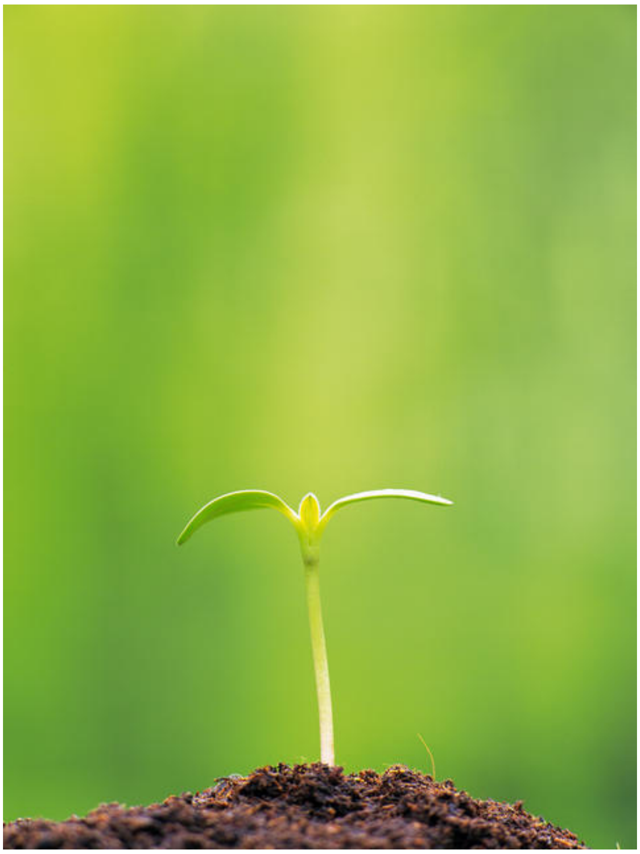
Material change for a better environment

Final report

Environmental benefits of recycling – 2010 update



An update to the 2006 WRAP report *Environmental Benefits of Recycling*, reviewing high quality Life Cycle Assessments from around the world to assess the impact of alternative waste management options for a range of materials, and discuss the findings for each material in the context of the UK.

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Executive summary

Context

In 2006, WRAP (Waste & Resources Action Programme) published a major research report, Environmental Benefits of Recycling, based on an international review of life cycle analyses (LCA) that evaluated the impact on the environment of recycling, landfilling or incineration of key materials in UK waste streams. The review assessed 55 'state of the art' LCAs on paper and cardboard, glass, plastics, aluminium, steel, wood and aggregates. The conclusion was clear – most studies show that recycling offers more environmental benefits and lower environmental impacts than the other waste management options.

With the emergence of new waste management options and new waste streams in the last three years, WRAP has decided to update this report and ensure that policy makers and stakeholders are aware of the latest conclusions from LCA data on waste management options. The methodology behind the new report remains the same[1] – careful screening of over 200 LCAs published worldwide since 2006 against strict criteria to focus on only the highest quality analyses. However, the scope of the review was changed in several ways:

- New waste management technologies were added: composting and energy from waste (EfW) technologies such as anaerobic digestion, pyrolysis and gasification.
- New waste streams/materials were added: food waste, garden waste, textiles and biopolymers.
- Some materials were excluded from further analyses – aluminium, steel, glass and aggregates – as the results of the first study (that recycling is the preferred waste management option for these materials) are not impacted by the new technologies.

In summary, the material / technology combinations of this study are shown in the following table (those included in the first report are highlighted in grey)

	Recycling	Composting	Incineration	Landfill	Anaerobic digestion	Pyrolysis	Gasification
Paper and card	x		x	x			
Plastics	x		x	x		x	
Biopolymers	x	x	x	x	x		
Food and garden waste		x	x	x	x		
Wood	x		x	x			
Textiles	x		x	x			

The key impact categories used for the assessment of the different waste management options were:

- depletion of natural resources
- climate change potential
- cumulative energy demand
- water consumption

[1] The criteria used for the selection were: (i) the study had to be an LCA or LCA-like; (ii) includes a comparison of two or more end-of-life scenarios for the material fraction under study; (iii) representation of recycling or composting among the waste management options assessed; (iv) robustness of the publication, either peer reviewed or published in a scientific journal; (v) transparency in the assumptions made; (vi) primary research and not a review of previous work; (vii) no ambiguity in the way impacts are ascribed to materials; (viii) plausibility of the waste management options.

Key conclusions from the LCA studies

Because of the international nature of the study, the review has attempted to interpret the results in terms of UK impact. The key parameter in this respect in the energy mix used in the scope of a specific LCA, which might be quite different from that in the UK. The key conclusions are outlined below by material/waste type.

Paper and cardboard

- The results of the first study are confirmed in that landfilling of paper and cardboard is the least preferable option, particularly from a climate change potential and energy demand perspective.
- The comparison between recycling and incineration appears more complex, as better energy recovery efficiencies have been built into the more recent LCAs. In general, the data shows that recycling is preferable for energy demand and water consumption, but they are comparable for climate change.
- The key parameter affecting the comparison between these two alternatives is the energy mix used in recycling and virgin paper manufacture. Where the energy recovered through incineration replaces the use of fossil fuels (as in the UK), the environmental benefits are augmented, especially with regard to climate change potential and depletion of natural resources.
- The type of paper and card also has a significant influence. For example, it is more beneficial from an environmental point of view to recycle high quality products such as office paper.
- Looking to the future, as the UK moves to a lower-carbon energy mix, collection quality improves and recycling technology develops, then recycling will become increasingly favoured over energy recovery for all impact categories

Plastics

- The results confirm that mechanical recycling is the best waste management option in respect of the climate change potential, depletion of natural resources and energy demand impacts. The analysis highlights again that these benefits of recycling are mainly achieved by avoiding production of virgin plastics.
- The environmental benefits are maximised by collection of good quality material (to limit the rejected fraction) and by replacement of virgin plastics on a high ratio (1 to 1).
- Incineration with energy recovery performs poorly with respect to climate change impact, but pyrolysis appears to be an emerging option regarding all indicators assessed, though this was only analysed in two LCA studies.
- Landfill is confirmed as having the worst environmental impacts in the majority of cases.
- As the UK moves to a lower-carbon energy mix, recycling will become increasingly favoured.

Biopolymers

- Although biopolymers are only just emerging in the various waste streams, the limited data shows the good environmental performances of mechanical and chemical recycling regarding energy demand, depletion of natural resources and climate change potential.
- However, for LCA studies that did not consider recycling as an option in the analysis, the data shows that incineration is a preferred option.
- A main advantage of biopolymers that is often highlighted is the fact that some of them are degradable or compostable. Nevertheless, the analysis pointed out that composting does not appear to be advantageous for energy demand and depletion of natural resources compared to the other alternatives.
- Two studies also assessed anaerobic digestion. The results for these scenarios showed that anaerobic digestion performs better than composting regarding both indicators analysed: climate change potential and energy demand. The advantage of anaerobic digestion over composting comes from the recovery of the biogas produced via electricity and heat production.

Food & garden waste

- Anaerobic digestion probably qualifies as the most preferable option, especially for climate change potential and depletion of natural resources. However, this conclusion should be qualified by the fact that this option was included in less than half of the selected studies.
- Composting brings benefits as a result of the compost that can be used as a substitute for products such as peat or fertilisers. However, as composting is not associated with energy recovery, it generally does not perform well compared to the other options for depletion of natural resources and energy demand.

- Following anaerobic digestion; composting and energy recovery are generally comparable in their contribution to climate change potential.
- The analysis also highlighted that home compost bins should be properly managed (aerated and with a mix of input materials) to avoid anaerobic conditions forming, leading to methane emissions.
- Incineration with energy recovery presents another good environmental performance for the four indicators, despite the relatively low heating value. The key parameter, especially regarding climate change potential, is the energy mix. The benefits brought by incineration are greater if the energy produced substitutes fossil energies.

Wood

- Based on the lack of published LCAs, recycling of wood waste has been given little attention by LCA practitioners. As a result, a comparative analysis between the waste management options for wood waste could not be conducted.
- However, from the data available, the key conclusion is that incineration with energy recovery is preferable for energy demand while recycling is preferable for climate change potential. On the other hand, landfill is to be avoided due to the associated methane emissions. Analysis of a larger set of indicators would be required in order to be able to come up with reliable evidence of the benefits of wood recycling.

Textiles

- There is a large gap in terms of LCAs conducted over the waste management options for textiles. Of interest is that no study has been found assessing ‘closed-loop’ recycling, whereby recycled fibres are used in the manufacture of new clothing.
- Despite this lack of data, four studies were reviewed to provide a qualitative comparison of the environmental impacts of different options. The overall conclusion is that textile recycling brings substantial environmental benefits. The scale of the benefits mainly depends on the recovery routes and the material production that is avoided.

General conclusion and recommendations

This report reinforces the key conclusion of the first report that recycling of paper/cardboard, plastics and biopolymers for most indicators assessed provides more environmental benefits than other waste management options. For wood and textiles, more studies are needed to be able to make firmer conclusions regarding the environmental benefits of recycling for these materials.

It is disappointing to note that there are very few LCAs which include an assessment of more innovative technologies such as gasification, pyrolysis and anaerobic digestion. This probably reflects the requirement for a lot of process data to model a particular option, which can be sparse in the case of the newer technologies. However, the results of the few selected studies that included anaerobic digestion and pyrolysis are very encouraging.

There needs to be a stronger evidence base on certain materials (textiles, biopolymers and wood) and the more innovative EfW technologies. LCA studies need to focus on a larger set of indicators rather than only on climate change potential or energy demand. There are also LCA methodological issues that need clarification, such as the treatment of biogenic carbon and the time period considered for landfill impacts; greater clarity on these matters will help in the comparison of waste management options.

Contents

1.0 Introduction

From the point of view of sustainable development, improving waste management is essential if society's environmental impacts are to be reduced. Identifying waste management channels with lower environmental impacts is thus a key issue. The waste hierarchy illustrated in Figure 1 is often used as a rule of thumb followed by public policies. However, a recurring theme in the debates that surround waste and resources management is the extent to which the recycling of materials offers genuine benefits to the environment. Often, critics of the policy drive towards greater recycling assert that the act of recycling may in fact have little or no benefit to the environment, suggesting that more energy may be used in getting materials to the recycling facility than is saved by the process of recycling.

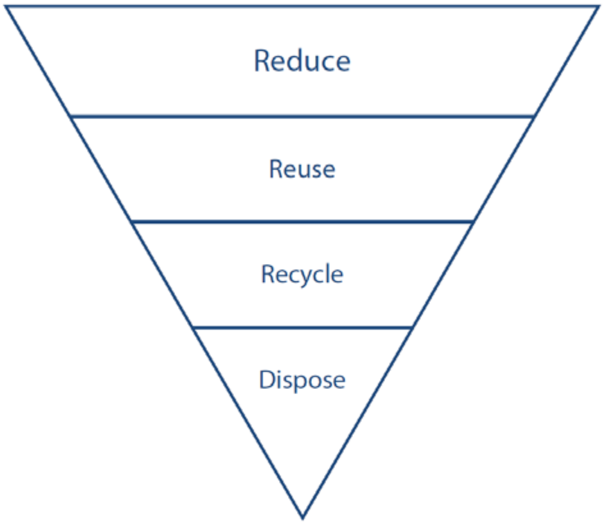

Figure 1 Schematic diagram showing the waste hierarchy

In order to compare waste management routes in environmental terms, the Life Cycle Assessment (LCA) methodology is currently seen as the best approach to use. The strength of LCA is that the methodology allows comparison of two or more different products or processes by quantifying the service given by the products or processes. The weakness of LCA is that the results of the assessment are very sensitive to the scope of the study, to the hypothesis made, etc. To compare environmental impacts of numerous waste management routes, one solution is to review and compare existing Life Cycle Assessment (LCA) studies on waste management and to analyse the impacts of each hypothesis.

