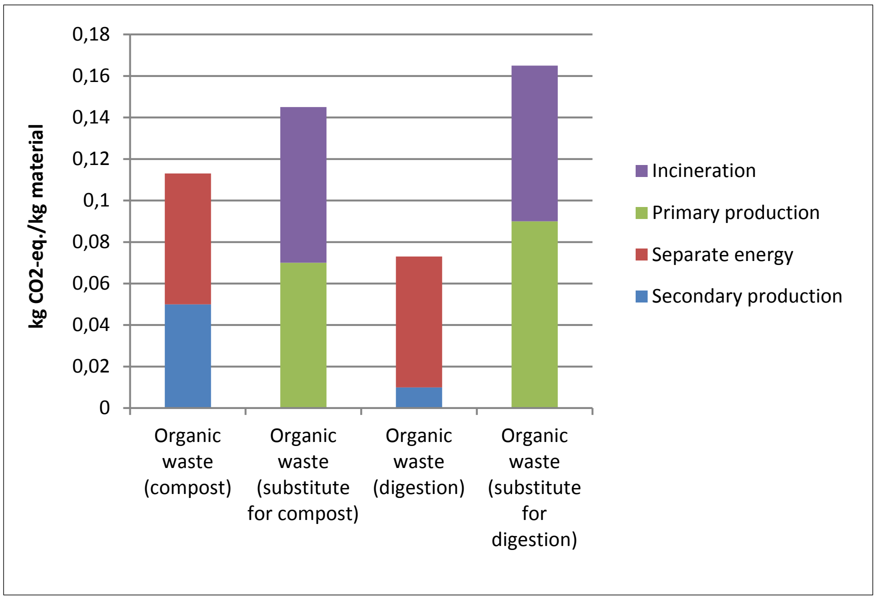
[15] As mentioned in Section 5.6, in the case of composting organic waste it is the nutrient contents and the organic material that is recycled, and in the case of digestion some of the energy is recovered in addition, through the production of biogas.

Figure 7. Greenhouse gas emissions from secondary production of plastics as well as paper and cardboard, complemented with a separate supply of energy (bars 1 and 3 from the left). These can be compared with emissions from incineration with energy recovery for the same amount of waste, complemented with primary material production (bars 2 and 4)



When it comes to organic waste (Figure 8), the first recycling alternative, composting, has 20% lower emissions than the incineration alternative, while the second recycling alternative, anaerobic digestion, has about half the emissions compared to the incineration alternative. The differences, ratios and percent variance between the recycling and the incineration alternatives (Table 12) can be interpreted as the climate benefit of material recycling compared to incineration. Further discussion of the collected results is offered in the following section.

Figure 8. Greenhouse gas emissions from composting and digestion of organic waste, complemented with a separate supply of energy (bar 1 and 3 from the left). These can be compared with emissions from incineration with energy recovery for the same amount of waste, complemented with primary production of fertiliser and organic substance, and when substituting digestion also with energy (bars 2 and 4)



6. Discussion

The discussion is divided into five parts that require separate elaboration: Comparison with previous recommendations (6.1), Impact of energy use and energy mix (6.2), Geographical differences (6.3), Quality of materials for secondary production (6.4), and Data availability and uncertainty (6.5).

6.1 Comparison with previous recommendations

The result of this project (Section 5) is in itself a review of existing data from selected sources. But since it concludes with new recommendations on consistent data to use, it is of some interest to compare these findings with previous documents that have been used for current recommendations. This comparison covers the following references:[16]

1. Miljöfördelar med återvunnet material som råvara, ÅtervinningsIndustrierna, 2002 (in Swedish) (Nordin, 2002).
2. Environmental benefits of recycling, WRAP 2006 (updated 2010) (WRAP, 2006; Michaud *et al.*, 2010).
3. Life Cycle Assessment of Energy from Solid Waste, SU & FOA, 2000 (Finnveden *et al.*, 2000).
4. Report on the Environmental Benefits of Recycling, Bureau of International Recycling (BIR), 2008 (Grimes *et al.*, 2008).

[16] Of these, only reference 4 lived up to the selection criteria of this project (Section 3.3). Henrysson & Goldmann (2007) is not included as it just refers to other studies, including reference 1–3.

Organic waste is not found in any of the references above, hence no comparison is possible. For glass and aluminium (Table 13) there is good correlation between this study and the listed studies. For glass there is a 50% difference, but given the uncertainties it is fair to say 0.4–0.6 kg CO_2-eq./kg material. For aluminium, source 4 reports a low figure (3.54) which is close to the low figure from source 1 (4.6) for the case when electricity is not included. All other sources report 10–12, i.e., good correlation given assumptions on electricity.