To analyse the different burdens or benefits of each waste management option, WRAP (Waste & Resources Action Programme) reviews and commissions relevant LCAs. The purpose of this study is to update the *Environmental Benefits of Recycling* published by the WRAP in 2006. This study reviews LCA studies and compares the various possible options for waste management. This study was undertaken by Bio Intelligence Service (BIOIS) and the Copenhagen Resource Institute (CRI, former Danish Topic Centre on Waste and Resources). Collaboration with WRAP took place throughout the study.

Materials covered by this study are paper and cardboard, plastics, biopolymers, food and garden waste, wood and textiles. The waste management options that are studied are composting, energy recovery (incineration, anaerobic digestion, pyrolysis and gasification), landfill and recycling. Table 1 shows the combinations of materials and treatment options covered in the study (the combinations materials/disposal options included in the previous edition are highlighted in grey). Some options, such as gasification or pyrolysis, could in theory be used for most of the fractions but the literature review has pointed out large data gaps, therefore these options could not be assessed.

Table 1 Overview of the materials and treatment options under study

	Recycling	Composting	Incineration	Landfill	Anaerobic digestion	Pyrolysis	Gasification
Paper and card	x		x	x			
Plastics	x		x	x		x	
Biopolymers	x	x	x	x	x		
Food and garden waste		x	x	x	x		
Wood	x		x	x			
Textiles	x		x	x			

2.0 Methodology for the selection and assessment of LCA studies

2.1 Literature review

The main objective of this step was to identify all published LCA studies that compare two or more waste management options for one or more fractions included in the field of this review.

An exhaustive review of LCA publications was carried out using the following sources of information:

- International scientific journals and databases: International Journal of LCA, Science Direct, Springer
- Publications by relevant worldwide organisations in waste management and life cycle assessment: National Environment Protection Agencies, European Joint Research Center (JRC), DEFRA, WRAP
- BIOIS and CRI's own databases
- BIOIS and CRI's contact network

The extensive literature review led to the identification of around 220 studies.

2.2 Publications selection criteria

In order to be able to choose the publications suitable and relevant for analysis, a list of selection criteria was established. The objective was to narrow the selection to transparent and high-quality studies.

The criteria used for the selection were:

- the study was an LCA or LCA-like study
- the study included a comparison of one or more end-of-life scenarios for the material fraction under study
- representation of recycling or composting among the waste management options assessed,
- robustness of the publication: the publication should have been either peer reviewed or published in a scientific journal
- transparency in the assumptions made
- primary research and not a review of previous work
- no ambiguity in the way impacts are ascribed to materials
- plausibility of the waste management options

Further details regarding these selection criteria are given below.

2.2.1 The study was an LCA or LCA-like study

The choice was made to focus on LCA studies because LCA is currently considered as the most reliable method for analysing the environmental impacts of products and services. One of the main advantages of LCA is that it enables a quantitative evaluation of potential environmental impacts on several indicators. The LCA methodology has been standardised by the International Standards Organization (ISO) (ISO 14040 and 14044 standards).

Within the requirements of ISO 14040 and 14044, the LCA must consist of the following steps:

- **Goal and scope definition** which defines the goal and intended use of the LCA, and scopes the assessment concerning system boundaries, function and flow, required data quality, technology and assessment parameters,
- **Inventory analysis** which consists in collecting data on inputs (resources and intermediate products) and outputs (emissions, wastes) for all the processes in the product system.
- **Impact assessment**, phase during which inventory data on inputs and outputs are translated into indicators of potential impacts on the environment, on human health, and on the availability of natural resources.
- **Interpretation of results** where the results of the LCI and LCIA are interpreted according to the goal of the study and where sensitivity and uncertainty analysis are performed to qualify the results and the conclusions.

In addition, the ISO standards require that LCAs disclosed to the public are submitted to a critical review performed by independent LCA experts to ensure that the methods and results are scientifically and technically valid. The fulfilment of the ISO standards is thus a guarantee for quality and transparency. Except for some studies published by recognised organisations (US EPA for example), the fulfilment of the ISO 14040-series was required for the publication selection.

2.2.2 The study included a comparison of two or more end-of-life scenarios for the material under study

In order to be able to conduct a comparison between various end-of-life scenarios, the systems compared must have the same functional unit and equivalent system boundaries, data quality and impact assessment methodologies. In practice, it is thus very difficult to compare LCA results for scenarios from different studies. In the present study, the choice has thus been made to conduct numerical comparisons only for scenarios analysed in a single publication. This implies that each selected study must include a comparison between at least two end-of-life options for a given fraction. **This criterion was the most restrictive one and some studies of high quality and interest had to be excluded with respect to this criterion. Nevertheless, it ensured the overall coherence of the study.**

2.2.3 Transparency in the assumptions made

The variability of the results from one LCA study to another is often very high since results are highly dependent on the assumptions made. It is also common for studies on similar systems to lead to different conclusions. When conducting comparisons across various studies, it is therefore essential to be able to identify the key parameters that can explain why conclusions differ from one study to another. The transparency of the assumptions made was thus considered as an important criterion for the publications selection step. Most identified studies satisfied this criterion fully but a lack of information in this area was sometimes observed when the study was only reported in a journal article without an associated report. Requests were made to authors for further information but this was very difficult obtain, in particular for studies over two years old.

2.2.4 No ambiguity in the way impacts are ascribed to materials

The objective of the study was to come up with an evaluation of the environmentally preferable end-of-life options for the range of considered fractions. The selected LCAs were thus required to present material-specific results. High quality LCAs comparing end-of-life options for municipal solid waste as a whole were therefore not suitable for selection.

2.2.5 *Plausibility of the waste management options*

As this report aims to provide support for decision making regarding the advantages and disadvantages of different waste management options for different products and materials, the options covered by the scope of the study are current common options in the UK as well as options that can potentially be developed on a large scale in the near future. Because of this, prospective scenarios unlikely to be significantly developed have not been considered.

2.3 Analysis of the selected studies

It should first be noted that the restricting criteria chosen for the publication selection led to difficulties in finding an adequate number of publications fulfilling these criteria for wood and textiles wastes. The number of publications that were reviewed and finally selected for detailed analysis for each material is reported in Table 2. The number of scenarios associated with the selected publication is also presented, a scenario being defined as a coupled material/waste treatment option.

Table 2 Overview of the number of selected publications for each fraction

Material	Number of evaluated studies	Number of selected studies	Number of scenarios identified
Food and garden waste	37	7	26
Paper and card	22	5	45
Biopolymers	29	7	36
Plastics	28	8	59
Textiles	31	/	/
Wood	19	/	/

The choice of the impact categories used for the assessment of the different end-of-life alternatives was established based on the indicators of main interest identified by WRAP, namely:

- depletion of natural resources
- climate change
- cumulative energy demand; and
- water consumption.

The climate change potential and energy demand were the most represented indicators among the selected studies. Almost all LCAs analysed included these two indicators. Depletion of natural resources was also included relatively often while on the contrary the water consumption indicator was rarely taken into account in the LCAs selected for the study.

Once the scenarios of interest had been identified within each study, the first step of the analysis of the studies was to identify the system boundaries and the main assumptions. For each study a table has thus been established presenting the scenarios, as given in the Appendices. Based on this information, a comparative analysis of the various end-of-life options could be conducted. The following chapter deals with the outcome from this comparative analysis for each material. The first two materials studied are the ones that were included in the previous edition in 2006, i.e. paper/cardboard and plastics. The next sections deal with biopolymers and food/garden waste. To finish, the two last sections focus on textile and wood waste, for which the analysis conducted is not as detailed as for the other fractions, due to a lack of published LCAs for these materials.

It must be highlighted that LCAs are carried out differently depending on the objective of the study, the systems under study, the data available and so on. All these parameters influence the choice of assumptions and of the modelling approach and eventually the results. This explains why results can differ widely from one LCA to another without the quality of the studies being at stake. This specificity of each LCA also means that value judgments cannot be made about the way the LCA has been performed (choice of system boundaries, use of substitute data, attributional or consequential approach, etc.).

3.0 Results of the comparative analysis of the selected publications

3.1 Introduction to the methodology used for results comparison

Throughout this section, results are presented by material for the four indicators previously listed that are considered to be of major concern. Other indicators, i.e. acidification, photochemical oxidation, eutrophication and toxicity, were also looked at but in a less detailed manner.

For comparability reasons, the end-of-life options have been compared to each other within one study. The system boundaries and assumptions are too different between studies to be able to calculate differences between alternatives across studies. For example, if study no X analyses two types of biopolymers, e.g. PLA and Mater-Bi, the various end-of-life alternatives for PLA are grouped under Case X[PLA] and the ones for Mater-Bi under Case X[MB]. If two end-of-life alternatives are compared for PLA and Mater-Bi, the study is then composed of two cases containing two scenarios each. A detailed description of each case and the results of each scenario are provided in the relevant Appendix.

In the graphs used to compare the various scenarios, the results are presented in terms of relative difference between the options being compared. For example, if composting is used as the reference, the relative difference calculation is as follows:

(Impact from end-of-life option A – Impact from composting)/ Impact from composting

A negative value on the scale means that the results for composting cause more environmental impact than the other end-of-life option. On the graphs, the size of the bubble is proportional to the number of scenarios coming up with a value within the same range as another as illustrated in the figure below. The scenarios coming up with values under -150% or above +150% are placed on the same line at both ends. This type of graph allows for some global trends to be discerned but does not enable the associated scenarios to be identified. The detailed results for the different scenarios are presented in tables.