Table 13. Differences in greenhouse gas emissions between primary and secondary production (in kg CO_2-eq./kg material) presented in previous studies, as compared with the proposed averages in this report

Material	Previous studies (kg CO_2-eq./kg)	This report (kg CO_2-eq./kg)
Glass	0.6	0.4
Aluminium	3.54–12.4	10.6
Steel	0.94–1.3	2.1
Plastics	4.26–4.5	0.8
Paper and cardboard	0.0003–1.7	0.4

For the other materials in Table 13 there is a huge difference between this report and previous studies. For raw steel 1.3 kg CO_2-eq./kg material is reported by source 1 where the GHG emissions for primary production including electricity is 1.5 while the corresponding figure in this report is 2.4.[17] There is also a minor difference for secondary production (0.2 and 0.3). The explanation behind the differences calls for further investigation. The estimated shares of different recycling processes is probably an important factor, while the choice of electricity generation is not, since the European mix used in source 1 gives an equal contribution of 0.2 for primary and secondary production.

There is a problem in comparing mixed plastic since figures reported in Nordin (2002) are for polycarbonate (PC) while the figure reported here is for a mixed plastic fraction.

Concerning paper, one study (source 4) shows a very low value of just 0.0003. This comes from extremely low figures for both primary (0.17 ktonnes CO_2-eq./100 ktonnes) and secondary (0.14 ktonnes CO_2-eq./100 ktonnes) production. These figures are unrealistic. The figure reported from source 2 is impossible to detect from the report, making

[17] The even lower figure is from the 2006 version of the WRAP study as referred to by Henrysson & Goldmann (2007). In our review of both 2006 and 2010 version of the WRAP study this figure could not be extracted from the reports.

it impossible to trace the figure further. This is also the case for the figure from source 3, as cited by Henrysson & Goldmann (2007). Based on figures in source 3 we have managed to calculate a figure of 1.182 tonnes CO_2-eq./tonne newspaper. This figure is actually in line with what has been reported by some sources (1.3) but still considerably higher than in this report, which can possibly be traced back to the use of coal electricity data.

6.2 Impact of energy use and energy mix

Industrial processes use energy to be able to manufacture products. In environmental assessments both the quantity (how much) and quality (what type) is of importance. Quality does not mean exergy, but the environmental impact of one unit of energy. When assessing CO_2 equivalent emissions it is a matter of whether the energy is from renewable or fossil sources. The assessment made in this report is based on an attributional approach which e.g. means that electricity is produced from a mix of different sources. Other studies use a consequential approach with marginal production. From this follows that the share of electricity in the total energy supply for a process is of importance since some processes/materials will be more sensitive to the type of power generation than others. All these aspects will be addressed in this section.

Which primary and secondary processes have high energy demand for processing the materials?

Based on the materials in this study, high energy use (per unit mass) is found for primary production of metals and plastics. For these, the potential for energy saving is substantial. For both materials the secondary processes have a much lower energy demand. There is however some uncertainty as to relevant comparisons.

One method is to compare direct energy use for the processes. Another method is to re-calculate energy use to the use of primary energy resources. How to do that (assumptions on degrees of efficiency, system boundaries, whether embodied energy should be included or not, etc.) is not evident. But, when using primary energy, both nuclear power and coal condense power will burden the use of electricity. High energy demand per unit of weight is one thing, the difference between primary and secondary production is maybe more interesting.

As mentioned above the values for metals and plastics are good in this respect. For aluminium it is a known fact that about 95% of the energy input in primary production is saved by recycling. In fact plastic is almost as good with almost 90% energy saving for some types of plastic.

How is the relationship between renewable and fossil energy use for different materials?

In many cases there is a larger share of fossil energy, in particular for metals and plastics. Except for paper, where there is no difference in this respect between primary and secondary production. The comparison of LCI data is however complicated by the fact that the environmental impact from electricity use (assuming e.g. European mix) is agglomerated with process emissions from use of fuels. In datasets where electricity is separated it may consist a high share of the total energy use.

How is the relationship between the use of electricity and fuels for different materials?

To retrieve LCI data displaying electricity as energy input in addition to fuels is not easy without performing a more thorough study. To illustrate this, one may consider the case of paper: Newsprint, cardboard and corrugated cardboard are made from mechanical pulp, which uses more electricity than the chemical process. The mechanical process has high electricity use in the pulp process for refiners with 1,800–2,300 kWh/tonne pulp (Dahlroth, 1998; Skogssverige, 2014). In the chemical process the lignin is combusted in the recovery boiler producing high pressure steam used for electricity generation.

The use of electricity in a process using recycled fibre requires approximately 400 kWh/tonne (Dahlroth, 1998). This means that for paper and cardboard the use of electricity is high, both as a share of the total energy use and in relation to secondary production. Thus, there is also a risk that LCA results are largely affected by the assumed electricity mix and internal use of energy.[18]

By far the highest use of electricity per unit of weight is found for primary production of aluminium. The use of additional fuels may be of the same magnitude. Secondary production is not so energy intense.

[18] This is included in a sensitivity analysis in Raadal *et al.* (2010), which is partly used for the proposed average for secondary paper production (Section 5.1).

How to account for the use of waste energy from the processes in, for example, district heating?

This can be dealt with in many ways. One option is to neglect the existence of waste heat delivery, which means including related emissions but assuming no substitution of other fuels for the heat delivery. Another option is to subtract the energy input with the energy content in waste heat. A third option would be to include emissions but also include avoided emissions in district heating.

How to decide on avoided emissions is also a delicate issue. Depending on which alternative is applied the energy use may differ. The total energy use may be lower than the sum of fossil and renewable energy for a pulp and paper factory delivering waste heat to the district heating grid.

6.3 Geographical differences

The data for primary and secondary production are, as mentioned, predominantly based on North European data, and sometimes compared to North American data. This means that it is assumed that the primary and secondary production takes place in the countries where the waste is produced and the products are consumed.

With regards to the secondary production there is indeed a good amount of the materials being remanufactured locally. But when considering the sources of some of the primary materials (especially plastic and metals), a large proportion are produced in Asia and the BRIC countries, and due to the free market it might even be these countries' products that consitute the primary sources rather than those produced locally. This means that the low grid mix discussed in the chapter above might look very different for some of these products, since the grid mix in Asia and the BRIC countries is based to a large degree on coal.[19] This highlights that when looking at recycling of materials where the primary production has a large influx of energy, the proposed savings are conservatively set, and they may be considerably

[19] As an example McMillan and Keoleian (2009) found that the emission factor for aluminium from Europe fell from 12.6 to 8.31 kg CO_2/kg primary ingot from 1990 to 2005; in the same period the world average rose to 14.7 kg CO_2/kg. The main reason for this was that the Asian emission factor was 21.9 kg CO_2/kg primary ingot with almost no change in this 15 year period. The main reason for this huge difference is that the Asian grid mix is predominantly based on coal, which gives these large differences in the emission factor.

larger if the primary production takes place outside northern Europe. This underscores the importance of material recycling.

6.4 Quality of materials for secondary production

For the assessment of data for secondary production it is important to consider that the data are based on inherent assumptions of a certain minimum of purity of the material stream. This context should be kept in mind when using the values in this report. If the data are used, for example, in connection with industry off-cuttings then the material is very homogeneous and can be easily recycled due to its composition and purity being known. If on the other hand the data are to be used with municipal waste then it is important to consider the quality of the material. There might be substantial losses if pre-sorting of a mixed material is needed.

As an example Miranda *et al.* (2013) looked at the quality of recovered paper from commingled collection systems coming to a paper mill. Here it was found that there were still 15% contaminants in the paper waste, and this both made the recycling process problematic, and meant that the emission factor was considerably higher than expected.

The issue of quality is of course higher for materials that exists in a large number of different chemical and physical entities (plastics and paper fibre) which are hard to separate into specific fractions, compared to materials that can be remanufactured more easily even with some contaminations (glass and metals). Therefore the above data should also be seen as averages and the savings might be smaller or larger depending on the quality of the material for secondary production.

6.5 Data availability and uncertainty

The approach and the selection criteria used in this investigation results in the refusal of a large amount of studies and data from studies, as described earlier. In fact there is a lot of data available, but in a specific context relevant data is difficult to extract from existing studies (see e.g. Brogaard *et al.*, 2014). Common problems with data are that they are not well documented and that methodological choices make them unusable for the actual purpose. In some cases recalculations can be made, but this has only been done to a very limited extent in this project, due to the focus on published data.

The result is that data for only a few common materials can be recommended, including paper and cardboard, glass, plastics, steel, aluminium and organic waste. In addition, the selected studies could not be used to present separate data for various paper qualities, types of plastic, or a range of metals.

When the selection criteria are fulfilled, this kind of LCA data is still associated with some uncertainty, due to the variety of possible sources and how data is measured or calculated from information available to the analyst. For example, performance differs between processes with similar function, which is also due to how processes are managed. After all, life cycle data is typically not requested for other industrial purposes. Accordingly, it should be stressed that small differences between values are not relevant. The uncertainties related to the assumed framework conditions, technology efficiencies, material qualities, etc. associated with specific values in literature do not warrant very detailed comparisons. It would be desirable to work with value ranges, which possibly could be done in future studies with a larger number of relevant data sources for each figure.

7. Conclusions

This project emanates from a perceived need for environmental data that can be used for communication in the recycling industry active in Norway, Denmark and Sweden. Its purpose is to compare material recycling with virgin material production, thus involving both material supply and recycling systems in the analysis.

The method for estimating greenhouse gas emissions and potential climate impact is based on life cycle assessment (LCA). In the project, we review, assess and select data from previous studies that are relevant – on an over-arching level – for the region comprising these three countries.

The results can be used as indications of the average climate performance of selected and typical material recycling routes in Norway, Denmark and Sweden. They are intended to be used by companies, industry associations and policy makers in the communication of the present performance in this sector.

The results should, however, not be used to draw conclusions beyond the scope of the study. There are five types of limitations that are of particular importance to define the role of the results in a larger perspective, and that are highlighted in this report:

- The retrospective approach relates to the present state of the systems and is not suited to answering questions about any future potential to reduce the climate impact through increased material recycling, support upcoming investments or strategies.
- Greenhouse gas emissions and potential climate benefits together form only one part of the environmental performance of recycling systems. It is necessary to take other indicators into account, such as resource depletion, energy use, eutrophication and toxicity, in order to get the complete picture. This could, in turn, lead to other priorities.
- Our approach is based on the assumption that the materials collected for recycling can replace virgin materials, though with certain losses, and the results are representative for the existing system. The existence of alloys, composites, contaminations and other impurities imply limitations in the actual amounts that can be recycled, today and in the future.