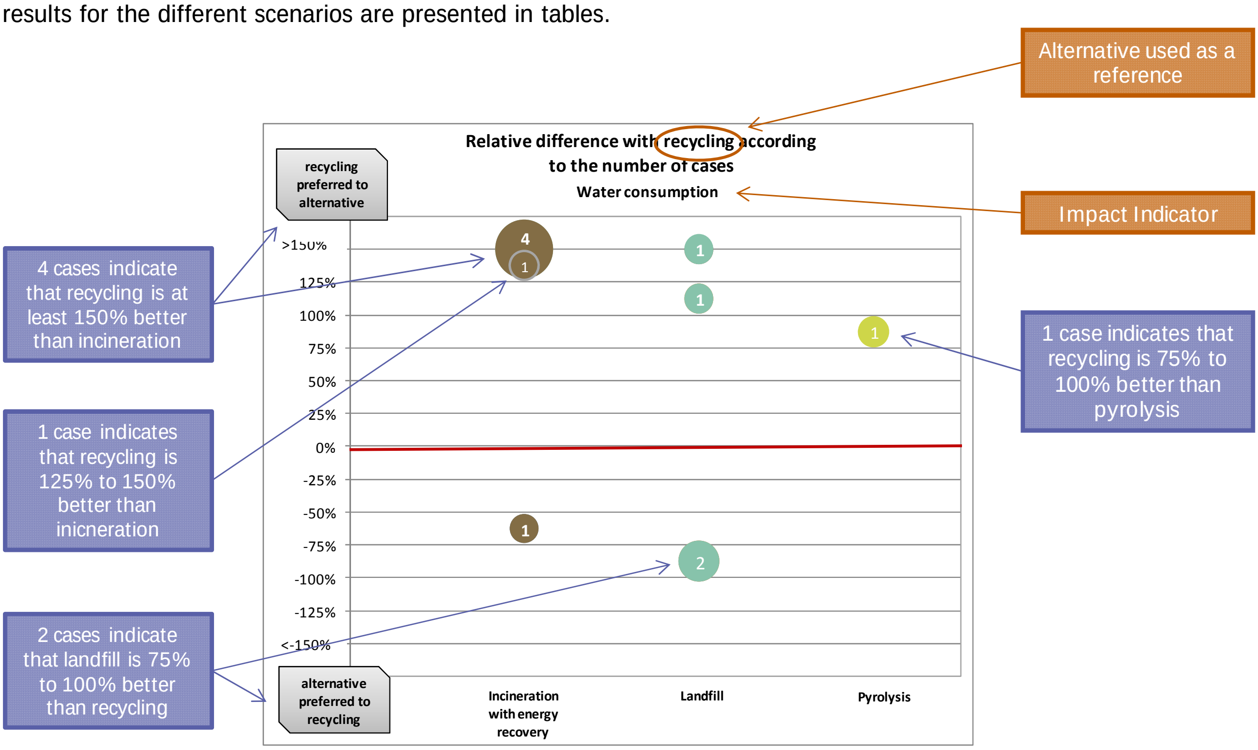

Figure 2 Guidance for reading the graphs used for the comparative analysis

3.2 Paper and cardboard

3.2.1 Presentation

The paper fraction is among the most important materials in Municipal Sold Waste (MSW) in terms of quantity, comprising approximately 20-25% of municipal waste generated in Europe (the UK does not report generation composition for municipal solid waste). However, paper waste is quite a diverse fraction as it consists of many materials, from cardboard to kitchen and bathroom towels. Each sub-material possesses different characteristics. Properties such as the heating value and the quality of the fibres are of specific importance for waste management as they can influence the LCA results greatly. The differences are greater between the two main types: paper and cardboard. In the presented studies, certain types of printed paper and cardboard are examined.

Traditionally, paper has been a very well investigated fraction as its recycling does not require high-technology applications. The recycling of paper, therefore, began quite early in the EU compared to other MSW fractions. The possibilities for paper waste management cover a wide spectrum of technologies, but by far the most dominant options are recycling, incineration with energy recovery and landfill. Consequently, the LCA studies that focus on paper mostly examine those three alternatives. Moreover, since the technological developments in paper treatment are slow, there has been little focus on paper LCAs recently. Few studies have been released since the previous WRAP review. These are presented in Table 3. It can be noted that study no 2 is relatively old but, as it is a quite a comprehensive study that was not covered in the previous report edition, it has been included here.

Table 3 Presentation of the selected studies

Study number	Title	Main author	Year	Geographical scope
1	Environmental Assessment of Paper Waste Management Options by Means of LCA Methodology	Arena	2004	Italy
2	Life cycle assessment of energy from solid waste	Finnveden	2000	Sweden
3	Analyse du Cycle de Vie comparative de différents modes d'adressage pour magazines et imprimés *(Comparative Life Cycle Assessment of differents ways of mailing magazines and printed matters)*	BIOIS	2007	France
4	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks	EPA	2006	USA
5	Klimaregnskap for avfallshåndtering *(Climate accounting for waste management)*	Raandal	2009	Norway

In addition to these five studies, an interesting Australian study dealing with composting entitled 'Life Cycle Inventory and Life Cycle Assessment for Window Composting Systems' (ROU, 2007) was identified. Unfortunately, it could not be analysed further as it does not include any comparison between different treatment options.

Each LCA study has to clearly define the boundaries of the system under analysis, which implies certain differences among the studies dependent on their goal and scope, as well as in their main assumptions, which are affected by the particularities of each case. A general system diagram is presented in figure 3 showing the usual processes involved in a paper waste management system:

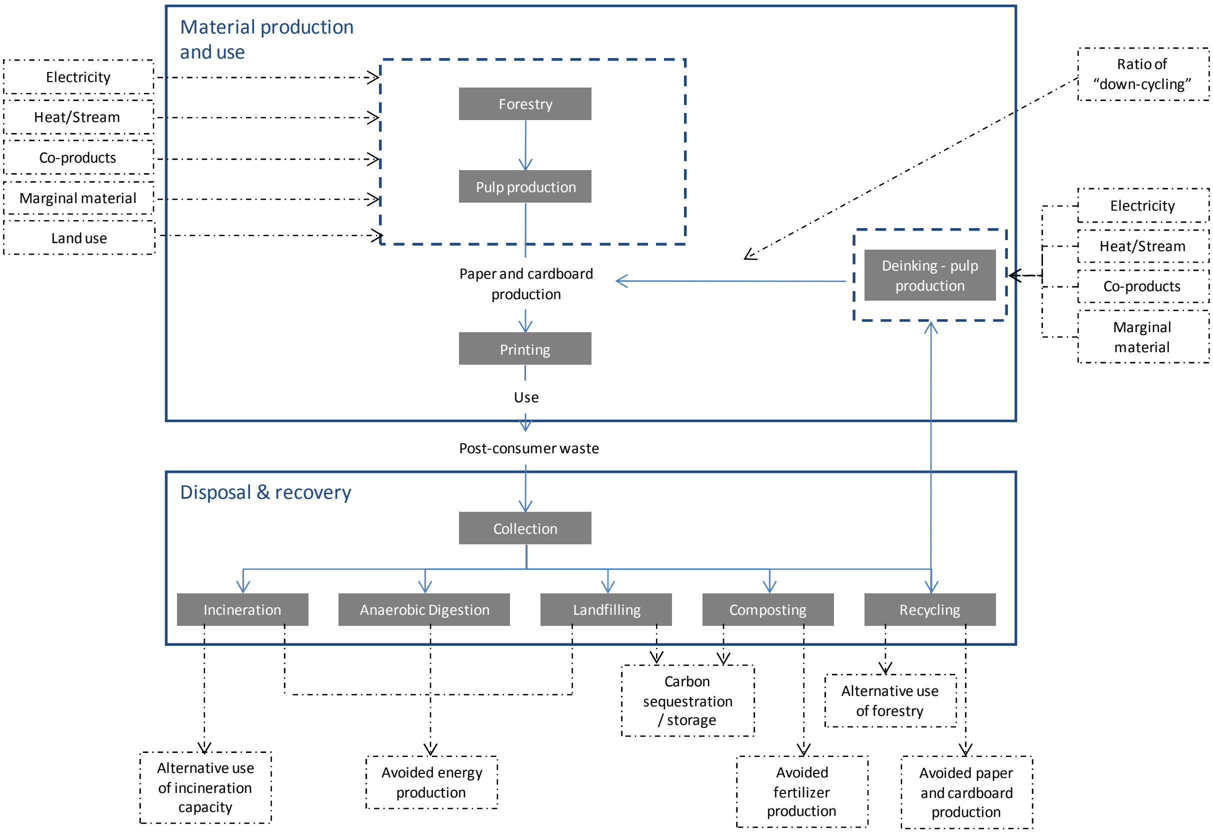

Figure 3 The paper waste systems and key parameters

3.2.2 Comparison between the various end-of-life options

Alternatives and materials compared

The selected studies only cover the traditional end-of-life options. The analysed options are:

- Recycling
- Incineration with energy recovery
- Landfill

All studies compare all three possible alternatives for treatment as illustrated in Table 4.

Table 4 Overview of the end-of-life alternatives compared within each case for paper

Case	Recycling	Composting	Incineration with electricity recovery only	Incineration with heat or combined heat/ electricity recovery	Landfill	Anaerobic digestion	Pyrolysis	Gasification
1[PB]	X		X		X			
2[NS]	X			X	X			
2[CC]	X			X	X			
2[MC]	X			X	X			
3[PS]	X			X	X			
3[EN]	X			X	X			
4[CC]	X		X		X			
4[MA]	X		X		X			
4[NS]	X		X		X			
4[OP]	X		X		X			
4[PB]	X		X		X			
4[TE]	X		X		X			
4[MP]	X		X		X			
5[PA]	X			X	X			
5[MC]	X			X	X			
Total number of cases	**15**	**0**	**8**	**7**	**15**	**0**	**0**	**0**

The material examined in each case is not the same. Some studies investigate only one type of paper waste while others compare different types. An overview of the materials in question is presented in Table 5 below.

Table 5 Overview of examined paper waste materials

Study number	Case	Material
1	1[PB]	Paper and board
2	2[NS]	Newspaper
	2[CB]	Corrugated board
	2[MC]	Mixed cardboard
3	3[PS]	Paper tape
	3[EN]	Envelope in vellum paper
4	4[CC]	Corrugated board
	4[MA]	Magazines
	4[NP]	Newspaper
	4[OP]	Office paper
	4[PB]	Phone books
	4[TE]	Textbooks
	4[MP]	Mixed paper
5	5[PA]	Paper
	5[CA]	Cardboard

Ranking between the various end-of-life options within each scenario

All studies analysed compare recycling and incineration with energy recovery and landfill. Table 6 compares the end-of-life options compared within each case. The parameters and assumptions differ from one study to another; therefore the results are not consistent across studies and the table should thus be interpreted with care.

Study no1

The first study takes climate change, primary energy demand and water use into account. According to the final results, incineration is the best option for climate change and energy demand. On the other hand, incineration is the most environmentally burdening option regarding water use (due to the cooling needs). Recycling is the worst option for climate change and second worst for energy demand. This can be (partially) explained by the fact that recycling in this study is not given substantial credit, as the substituted process of paper production occurs in Sweden using an average Swedish energy mix which has a significant contribution from CO_2 free energy sources such as renewable and nuclear power. On the other hand, the substituted energy mix from energy recovery in the incineration is calculated based on the Italian energy mix, which is much more carbon intensive.

Study no2

The second study presents a breakdown of the paper fraction into three different materials. For two of the materials (newspaper and mixed cardboard), recycling is the best option (and incineration the worst) for resource depletion, while recycling is the worst alternative for corrugated board and landfill is the best. Corrugated board is the worst type of paper for recycling, as the material's fibres are already of poor quality. The extra loss of fibre quality that occurs during recycling would lead to the recovery of low quality products. Recycling is preferable for climate change and energy demand for all materials concerned. Landfill is the worst option in these two impact categories.

Study no3

Incineration dominates all impact categories except for water use, where incineration is the worst alternative. Recycling is the best option when it comes to water consumption, whilst landfill takes last place for climate change and energy demand. In this study, the results for each alternative do not diverge as greatly as in other studies. This study is also performed in a French context, where a major part of the energy requirements is covered by nuclear power.

Study no4

This study scopes US systems of paper treatment and includes climate change and energy demand as impact categories. It also investigates seven different types of paper waste, presenting more or less consistent results. Recycling is proven to be the best route for all types and landfill is the worst (with two exceptions) regarding climate change. A similar distribution is observed in the energy category: all cases agree that landfill is the worst option. Recycling is the best for five types of paper.

Study no5

The last study distinguishes paper and cardboard, but it only refers to climate change. The results are analogous for both materials, as incineration with energy recovery is the preferable option, followed by recycling.

Table 6 Ranking of end-of-life options within each scenario for paper

	Case	Recycling	Incineration with energy recovery	Landfill
Climate change (kg CO_2 eq)	1[PB]	+	+++	++
	2[NS]	+++	++	+
	2[CC]	+++	++	+
	2[MC]	+++	++	+
	3[PS]	++	+++	+
	3[EN]	++	+++	+
	4[CC]	+++	++	+
	4[MA]	+++	++	+
	4[NS]	+++	+	++
	4[OP]	+++	++	+
	4[PB]	+++	+	++
	4[TE]	+++	++	+
	4[MP]	+++	++	+
	5[PA]	++	+++	+
	5[MC]	++	+++	+
Depletion of natural resources (kg Sb eq)	2[NS]	+++	+	++
	2[CC]	+	++	+++
	2[MC]	+++	+	++
	3[PS]	+	+++	++
	3[EN]	+	+++	++
	Studies n° 1, 4 and 5 do not include this indicator			
Energy demand (MJ)	1[PB]	++	+++	+
	2[NS]	+++	++	+
	2[CC]	+++	++	+
	2[MC]	+++	++	+
	3[PS]	++	+++	+
	3[EN]	++	+++	+
	4[CC]	+++	++	+
	4[MA]	++	+++	+
	4[NS]	+++	++	+
	4[OP]	+++	++	+
	4[PB]	+++	++	+
	4[TE]	++	+++	+
	4[MP]	+++	++	+
	Study n°5 does not include this indicator			
Water Consumption (m^3)	1[PB]	+++	+	++
	3[PS]	+++	+	++
	3[EN]	+++	+	++
	Studies n° 2, 4 and 5 do not include this indicator			

+++	best option
++	intermediary option
+	worst option
	option not assessed

3.2.3 Detailed comparison between the various treatment options

Climate change

Figure 4 depicts the relative preferability of one treatment option over another. First recycling is compared to the other options and then incineration.

An overall conclusion would be that landfill is generally the worst option regarding climate change. The results for incineration and recycling are inconsistent, as many studies disagree about which is preferable. Three studies support incineration and only two recycling, but many more cases are included in the latter analyses.

When comparing recycling to other options, it is quite clear that landfill is the worst. Indeed, the majority of cases in this comparison are gathered in the far upper part of the diagram, which should be interpreted as a large difference in the global warming contribution (relative preference of more than 150%). Only one case classifies landfill as a better option, but when the specific conditions of the studies are examined the explanation becomes clear: in that study (Study no 1) the simulated landfill is assumed to apply state-of-the-art technologies such as reverse osmosis, flaring of uncontrolled gas and others that lead to a relative high landfill gas collection efficiency. This configuration, combined with the fact that the virgin paper is assumed to be produced in Sweden (where the electricity mix is less carbon intensive than in many other countries) results in the relative preference of landfill over other options. This case is a perfect example of how the assumptions and parameters assumed in the LCA can have a drastic effect on the final outcome.

On the other hand, when recycling is compared to incineration, a more balanced image appears. A case-by-case analysis shows that recycling might be preferable since there are more cases on the positive side of Figure 4. An interesting observation is that the selected studies are consistent regarding the included cases: all cases within the same study agree on which is the best alternative. The result is that there are three studies in favour of incineration and two in favour of recycling. Of the studies favouring incineration:

- Study no1, as explained above, is configured in such a way that the results can be easily explained.
- Study no 3 has a French context but as the study does not focus specifically on end-of-life, so the result favouring incineration cannot be investigated further.
- Study no 5 also takes place in a less carbon-intensive environment in terms of electricity mix.

An important observation is that all three studies that classify incineration as preferable base their geographical scope assumptions in countries with a high share of CO_2 free energy mixes (France, Sweden). In all these cases, the benefits from choosing incineration are higher which can seem contradictory since the energy credits are lower than when the energy mix relies on fossil fuels. An explanation for this preference for incineration could be that the balance between the energy used directly in recycling processes versus the energy saved by avoiding the production of primary material is not very advantageous for recycling. A disaggregation of the processes and corresponding energy balances involved in each treatment alternative (e.g. energy used directly in recycling processes versus energy saved by recycling processes) could give a better understanding of the situation, but this would require the examination of the LCA modelling used as well as the inventory data which are not published in the studies. In each study only aggregated results are presented, namely the final sum of the recycling route including all direct and indirect processes, as well as transport and other energy.

Figure 5 compares incineration to the other end-of-life alternatives. The comparison to landfill is clearly in favour of incineration except for two cases where landfill appears slightly superior. The two cases (newspaper and phonebooks cases included in study no 4) that favour landfill refer to two materials with similar waste characteristics (according to the model), but their differentiation from the other materials is not explained. The degradation rate, which is not mentioned in the study, might be responsible for the better performance of landfill in these cases. This lack of transparency is among the weaknesses of the study.

Table 7 Relative difference between the impacts from the different end-of-life options vs. recycling for climate change for paper. A positive value means that recycling is preferable to the other end-of-life option. A negative value means that recycling causes more environmental burden than the other end-of-life option.

	Recycling versus other alternatives						
N° case	1[PB]	2[NS]	2[CC]	2[MC]	3[PS]	3[EN]	4[CC]
Incineration with energy recovery	-290%	550%	110%	250%	-30%	-30%	80%
Landfill	-130%	11460%	1430%	1180%	90%	100%	110%

	Recycling versus other alternatives							
N° case	4[MA]	4[NS]	4[OP]	4[PB]	4[TE]	4[MP]	5[PA]	5[MC]
Incineration with energy recovery	80%	70%	80%	70%	80%	80%	-90%	-140%
Landfill	90%	70%	170%	70%	160%	110%	1260%	1630%

Table 8 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for climate change for paper. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes more environmental burden than the other end-of-life option.

	Incineration with energy recovery versus other alternatives						
N° case	1[PB]	2[NS]	2[CC]	2[MC]	3[PS]	3[EN]	4[CC]
Recycling	150%	-120%	-850%	-70%	40%	50%	-370%
Landfill	80%	2400%	9900%	260%	160%	200%	160%

	Incineration with energy recovery versus other alternatives							
N° case	4[MA]	4[NS]	4[OP]	4[PB]	4[TE]	4[MP]	5[PA]	5[MC]
Recycling	-550%	-280%	-360%	-260%	-400%	-430%	50%	60%
Landfill	40%	-20%	410%	-20%	410%	150%	730%	740%

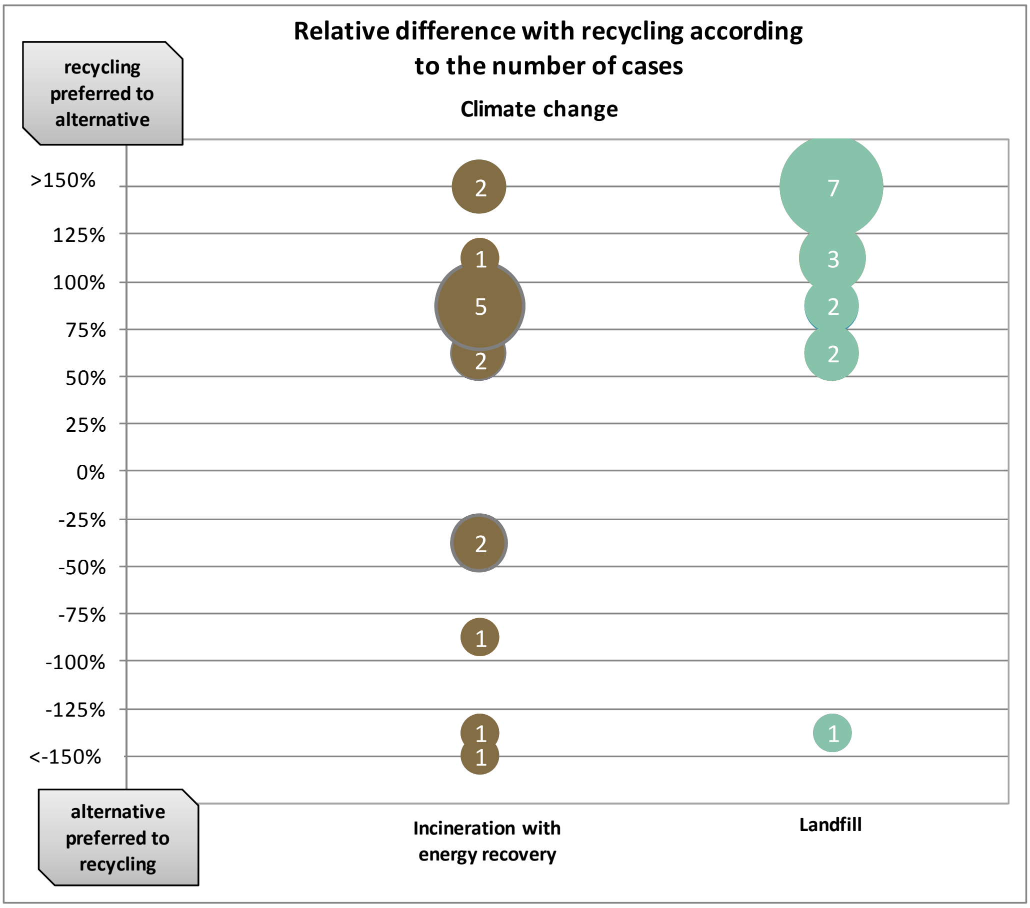

Figure 4 Relative difference between the impacts from the different end-of-life options vs. recycling for climate change for paper. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

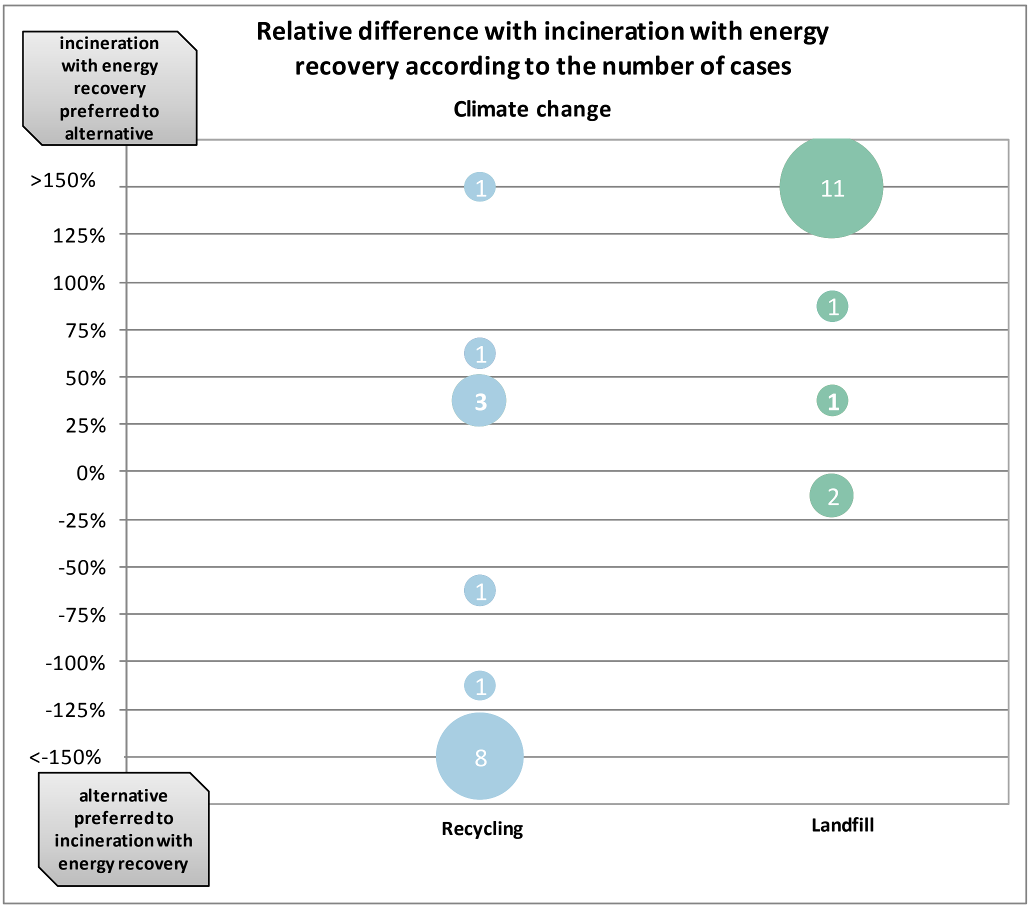

Figure 5 Relative difference between the impacts from the different end-of-life options vs. incineration for climate change for paper. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Depletion of natural resources