- Working with averaged data, the results can be used to indicate the general performance of material recycling in Norway, Denmark and Sweden. This means that the data will typically not be appropriate for a specific context or scenario, due to divergence in systems, processes and how they are managed. Particularly, the environmental performance of supplied and replaced energy has a decisive impact on the results, and it differs between localities and also between methodological approaches.
- There is always uncertainty in LCA data, because of variations between data sources. This is due to the immaturity of processes and how they are managed, and the methods used to measure or calculate data.

In relation to both material supply and recycling systems, two perspectives are examined to analyse the climate benefit of current material recycling. The first perspective, comparing the supply of material to be used in new products, is based on emissions data for secondary and primary production. Data for recycled material, from secondary production, then includes emissions from collection and pre-treatment processes. Data for virgin material, from primary production, includes emissions from the upstream processes starting with raw material acquisition, and ending with a material that can be used in a production process. The emissions from secondary production are lower for all materials, implying that both the difference and the percent variance between secondary and primary production are negative.

The second perspective, comparing the choice of recycling method, requires an expanded system approach. To be able to compare different waste treatment processes it is important that functions are the same for the relevant alternatives related to a waste fraction. For the non-metal fractions investigated in this project material recycling and incineration are considered. To make the alternatives functionally equivalent, incineration with energy recovery is combined with primary production, while material recycling (secondary production) is combined with a separate energy supply. What can then be compared are the emissions from the treatment of an equal amount of waste and supply of energy. The emissions from the recycling alternative are lower for all materials, implying that both the difference and the percent variance between the recycling and the incineration alternatives are negative.

The presented results indicate the present overall performance of material recycling in Norway, Denmark and Sweden, when it comes to greenhouse gas emissions and climate benefits. Accordingly, the results should not be used to compare specific recycling routes or firms, they

should not be used to support large scale decisions regarding future developments, and conclusions should not be drawn for other environmental impacts. They can, however, be used by companies and industry associations to communicate the general climate benefits in annual reports and similar publications, and on web pages. They may also be used by public authorities and contribute to discussions on a societal level, as long as their average and historic nature are recognised.

Finally, this project points out that while there are many existing studies providing and reviewing greenhouse gases and other environmental data results, there is a lack of consistent overviews and guidelines for the selection of the most appropriate emissions data to be used in, for example, the Nordic countries. In other words, data exist, but they are often of poor quality or may be inappropriate for a specific context.

The primary contribution from this project is thus to provide an overview and offer a recommended dataset that may be used by the stakeholders. This offers transparency and better possibilities for comparison between studies, and a potential for more consistent conclusions in the future.

8. Further work

Given the results presented in this report and the limitations of this kind of study, there are several possibilities for further study concerning the environmental benefits of material recycling. When considering possible continuation it should be acknowledged that potential climate impact is only one of several environmental indicators, though one that has been given much attention in recent years. However, there are other issues that are important in relation to recycling systems, such as resource depletion, energy use, eutrophication and toxicity. The alternative paths are briefly described below.

Firstly, in this report, it is documented to what extent the investigated studies consider emissions other than greenhouse gases. Thus some of these studies may be used directly to analyse results for other impacts, and the selection process conducted in this project may also be helpful in such work. The limited availability of data recognised here will, however, be an even bigger problem in an expanded scope.

Secondly, there is also a need to generate new data in various ways, both for secondary and primary production. Further literature searches may find more specific studies on separate fractions and impact categories, and recalculations may open up the possible use of a larger share of the studies that are available. Furthermore, using available data in new modelling exercises or with existing software and databases could make better use of different studies in a certain contexts, such as for the Nordic countries.

Thirdly, considering the lack of data for specific contexts, there is a need to collect new primary data that can be used in future assessments. Such data collection could possibly be shaped by crucial issues agreed by stakeholders concerned with future decision-making related to materials and recycling, and the development of a circular economy.

Finally, there are a number of methodological issues that would merit further attention. For instance, the way residues and losses are treated, and how recycling rates and substitution factors are taken into account is not identical between studies, and sometimes it is even unclear. This problem is particularly apparent in the case of food waste, which is obviously not being reprocessed into food products, but nutrients and organic matter are recovered through composting, and with anaerobic digestion also energy can be utilised. Thus, there are several functions that can be used as a base for calculating recycling rates.

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Svensk sammanfattning

Det här projektet har sitt ursprung i ett av återvinningsbranschen upplevt behov av miljödata som kan användas för kommunikation i återvinningsindustrin i Norge, Danmark och Sverige. Syftet är att jämföra utsläpp av växthusgaser från materialåtervinning och jungfrulig produktion av material, vilket innebär att både materialförsörjning och återvinningssystem inkluderas i analysen. Metoden för att uppskatta utsläpp och potentiell klimatpåverkan baseras på livscykelanalys (LCA). Litteraturgranskningen baseras på vetenskapliga artiklar, rapporter från myndigheter och branschorganisationer, samt bidrag från intressenter involverade i projektet. Dessa intressenter utgjorde en referensgrupp som bistod processen på olika sätt.