In this impact category the situation is more complex, as the treatment options are more similar than in the case of climate change. There are no clear-cut conclusions regarding the most preferable option. Only two studies take resource depletion into account. Study no 2 shows that the classification of options depends on the specific material in question. On the other hand, study no 3 is consistent for both materials it examines.

Figure 6 shows the relative difference of recycling versus the two remaining treatment options. Recycling appears to be inferior to incineration for three cases out of five, but where recycling prevails, the relative difference is greater. Two cases where incineration is better are from study no 3, which assumes a down-cycling of paper products to corrugated board. This assumption is translated to an increased need for virgin fibres during the recycling process which affects the results for resource depletion. The third case can be also justified by the down-cycling assumption as it refers to a low quality paper, such as corrugated board, which can only be down-cycled.

An analogous situation is observed when comparing recycling to landfill: the studies reviewed do not concur on which is the best option. This impact category, therefore, depends heavily on the particular modelling assumptions. Figure 7 indicates that landfill seems to be rather superior to incineration as more cases support this argument.

Landfill causes relatively low direct impacts to resource depletion, since paper requires no particular treatment before disposal. The superiority of the other options observed for some cases is explained mainly by the indirect savings of resources brought by the energy or material recovery. There is one case for which landfill largely appears to be the best option (case 2[CC]). This case simulates the treatment of corrugated board, which is a low quality paper consisting of relatively more degraded fibres than other paper types. This means that the loss rates from recycling are higher than for higher quality papers and so recycling cannot produce benefits as significant as for other paper types. Consequently, in this study landfill appears to cause fewer burdens in this case. The results of the study confirm this statement, as recycling has a net positive value only for this type of paper. The study did not explore options for dealing with the fraction of the board which would not be recycled and how these would affect the outcomes.

Incineration with energy recovery and recycling should be further investigated in site-specific studies in order to give an accurate documentation of the prevailing technology.

This impact category is affected by a lot of processes which are aggregated in an LCA, so the disaggregation necessary to determine which precise steps are responsible is quite difficult. In general, resource depletion is affected by the energy input to the various treatment processes, and the amount of virgin material required for recycling, as well as indirect process parameters such as incineration efficiency and landfill gas capture rate.

Table 9 Relative difference between the impacts from the different end-of-life options vs. recycling for depletion of natural resources for paper. A positive value means that recycling is preferable to the other end-of-life option. A negative value means that recycling causes more environmental burden than the other end-of-life option.

	Recycling versus other alternatives				
N° case	2[NS]	2[CC]	2[MC]	3[PS]	3[EN]
Incineration with energy recovery	100%	-70%	110%	-30%	-40%
Landfill	90%	-260%	30%	-10%	-20%
Studies n°1, 4, and 5 do not include a comparison with recycling for this indicator and thus are not included in this table					

Table 10 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for depletion of natural resources for paper. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes more environmental burden than the other end-of-life option.

	Incineration with energy recovery versus other alternatives				
N° case	2[NS]	2[CC]	2[MC]	3[PS]	3[EN]
Recycling	-3040%	260%	-780%	50%	70%
Landfill	-510%	-690%	-560%	40%	30%
Studies n°1, 4, and 5 do not include a comparison with incineration wiht energy recovery for this indicator and thus are not included in this table					

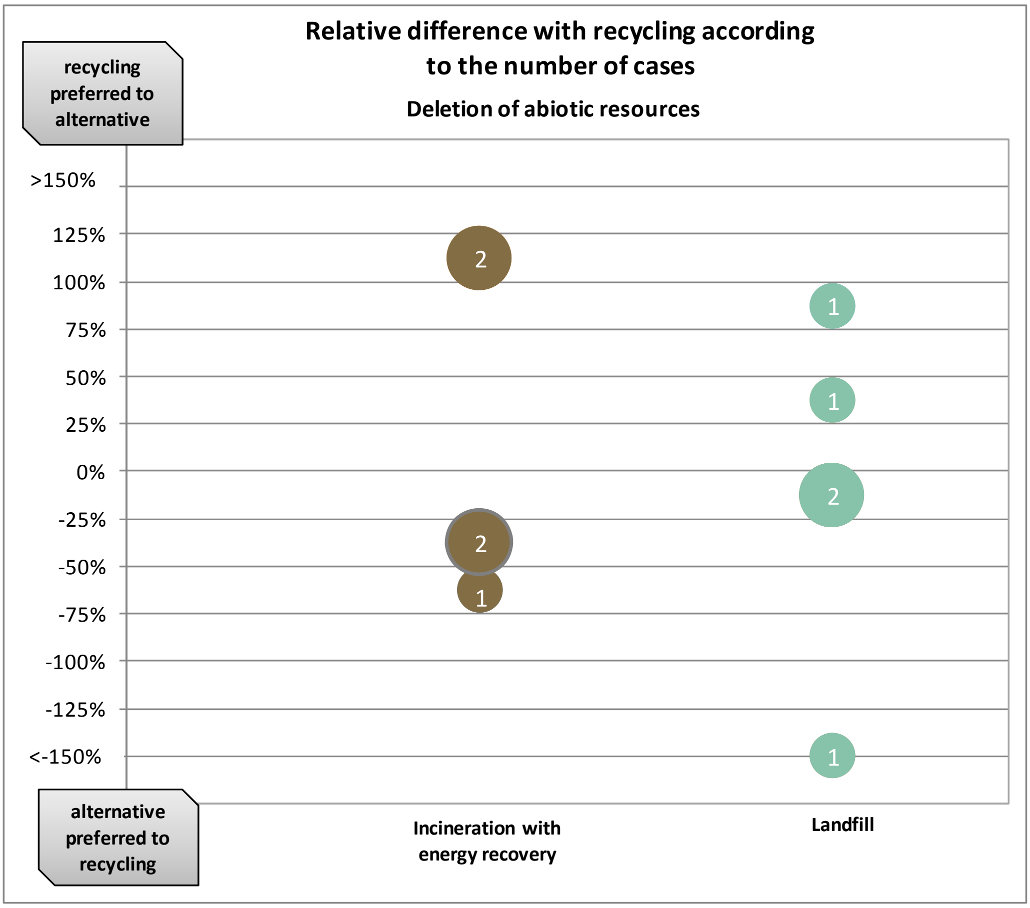

Figure 6 Relative difference between the impacts from the different end-of-life options vs. recycling for depletion of aboitic resources for paper. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

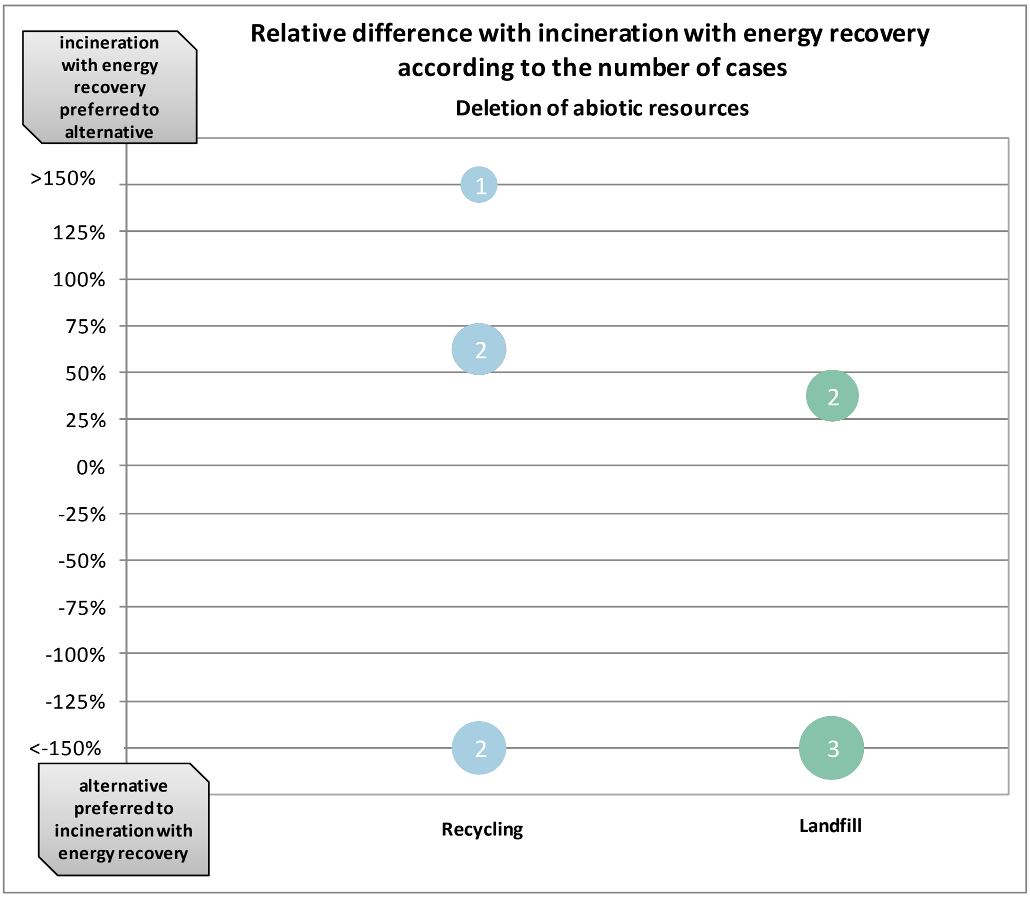

Figure 7 Relative difference between the impacts from the different end-of-life options vs. incineration for depletion of aboitic resources for paper. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Energy demand

In all cases in this impact category, landfill is the worst option. The reduced energy recovery compared to incineration or avoided energy consumption compared to recycling mean that the results are very clear on this point. The choice between recycling and incineration depends on the plants' individual data and efficiencies as the review of the studies reveals a controversy.

Figure 8 compares recycling to the other two options. Its superiority over landfill is beyond any doubt, as all thirteen cases are consistent. The only difference lies in the intensity of preference observed, which is regulated by the recycling technologies assumed and the efficiency of the landfill (both in terms of gas collection and conversion to electricity). The majority of cases concede that recycling is also better than incineration. Interestingly, though, there is a larger difference in the energy demand results for the two cases where incineration is better. These cases refer to magazines and textbooks, materials that differ from each other and have relatively low heating values compared to other cases in the same study. An explanation given in the study is that the energy savings from recycling of these two materials are 10-17 times lower than for the other paper products examined in the study.

In Figure 9, incineration appears to be absolutely better than landfill. The rate of energy recovery from paper, which can reach higher overall efficiencies in incineration than landfill gas recovery (assumed in all studies) is mainly responsible for this outcome. In only three cases out of thirteen do the burdens from incineration supersede the benefits for this impact category, while landfill burdens are higher than the savings in ten cases. From this figure, it is also clear that recycling has a statistical advantage versus incineration.

Table 11 Relative difference between the impacts from the different end-of-life options vs. recycling for energy demand for paper. A positive value means that recycling is preferable to the other end-of-life option. A negative value means that recycling causes more environmental burden than the other end-of-life option.

	Recycling versus other alternatives					
N° case	1[PB]	2[NS]	2[CC]	2[MC]	3[PS]	3[EN]
Incineration with energy recovery	-40%	60%	10%	10%	-10%	-10%
Landfill	80%	90%	100%	80%	10%	20%

	Recycling versus other alternatives						
N° case	4[CC]	4[MA]	4[NS]	4[OP]	4[PB]	4[TE]	4[MP]
Incineration with energy recovery	90%	-130%	80%	80%	80%	-300%	90%
Landfill	100%	160%	100%	100%	100%	100%	100%
Studies n°5 does not include a comparison with recycling for this indicator and thus is not included in this table							

Table 12 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for energy demand for paper. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes more environmental burden than the other end-of-life option.

	Incineration with energy recovery versus other alternatives					
N° case	1[PB]	2[NS]	2[CC]	2[MC]	3[PS]	3[EN]
Recycling	70%	-180%	-10%	-10%	10%	10%
Landfill	200%	80%	100%	70%	20%	30%

	Incineration with energy recovery versus other alternatives						
N° case	4[CC]	4[MA]	4[NS]	4[OP]	4[PB]	4[TE]	4[MP]
Recycling	-600%	60%	-550%	-370%	-350%	80%	-930%
Landfill	110%	130%	120%	100%	120%	100%	110%
Studies n°5 does not include a comparison with incineration with energy recovery for this indicator and thus is not included in this table							

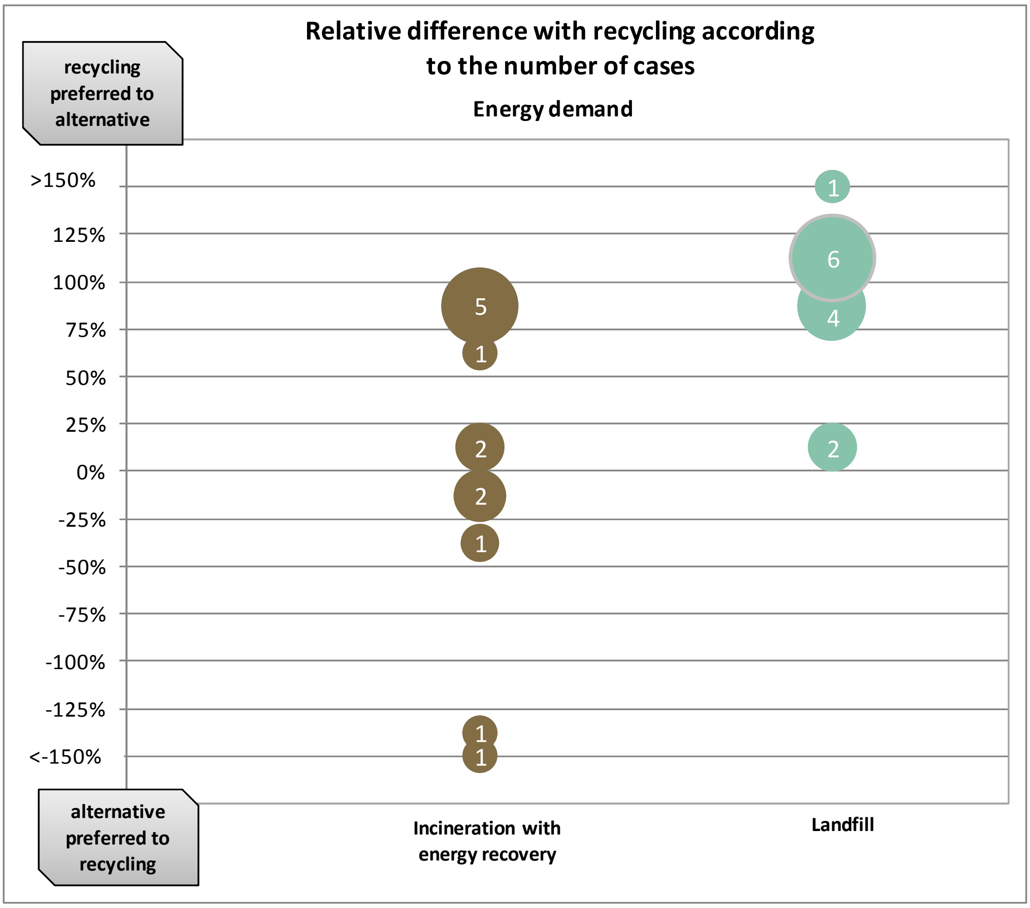

Figure 8 Relative difference between the impacts from the different end-of-life options vs. recycling for energy demand for paper. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

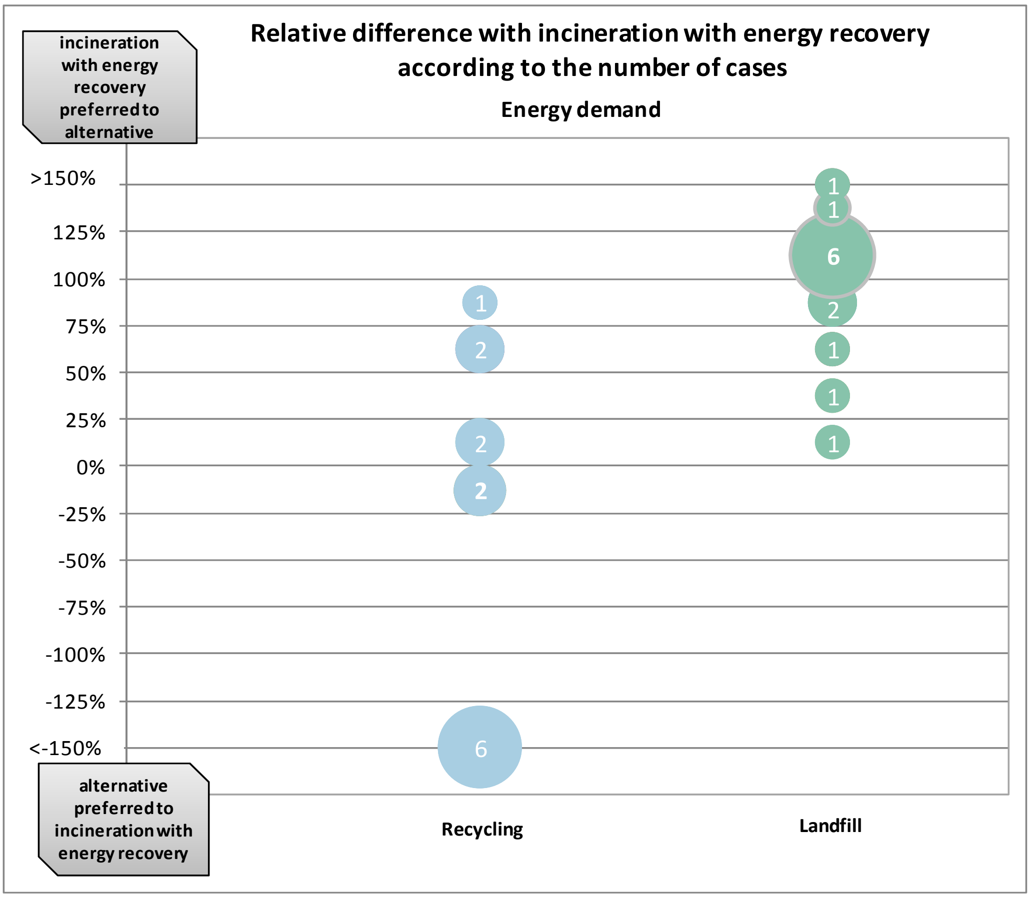

Figure 9 Relative difference between the impacts from the different end-of-life options vs. incineration for energy demand for paper. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Water consumption

The total water use was only examined by studies no 1 and 3 and they both display a clear preference for recycling, followed by landfill and incineration. In study 3, incineration and landfill share the same figure, while the results for these alternatives in study 1 are also almost identical.

The following tables and graphs below illustrate this statement. Table 13 expresses the preference for recycling for this impact category. Recycling performs better than landfill in all cases examined. Study n°1 claims that the substituted virgin paper production reduces the water demand significantly as it is assumed to occur in Sweden. In general, the process of recycling itself is much more demanding in water than the other alternatives, but still less than the water demand for primary paper production.

On the other hand, Table 14 illustrates the fact that incineration ranks last for water consumption. The operational requirements of an incineration plant include large amounts of water (mainly for cooling purposes) which are responsible for the increased values of incineration versus other alternatives. However, the latest technological developments (such as water recirculation internally in a modern incineration plant) might minimise the water use and render incineration comparable to other treatment options.

Table 13 Relative difference between the impacts from the different end-of-life options vs. recycling for water consumption for paper. A positive value means that recycling is preferable to the other end-of-life option. A negative value means that recycling causes more environmental burden than the other end-of-life option.

	Recycling versus other alternatives		
N° case	1[PB]	3[PS]	3[EN]
Incineration with energy recovery	530%	30%	30%
Landfill	530%	30%	30%
Only studies n°1 and 3 include a comparison with recycling for this indicator			

Table 14 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for water consumption for paper. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes more environmental burden than the other end-of-life option.