Resultaten som presenteras i den här rapporten kan användas som indikationer på genomsnittliga klimatprestanda för utvalda och typiska kedjor för materialåtervinning i Norge, Danmark och Sverige. De är tänkta att användas av företag, branschorganisationer och offentliga aktörer för kommunikation av dagens prestanda inom sektorn. Resultaten ska däremot inte användas för att dra slutsatser bortom studiens omfattning. Det finns fem typer av begränsningar som är av särskild betydelse för att definiera vilken roll resultaten har i ett större perspektiv, och som belyses i rapporten:

- Det tillbakablickande perspektivet i projektet omfattar dagens system och är inte lämpligt att använda för att besvara frågor om framtida potential för minskad klimatpåverkan genom ökad materialåtervinning eller för att understödja kommande investeringar och strategier.
- Användning av medelvärdesdata innebär att resultaten kan användas för att indikera den generella prestandan för materialåtervinning i Danmark, Norge och Sverige. Detta betyder att siffrorna inte är användbara i varje enskilt fall eller scenario, beroende på skillnader i energisystem och processer, samt i hur de styrs.

- Växthusgaser och potentiell klimatnytta utgör tillsammans bara en del av miljöpresentandan för återvinningssystem. Det är nödvändigt att ta hänsyn till andra indikatorer, såsom utarmning av resurser, övergödning och toxicitet för att ge en fullständig bild. Det kan i sin tur leda till andra prioriteringar.
- Upplägget baseras på antagandet att material som samlas in för återvinning kan ersätta jungfruliga material, dock med vissa förluster, och resultaten är representativa för existerade system. Förekomsten av legeringar, kompositmaterial, föroreningar och andra orenheter innebär begränsningar av hur mycket som kan återvinnas, både idag och i framtiden.
- Det finns alltid osäkerheter i LCA-data på grund av variationer mellan datakällor. Detta beror i sin tur på hur processerna är utformade, hur de styrs, och vilka metoder som används för att mäta och beräkna data.

Som en följd av dessa begränsningar bör resultaten användas varsamt. I rapporten tillämpas två olika perspektiv med koppling till både materialförsörjning och återvinning, vilka undersöks för att analysera klimatnyttan med dagens materialåtervinning:

1. Val av material: Vilken är den förväntade klimatnyttan med att använda återvunnet material i nya produkter?
2. Val av återvinningsmetod: Vilken är den förväntade klimatnyttan med att avfall går till materialåtervinning?

Det första perspektivet är baserat på utsläppsdata för sekundärproduktion (materialåtervinning) och primärproduktion (jungfrulig produktion). De föreslagna medelvärdena visar att utsläppen från sekundärproduktion är lägre för alla material, vilket innebär att både differensen och den procentuella skillnaden mellan sekundär- och primärproduktion är negativ (Tabell S1).

Tabell S1. Utsläpp av växthusgaser från sekundär- och primärproduktion, samt jämförelser mellan sekundär- och primärproduktion. Enheten som används är kg CO_2-ekvivalenter/kg material, och mängden material ut antas vara lika med mängden behandlat avfall (efter förluster), förutom för organiskt avfall

Material	Sekundär-produktion (kg CO_2-ekv./kg)	Primär-produktion (kg CO_2-ekv./kg)	Differens: sekundär – primär (kg CO_2-ekv./kg)	Kvot: primär-/ sekundär-produktion	Procentuell skillnad: sekun-där-vs. primär-produktion
Glas	0,5	0,9	-0,4	1,7	-41%
Aluminium	0,4	11,0	-10,6	28	-96%
Stål	0,3	2,4	-2,1	7,5	-87%
Plast	1,3	2,1	-0,8	1,6	-37%
Papper och kartong	0,7	1,1	-0,4	1,6	-37%
Organiskt avfall (kompostering)*	0,05	0,07	-0,02	1,4	-27%
Organiskt avfall (rötning)*	0,01	0,09	-0,07	7,4	-87%

* För organiskt avfall är det näringsinnehåll och organiskt material som återvinns, och vid rötning utvinns även en del energi i form av biogas.

Det andra perspektivet, där val av återvinningsmetod jämförs, kräver en utvidgning av det analyserade systemet. I projektet jämförs ett återvinningsalternativ med ett förbränningsalternativ, för de material där det är relevant. Utsläpp från behandling av lika mängder avfall och energitillförsel beaktas; för att alternativen ska vara jämförbara kombineras förbränning (inklusive energiutvinning) med primärproduktion, medan materialåtervinning (sekundärproduktion) kombineras med separat energitillförsel. De föreslagna medelvärdena visar att utsläppen från återvinningsalternativet är lägre för alla material, vilket innebär att både differensen och den procentuella skillnaden mellan återvinnings- och förbränningsalternativen är negativ (Tabell S2).