	Incineration with energy recovery versus other alternatives		
N° case	1[PB]	3[PS]	3[EN]
Recycling	-80%	-20%	-20%
Landfill	0%	0%	0%
Only studies n°1 and 3 include a comparison with incinerarion with energy recovery for this indicator			

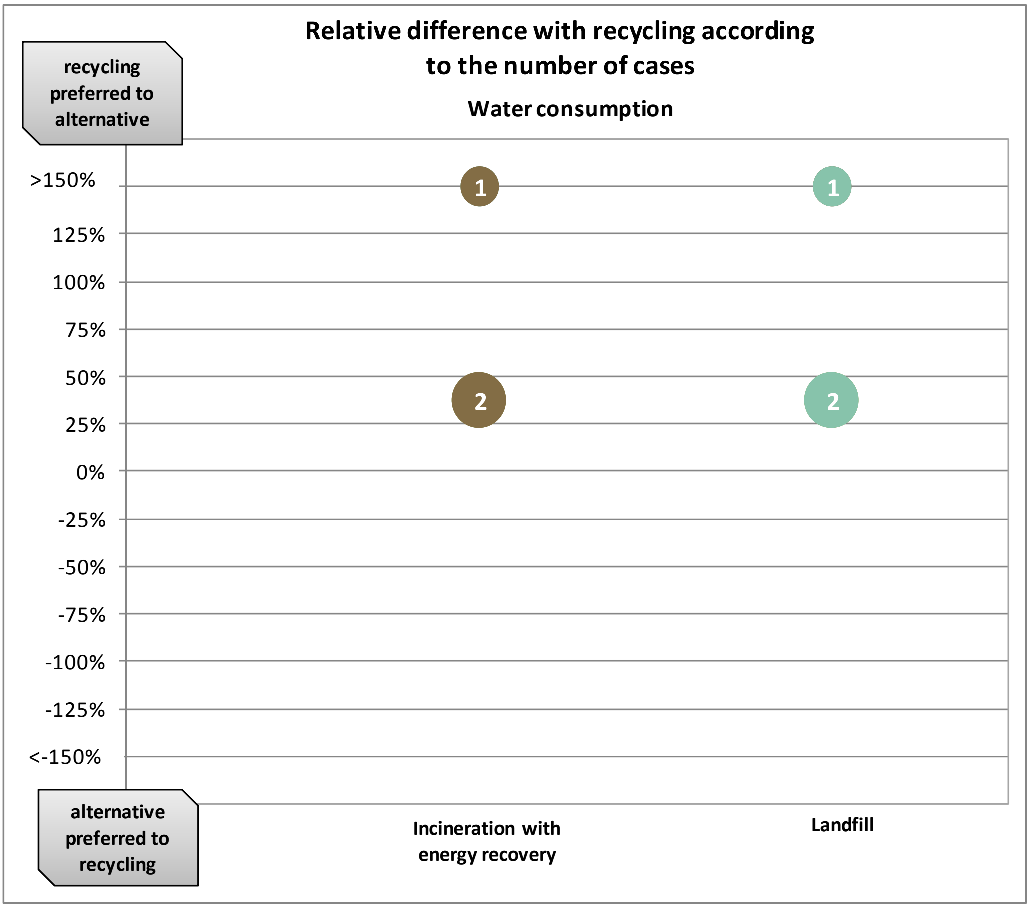

Figure 10 Relative difference between the impacts from the different end-of-life options vs. recycling for water consumption for paper. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

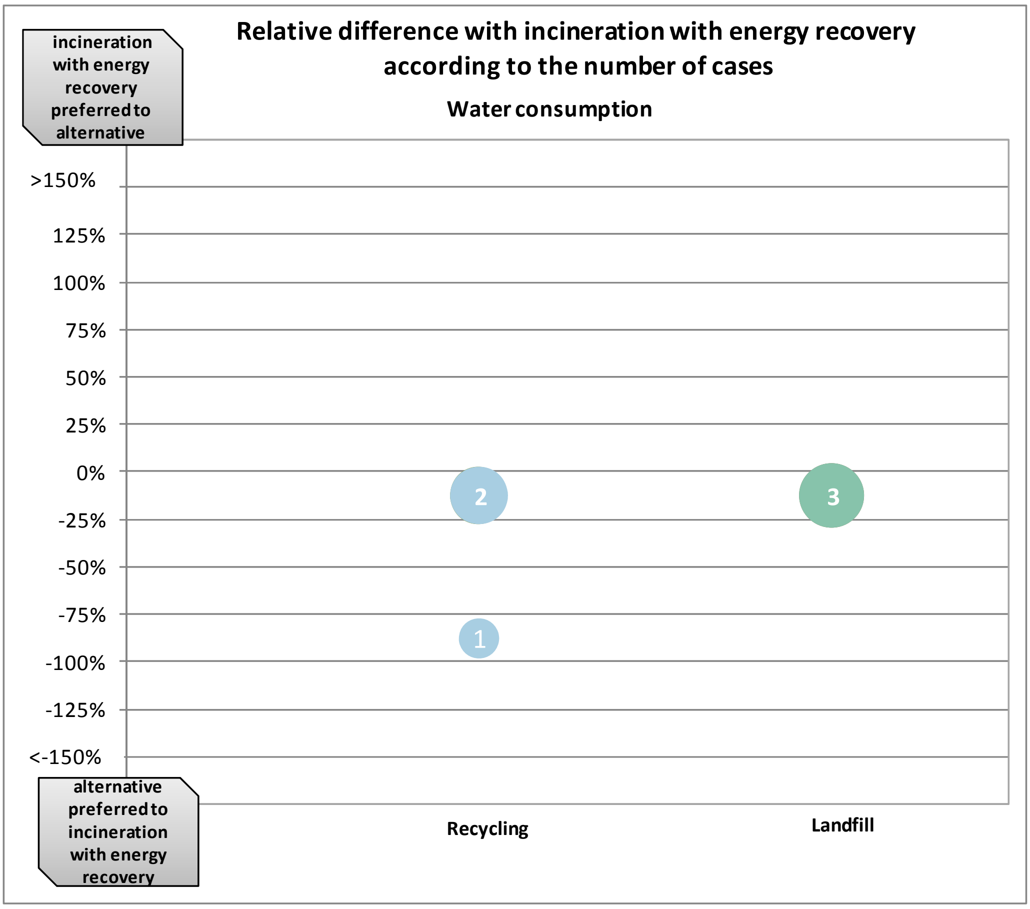

Figure 11 Relative difference between the impacts from the different end-of-life options vs. incineration for water consumption for paper. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Other indicators

Acidification

From the table below, it is evident that, for those studies that present results on acidification, recycling is better than incineration, which is better than landfill.

Table 15 Ranking of end-of-life options within each scenario for acidification

	Case	Recycling	Incineration with energy recovery	Landfill
Acidification (kg SO2 eq)	1[PB]	+++	++	+
	3[PS]	+++	++	+
	3[EN]	+++	++	+
	Studies n° 2, 4 and 5 do not include this indicator			

+++	best option
++	intermediary option
+	worst option
	option not assessed

Photochemical oxidation

According to the existing results, landfill appears to be the worst option, while recycling has a minor advantage compared to incineration

Table 16 Ranking of end-of-life options within each scenario for photochemical oxidation

	Case	Recycling	Incineration with energy recovery	Landfill
Photochemical oxydation (kg ethylene eq)	2[NS]	++	+++	+
	2[CC]	++	+++	+
	2[MC]	+++	++	+
	3[PS]	+++	++	+
	3[EN]	+++	+	++
	Studies n° 1, 4 and 5 do not include this indicator			

+++	best option
++	intermediary option
+	worst option
	option not assessed

Eutrophication

Unfortunately, only one study includes eutrophication in the impact categories. In this study, for both materials analysed, landfill seems to be the best option.

Table 17 Ranking of end-of-life options within each scenario for eutrophication

	Case	Recycling	Incineration with energy recovery	Landfill
Eutrophication (kg PO4 eq)	3[PS]	+	++	+++
	3[EN]	++	+	+++
	Studies n° 1, 2, 4 and 5 do not include this indicator			

+++	best option
++	intermediary option
+	worst option
	option not assessed

Human Toxicity

With one exception, recycling is classified as the best option, while landfill is the worst in terms of human toxicity.

Table 18 Ranking of end-of-life options within each scenario for human toxicity

	Case	Recycling	Incineration with energy recovery	Landfill
Human Toxicity (kg 1,4-DB eq)	2[NS]	+++	++	+
	2[CC]	+	+++	++
	2[MC]	+++	++	+
	3[PS]	+++	++	+
	3[EN]	+++	++	+
	Studies n° 1, 4 and 5 do not include this indicator			

+++	best option
++	intermediary option
+	worst option
	option not assessed

Key parameters

There are many parameters and assumptions that affect the outcome of the LCAs in question. Moreover, those parameters might function in combination and give more diverging results when trying to compare across studies. However, there are some key parameters that have a decisive influence on the overall results:

- Electricity mix
- Technological efficiencies
- Inclusion of carbon sequestration / storage
- Other (material composition, substitution ratio)

Electricity mix

The effect of the electricity mix can be seen in many steps of paper's waste system. The upstream processes and the waste management processes require electricity, but also the substituted electricity's composition has an impact on determining the overall LCA's results.

Moreover, **some studies (studies no 1, 3, 4 and 5) chose to work based on the attributional LCA approach, using average mixes, while others opt for the consequential approach, using marginal mixes** (Ekvall and Weidema, 2004). **The difference for a country with a high share of carbon-neutral energy sources is quite substantial**, when examining global warming as an impact category. Study no 2 refers to a geographical scope in Sweden, where the average mix is used for production of paper. Even though the recovered electricity replaces hard coal, attributing more benefits to incineration and landfill, recycling is still the most preferable option. The same study (although without a proper sensitivity analysis) claims that if an average mix was substituted instead, the results would be quite different, probably even more in favour of recycling.

Differences across studies can only be partly explained by the choice of electricity mix. Studies no 1, 3 and 5 substitute a less carbon intensive electricity mix, resulting in a decrease for the benefits of incineration and landfill for climate change. Studies n°2 and 4 substitute fossil fuels exclusively, which results in reinforced benefits from all energy recovery activities (mainly incineration). The expected outcome would be that studies n°2 and 4 would rank incineration higher and recycling lower than in studies no 1, 3 and 5, however the LCA results show the exact opposite. This paradox could be explained by the choice of different parameters that are related to recycling itself; recycling is also related to electricity mixes, because the avoided paper production, which is itself quite an energy demanding process (study no 1 assumes production of virgin paper in Sweden where the electricity mix is much less carbon intensive than the Italian mix substituted for energy recovery).

Table 19 Substituted electricity mixes used in the reviewed studies

Study number	Substituted electricity	Mix composition
1	Italian average	81% fossil - 19% renewable
2	Hard coal	100% fossil
3	French average	10% fossil - 78% nuclear - 12% renewable
4	fossil mix	100% fossil
5	Scandinavian average	14% fossil - 23% nuclear - 63% renewable

Technological efficiencies

The effect of the chosen level of technology on the results is evident. However, some efficiencies within the paper waste management system are more important than others.

A vital parameter when simulating a landfill is the extraction efficiency of the landfill gas. The losses of this procedure determine the methane emissions from the landfill while the captured quantities are used for electricity and/or heat production. Study no 1 uses a state-of-the-art landfill with both high extraction efficiency (55%) and efficient electricity conversion. Study no 3 also presents a high extraction efficiency of 50%. On the other hand, study no 5 reduces the efficiency to 25% and, consequently, the results are worse for the landfill option in that study. In Table 20 below, the relation between the assumed methane recovery efficiency for each study is compared to the relative preference for landfill over recycling. Although the overall climate change results are dependent on many factors, there seems to be a relation between the level of preference for landfill and the level of technology applied on the landfill. The more efficient the biogas recovery, the better the results for landfill compared to recycling.

Table 20 Influence of the methane extraction rate on the environmental assessment of landfill regarding climate change

Case	Landfill	
	Methane recovery efficiency	Relative difference of landfill vs recycling
1[PB]	55%	-134%
3[PS]	50%	88%
3[EN]	50%	101%
5[PA]	25%	1260%
5[MC]	25%	1633%

The same level of importance could be attributed to incineration plants as well. However, only two studies mention the selected efficiency as shown in the following table, while others assume an average incinerator efficiency within their geographical scope. The limited efficiency interval, though, still renders the studies valid and approximately comparable to each other.