Tabell S2. Utsläpp av växthusgaser från återvinning (sekundärproduktion och separat energitillförsel) och förbränning (förbränning och primärproduktion), samt jämförelser mellan återvinning och förbränning. Enheten som används är kg CO_2-ekvivalenter/kg material, och mängden material ut antas vara lika med mängden behandlat avfall (efter förluster), förutom för organiskt avfall

Material	Återvinning: sekundär + energi (kg CO_2-ekv./kg)	Förbränning: förbränning + primär (kg CO_2-ekv./kg)	Differens: återvinning – förbränning (kg CO_2-ekv./kg)	Kvot: Förbränning/återvinning	Procentuell skillnad: återvinning vs. förbränning
Plast	2,2	4,9	-2,7	2,2	-55%
Papper och kartong	1,1	1,2	-0,1	1,1	-6%
Organiskt avfall (kompostering)*	0,11	0,14	-0,03	1,3	-21%
Organiskt avfall (rötning)*	0,07	0,16	-0,09	2,2	-54%

* För organiskt avfall är det näringsinnehåll och organiskt material som återvinns, och vid rötning utvinns även en del energi i form av biogas.

Resultaten kan användas av företag och branschorganisationer för att kommunicera klimatnytta i årsrapporter och liknande publikationer, samt på webbsidor. De kan också användas av myndigheter och bidra till diskussioner på samhällsnivå, så länge det beaktas att det handlar om historiska medelvärden. Däremot kan resultaten inte användas för att jämföra specifika återvinningskedjor eller företag, och de ska inte användas för att understödja storskaliga beslut beträffande framtida utveckling av systemen.

Appendices

A. Rejected studies

The studies that include other impact categories than global warming potential are marked with colours in the table below. Red colour indicates that indicators for energy and/or water use are included, while green colour indicates the inclusion of one or several other LCA impact categories ("LCA" or "Full LCA" indicates that many impact categories are included). For convenience, studies not containing relevant data and studies of informal character are not included in the list.

	Title	Authors	Year	Origin	Region	Fractions	Indicators	Reason for not using the source
	Bilan du Recyclage 1999–2008	Gérard Gie, Laurence Haeusler, Arthur Kibongui Mougani	2010	L'ADEME	France	Cardboard packing, graphic papers, special and hygiene papers, PE, PET, glass, ferrous metals, aluminium, copper wire, lead	Greenhouse gases	Aggregated results
B)	Bilan du recyclage 2001–2010	Jérôme Betton	2012	L'ADEME	France	Ferrous metals, non-ferrous metals, paper, glass, plastic	Multiple	Aggregated results
	Carbon Balances and Energy Impacts of the Management of UK Wastes	Karen Fisher, Michael Collins, Simon Aumônier and Bob Gregory	2006	ERM, Golder Associates	UK	Paper/card, kitchen/food waste, green waste, agricultural crop waste, manure/slurry, other organics, wood, dense plastic, plastic film, textiles, ferrous metals, non-ferrous metals, silt/soil, minerals/aggregate	Greenhouse gases	Diverging functio-nal unit
A)	Carbon footprint of recycling systems	David Palm	2009	Master of Science Thesis, Department of Energy and Environment Division of Physical Re-source Theory CHALMERS UNIVERSITY OF TECHNOLOGY, Göteborg	Sweden	Glass, paper packaging, news-print, metals, plastics	Greenhouse gases, energy demand	Refer to other sources
A)	Climate Protection Potential in the Waste Management Sector	Guenter Dehoust, Doris Schueler	2010	Umweltbundesamt	Germany	Residual waste, bio and green waste, paper, board and cartons (PBC), glass, lightweight packag-ing (LWP), waste wood	Greenhouse gases (GG) and energy resources (CED fossil)	Diverging functio-nal unit
B)	Comparing Energy Use and Environmental Impacts of Recycling and Waste Incineration	Tyskeng & Finnveden	2010	KTH	Sweden	Paper, cardboard and newsprint, plastics, metal, glass	GHG emissions, acidifica-tion, eutrophication, photochemical ozone formation	Refer to other sources
	CO_2-kentallen afvalscheiding	J.H.B. (Jos) Benner, M.B.J. (Matthijs) Otten, L.M.L. (Lonne-ke) Wielders, J.T.W. (Jan) Vroon-hof	2007	Opgesteld voor Senter-Novem, Afdeling Uitvoering Afvalbeheer	Netherlands	Paper, organic waste, vegetable, fruit and garden waste, HDPE, PET, glass, textiles	Greenhouse gases	Language not available
	Energi- och miljömässiga skillna-der mellan materialåtervinning och energiutvinning av avfall – en litteratursammanställning	Tyskeng & Finnveden	2007					Refer to other sources, not available

	Title	Authors	Year	Origin	Region	Fractions	Indicators	Reason for not using the source
	Energy use and recovery in waste management and implications for accounting of greenhouse gases and global warming contributions	Fruergaard, Astrup & Ekvall	2009	DTU, IVL	Denmark, Sweden			Contains no data
	Environmental benefits of recycling – 2010 update – WRAP	Michaud, Farrant, Jan, Kjær & Bakas	2010	Waste & Resources Action Programme (WRAP)				Refer to other sources
B)	Environmental benefits of recycling – 2006 – WRAP	WRAP	2006	Waste & Resources Action Programme (WRAP)	UK	Paper and card, plastics, biopolymers, food and garden waste, wood, textiles	Full LCA	Refer to other sources, not available
	Evaluating waste incineration as treatment and energy recovery method from an environmental point of view	Profu	2004	Profu	Europe		Greenhouse gases	Contains no data
	Evaluation of life cycle inventory data for recycling systems	Brogaard, Damgaard, Jensen, Barlaz & Christensen	2013	DTU	US and Europe	Fibre materials, glass, plastics, steel, aluminium	Greenhouse gases	See original source from DTU
	Fastlæggelse af data for materialegenanvendelse til brug i CO_2-opgørelser	Wenzel & Brogaard	2011	Dakofa	Denmark	Paper, steel, aluminium, copper, glass, plastics	Greenhouse gases	See original source from DTU
	Greenhouse Gas Emissions and the Potential for Mitigation from Materials Management within OECD Countries	Evans, Brundage, Lizas, Kennedy, Nadkarni, Rowan & Freed	2012	OECD	Australia, Mexico, Slovenia, Germany		Greenhouse gases	Refer to other sources
A)	Hur skall hushållsavfallet tas om hand – Utvärdering av olika behandlingsmetoder	Sundqvist, Baky, Carlsson Reich, Eriksson & Granath	2002	IVL	Sweden	Organic waste, plastics, paper	Greenhouse gases, energy use	Older than 10 years
B)	LCA of a Swedish national policy proposal	Björklund & Finnveden	2007	KTH	Sweden	Multiple	Greenhouse gases, energy resources, eutrophication,…	Refer to other sources
A)	LCI_of 100% Postconsumer HDPE and_PET recycled resin from postconsumer containers and packaging	Franklin Associates	2010	The plastics division of the American chemistry council, APR, NAPCOR, PETRA	USA	PET, HDPE	Energy use, water use, greenhouse gases	Diverging energy mix

	Title	Authors	Year	Origin	Region	Fractions	Indicators	Reason for not using the source
B)	Life Cycle Assessment of consumer packaging for liquid food	Kristian Jelse, Elin Eriksson and Elin Einarson	2009	IVL Swedish Environmental Research Institute	Sweden		Greenhouse gases, acidification, eutrophication, energy use, water use, photo-oxidant formation	Diverging functional unit
B)	Life Cycle Assessment of consumer packaging for liquid food – Results for the Danish market	Elin Eriksson, Kristian Jelse, Elin Einarson & Tomas Ekvall	2009	IVL Swedish Environmental Research Institute	Denmark	Paperboard	LCA	Diverging functional unit
A)	Life cycle assessments of energy from solid waste part 1	Finnveden, Johansson, Lind & Moberg	2005	SU, FOA	Sweden	Food waste, newsprint, corrugated board, mixed cardboard, PE, PP, PS, PET, PVC	Greenhouse gases, energy use	Refer to other sources
B)	Life cycle assessments of energy from solid waste part 2	Moberg, Finnveden, Johansson & Lind	2005	SU, FOA	Sweden	PET, newspaper	Full LCA	Refer to other sources
B)	Life Cycle Assessments of Energy from Solid Waste, Life Cycle Assessments of Energy from Solid Waste – Appendix 6	Finnveden, Johansson, Lind & Moberg	2000	SU, FOA	Sweden	Food waste, newspaper, corrugated cardboard, mixed cardboard, PE, PP, PS, PET, PVC	Full LCA	Older than 10 years
B)	Life cycle assessment of waste management systems: Assessing technical externalities	Brogaard	2013	DTU	Denmark	Paper, glass, aluminium, steel, plastics	LCA	Refer to other sources
A)	Material recycling versus energy recovery of used beverage cartons	Hallberg & Ljungkvist	2013	IVL	Sweden	Beverage cartons	GHG emissions, energy resources	Diverging functional unit
A)	Miljöfördelar med återvunnet material som råvara	Nordin	2002	Återvinnings-industrierna	Sweden	Aluminium, polyethylene (HDPE), copper, polycarbonate, steel	Greenhouse gases and energy use	Older than 10 years
B)	Miljöpåverkan från avfall: underlag för avfallsprevention och förbättrad avfallshantering	Sundqvist & Palm	2010	IVL	Sweden		GHG emissions, acidification, eutrophication, photochemical ozone formation	Diverging functional unit
B)	Municipal solid waste management from a systems perspective				Sweden	Food waste, newsprint, corrugated cardboard, mixed cardboard, PE, PP, PS, PCV, PET	GHG emissions , acidification, eutrophication, photo-oxidant formation, NO_x, heavy metals	Diverging functional unit

	Title	Authors	Year	Origin	Region	Fractions	Indicators	Reason for not using the source
	Norsk Industri – klimanytte av gjenvinning	Bergfald & Co	2007	Norsk Industri			Greenhouse gases	Refer to other sources
B)	Paper waste – Recycling, incineration or landfilling – A review of existing life cycle assessments	Villanueva & Wenzel	2007	DTU	Denmark	Paper, cardboard	LCA	Refer to other sources
	Potensiale for økt materialgjenvinning av tekstilavfall	Laitala *et al.*	2012	Statens institutt for forbruksforskning	Norway	Textiles, Paper, cardboard and beverage cartons, metal, glass	Greenhouse gases	Only textiles
	Praktikable Klimaschutz-Potenziale in der Abfallwirtschaft	Prof. Dr.-Ing. Arnd I. Urban, Dipl.-Ing. Gerhard Halm	2010	Verein zur Förderung der Fachgebiete Siedlungswasserwirtschaft und Abfalltechnik an der Universität Kassel e.V.	Germany		Greenhouse gases	Aggregated results
	Protocol for the quantification of greenhouse gases emissions from waste management activities – Version 5	EpE	2013	EpE	international	Multiple	Greenhouse gases	Refer to other sources
	Recycling fuer den Klimaschutz	ALBA Group, Fraunhofer Institut	2011	Interseroh	Germany	Steel, aluminium, copper, paper, polyethylene (PE), polyethylenterephtalat (PET), wood	Greenhouse gases	Data origin unknown
	Solid Waste Management and Greenhouse Gases	U.S Environmental Protection Agency	2006	EPA	US	Multiple	Greenhouse gases	Diverging energy mix
	Supporting environmentally sound decisions for construction and demolition (C&D) waste management	Manfredi & Pant (eds)	2011	JRC	UK	Plastic, wood	Greenhouse gases	Aggregated results, refer to other sources
	Waste Management Options and Climate Change	Alison Smith, Keith Brown, Steve Ogilvie, Kathryn Rushton and Judith Bates	2001	Final report to the European Commission, DG Environment, AEA Technology	Europe	Paper, HDPE, PET, glass, ferrous metals, aluminium, textiles	Greenhouse gases	Older than 10 years
	Återvunnen råvara – en god affär för klimatet	Henryson, Goldmann	2007	Återvinnings-industrierna	Sweden	Aluminium, glass, copper, paper, plastics, steel	Greenhouse gases	Refer to other sources

A) indicates that indicators for energy and/or water use are included.
B) indicates the inclusion of one or several other LCA impact categories.

B. Provisional list of materials

Treatment alternatives pointed out by the reference group are marked by an "X". The table is written in Swedish as it has been part of a working process.

	Material-återvinning	Energi-utvinning	Rötning	Kompo-stering	Deponi
Metaller					
Järn och stål	X				
Koppar	X				
Aluminium	X				
Bly	X				
Nickel	X				
Nickel/krom-legeringar	X				
Mässing	X				
Zink	X				
Någon kritisk jordartsmetall	X				
Plast					
Plast	X				
Polykarbonat (kontruktionsplast)	X	X			
PET	X	X			
Lågdensitets-polyetylen (LDPE)	X	X			
Högdensitets-polyetylen (HDPE)	X	X			
Polystyren	X	X			
EPS-plast (frigolit)	X	X			
Polypropylen (PP)	X	X			
Polyvinylklorid (PVC)	X	X			
Polyetylentereftalat (PET)	X	X			
Papper					
Dryckeskartong	X	X			
Emballagekartong	X	X			
Tidningspapper	X	X			
Kontorspapper	X	X			
Wellpapp	X	X			
Avfall					
Organiskt avfall		X	X	X	
Matavfall från hushåll och verksamheter	X	X	X	X	
Våtorganiskt avfall från livsmedelsproduktion		X	X	X	
Trädgårds- och parkavfall					
GROT	X	X			
Glas					
Glasförpackningar	X				
Bilglas	X				
Övrigt glas	X				
Byggavfall					
Trä	X	X			
Gips	X				X
Asfalt					
Betong	X				X
Stenmaterial					
Jordar					

	Material-återvinning	Energi-utvinning	Rötning	Kompo-stering	Deponi
Restavfall					
Hushåll	X	X			
Verksamheter	X	X			
Bygg		X			
Övrigt					
Spillolja	X	X			
Gummi					
Textil	X	X			

C. Reference group

The people listed here were invited to discussions and meetings throughout the project, and were considered part of the reference group.

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- Ola Eriksson, University of Gävle.
- Karl Hillman, University of Gävle.
- Daniel Jonsson, University of Gävle.

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- Peter Andersson, General Plastics Scandinavia.
- Aurore Byström, Stena Recycling.
- Karin Comstedt Webb, Heidelberg Cement.
- Viveke Ihd, Återvinningsindustrierna.
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- Britt Sahleström, Återvinningsindustrierna.
- Camilla Slunge-Dowling, IL Recycling.

- Hans Säll, NCC.
- Cecilia Våg, Stena Recycling.
- Magdalena Westerberg, SITA.

Norsk Industri & Norsk Returmetallforening

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Climate Benefits of Material Recycling

The purpose of this project is to compare emissions of greenhouse gases from material recycling with those from virgin material production, both from a material supply perspective and from a recycling system perspective. The method for estimating emissions and climate benefits is based on a review, followed by a selection, of the most relevant publications on life cycle assessment (LCA) of materials for use in Denmark, Norway and Sweden. The proposed averages show that emissions from material recycling are lower in both perspectives, comparing either material supply or complete recycling systems. The results can be used by companies and industry associations in Denmark, Norway and Sweden to communicate the current climate benefits of material recycling in general. They may also contribute to discussions on a societal level, as long as their average and historic nature is recognised.

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