Table 21 Overview of the incinerator efficiencies in the selected studies for paper and card

Study number	Energy produced with incinerator	Efficiency
1	electricity	27.7%
2	electricity + heat	n.a.
3	electricity + heat	32%
4	electricity	n.a.
5	electricity + heat	n.a.

Inclusion of carbon sequestration / storage

Carbon sequestration and carbon storage are two concepts developed in order to better describe the carbon cycle. When the carbon uptake in a specific area (e.g. a forest) is higher than the release, then carbon is sequestered in the biomass. In an LCA context, when recycling causes resource savings, the saved biomass contributes to carbon sequestration. The net uptake of carbon from the atmosphere can be credited to the recycling system as CO_2 savings.

Moreover, when biogenic carbon is stored in soil for more than a chosen time interval (usually 100 years), its effect on global warming can, by convention, be ignored. According to this convention, the carbon stored in landfills is not released in the atmosphere and the landfill system could be credited with the corresponding CO_2 savings. However, the calculation of the remaining carbon after a certain time period is quite complex and based on many diverse assumptions such as the degradation ratio, weather conditions, etc. Since this period usually extends far into the future, the estimate of the CO_2 savings due to carbon storage is uncertain.

Carbon sequestration is applied in only one study (no 4) for the recycling scheme. The resource (forest) savings due to recycling increase the uptake of carbon dioxide by the remaining trees and the carbon is, therefore, sequestered. This amount of carbon (0.55 or 0.83 metric tons of carbon equivalent) is credited to the recycling system that provoked the phenomenon. In this study, recycling has a clear advantage in the affected impact category (climate change) compared to all other options. Moreover, the difference in the impact assessment results is quite high.

Although there is no carbon sequestration taken into account in the second study, recycling still is the best option, according to Table 22. Carbon sequestration is not the sole decisive factor for the ranking of recycling and many other parameters might have influenced the results. However, study no 2 does not reveal much information about the incineration configuration rendering the investigation of this classification difficult.

Table 22 Influence of the carbon sequestration on the environmental assessment of recycling regarding climate change

Case	Recycling		Landfill	
	Carbon sequestration	Ranking of alternative	Carbon storage	Ranking of alternative
1[PB]	No	+	No	++
2[NS]	No	+++	Yes	+
2[CC]	No	+++	Yes	+
2[MC]	No	+++	Yes	+
3[PS]	No	++	No	+
3[EN]	No	++	No	+
4[CC]	Yes	+++	Yes	+
4[MA]	Yes	+++	Yes	+
4[NS]	Yes	+++	Yes	++
4[OP]	Yes	+++	Yes	+
4[PB]	Yes	+++	Yes	++
4[TE]	Yes	+++	Yes	+
4[MP]	Yes	+++	Yes	+
5[PA]	No	++	No	+
5[MC]	No	++	No	+

Carbon storage is modelled in studies 2 and 4. However, the specifics of the modelling are not given, and therefore it is difficult to assess the effect of this inclusion on the overall results. However, carbon storage is more relevant for paper than for the organic fraction (i.e. food and garden waste). This is due to paper's lower degradation ratio which means that high amounts of carbon may remain stored during the climate change assessment time frame of 100 years.

The issue of alternative use of forest/wood because of the recycling savings was addressed in only one study (no 1) and was not assessed in any of the studies. This issue is quite controversial and a consensus has not yet been reached yet by the international scientific community. However, the effect of this alternative use can be quite high (Merrild et al. 2008).

Other parameters

There are some other assumptions that influence the results and that can potentially affect the classification of the treatment options. First of all, the composition of the material in question, as well as the purity when collected, are quite vital, as they determine all the resulting characteristics, such as heating values, recycling ratio etc. Moreover, different types of paper are produced from differently processed pulp (e.g. using steam or electricity) and therefore have different environmental burdens (or benefits when recycled). Studies 2 and 4 show that different types of paper can produce different results. Especially in study no 4, where many different types of paper are examined, the differences in the results are indicative of the different systems examined. However, as many assumptions differ between studies, it is not possible to draw out specific conclusions for the different materials. The energy balances for both processes involved in the treatment and avoided processes saved by energy or material recovery are quite different as the study underlines and it is the energy budgets which are considered mainly responsible for the variations on the results. Another parameter that depends on the material and the technological assumptions is the loss rate in the case of recycling. Study no 4 assumes different rates for different materials according to the condition of the paper fibres. The level of the benefits for each material recycled is multiplied by the recycling ratio, reducing the negative contributions substantially in some cases.

3.2.4 Conclusion

Overall, the conclusions from this review can be summarised in two main axes. The first is a comparison of end-of-life options and the second is the location of important factors influencing the results.

Generally, the quality of the selected LCAs was satisfactory, as full transparency and elaborate analysis of the assumptions was a precondition for the short-listing. The systems under study were comprehensively described, ensuring clarity and coherence for the results.

Therefore, the isolated results for each of the three treatment options could be further summarised across studies by taking into account the relative differences in the configuration of each study. In spite of the absence of alternative options, well documented results were produced for landfill, recycling and incineration individually. **In most impact categories and the majority of cases, landfill was proven to be the least preferable option.** Some fluctuations in the classification of landfill can be explained by the choice of parameters of the system.

The comparison between incineration and recycling is more complex. In most impact categories (depletion of natural resources, climate change, primary energy, eutrophication, photochemical oxidation, non-treated waste, ecotoxicity, human toxicity and ecotoxicity in water), it is **difficult to establish a relative preference** as there is inconsistency among the studies. In some impacts, there is a clear superiority of one option (water consumption, acidification, ecotoxicity in sediments and ecotoxicity in soil). If a summary of the un-weighted impact potentials is attempted, recycling might have a slight superiority. However, the importance of each impact indicator is dependent on the scope of each LCA and an ad hoc comparison of the sums is ill-advised.

The absence of an elementary sensitivity analysis in most studies is a barrier to determining the real hotspots in the life-cycle of waste paper, but some important parameters are mentioned or can be located through the results.

Since the benefits attributed to the paper waste management system are strongly associated with energy savings, **one of the most important parameters is the electricity mix**. Especially for some impacts, such as global warming, the origin of the fuels used for energy production can be decisive for the results. Therefore, the geographical scope of the system as well as the expansion of the system should be very clearly defined. This choice also gives an indication about the type and level of technologies used, together with the relevant efficiencies. As described in the section 3.2.3, not all results can be explained by a sole parameter. Therefore, although all studies stress the importance of the energy mix, the synergies and combinations of factors might influence the results in an unpredicted manner. The interpretation of a life cycle impact assessment should take into account all the parameters that affect the overall results.

Moreover, not many studies dealt with the **issues of carbon sequestration/storage, land use change or alternative use of wood**. The complexity of this issue and the variety of assumptions that are associated with it, prevented the LCA teams from including them. Since these processes produce high indirect emissions, the benefits attributed to the system are not fully accounted for and the results in these cases are, to a certain degree, underestimated.

3.2.5 Comparison with the results from the previous report edition

The previous WRAP report included paper in the selected fractions. This report only analyses studies that have been published since the previous report and therefore functions as supplementary to the previous conclusions.

The overall situation has not changed significantly with the inclusion of new LCAs. The general idea that landfill is, in most cases, the worst option is maintained. However, the results of comparing recycling to incineration are less concrete than in the previous report, where recycling had a slight advantage. Most probably the advancements in incineration technologies (mainly energy recovery efficiencies) have been integrated to the recent LCAs. In this new group of studies, there is no case where incineration is used as a disposal option with no energy recovery, as opposed to the previous report where two out of nine studies do not include energy recovery from incineration at all. Three out of five studies include heat production from incineration as well. On the other hand, there was no analysed study that took into account the alternative use of the incineration capacity, a factor that was deemed quite decisive in the previous study.

The comparison between incineration and landfill is quite well documented in this review, as many studies include it. In most cases and for most environmental indicators, incineration performs better. A more comprehensive picture is thus built, while the previous study only identified one study with this comparison, which showed a clear preference for incineration.

Regarding the most influential parameters, the issue of alternative use of wood thanks to the wooden resources saved in case of recycling has not been assessed at all in the recent studies. The old report included one LCA that credited the system for this function, while two others examined the issue in detail. In the new analysis, only one study addresses the remaining wood matter with no assessment whatsoever included in the results.

Regarding the energy provision and recovery assumptions, in both studies, the examined LCAs were fully transparent. In the previous WRAP report not many studies including marginal energy sources were found. In the present review, in spite of the gradual integration of the marginal concept to life cycle thinking, only one out of the five studies (study no 2) follows the marginal approach.

3.2.6 Data gaps/further research

Key parameters

Most studies present the electricity mixes used in the LCA for substituted energy but do not mention the mix used for virgin production. Moreover, most of the other key parameters are not analysed sufficiently. Various conversion efficiencies, mainly associated with energy recovery processes are seldom stated, resulting in uncertainties in the overall classification (e.g. comparing a state-of-the-art incinerator to an unengineered landfill).

Carbon storage/sequestration, as well as the alternative use of wood, are quite new fields and have not been fully analysed yet. However, their effect on the life cycle impacts is quite substantial. The studies that take any of these issues into account fail to give specific details and assumptions about modelling of carbon. In the case of recycling it would be relevant to investigate the effects of paper recycling on wood demand and of the related consequences on land use. Issues around sustainability of wood supply and the contribution of demand for new and recycled paper to land use change would also benefit from further research.

Another important aspect that has not been addressed properly by the selected studies is sensitivity analysis. None of the studies included a section where the most important parameters were tested in terms of their influence on the results. Therefore, the studies gave no indication of the relative importance of the different parameters by the studies themselves. The only study that included a sensitivity analysis was study no 3, but the sensitivity of transport during use phase of the material was tested, which is irrelevant to the end-of-life phase.

Coverage of the various end-of-life alternatives

All selected studies examine the three traditional treatment options for paper. New technologies, such as pyrolysis, gasification or anaerobic digestion and composting are not investigated. The two latter technologies are applied mainly on the entire organic part of municipal waste or on more appropriate fractions (food, garden waste, etc). The exclusion of new technologies can be partly explained by their infancy, which makes the provision of solid background data for an LCA study more difficult, both in terms of assumptions and data. Moreover, paper waste has been traditionally been handled by the three major treatment options and it is difficult to divert waste from such a well established management system.

As already mentioned, a study was located that focuses on the composting of paper (ROU, 2007). The absence of comparisons among different treatment options was the reason for its exclusion. However, if specific environmental arguments are required, this study figures as a reliable source of information for composting of paper, as it compares different compost system configurations.

Environmental indicators

There is a clear preference observed for global warming potential when selecting impact categories. All studies contain results about the climate change contribution, which does not happen for any other category. Primary energy demand is also preferred by the LCA teams, while for the rest of the indicators, only one or two results are presented.

The choice of impact categories is informed by the scope of the study, which is determined by the interest the commissioner of the study has. Therefore, the relative preference for certain indicators is subjective and does not reduce in any way the quality of the LCA.

3.3 Plastics

3.3.1 *Presentation*

According to the Association of European Plastics Manufacturers (APME, now called PlasticsEurope), in 2000 municipal solid waste (MSW) was the primary source of plastic waste and around 70% of waste plastics disposed of through households consisted of packaging. It is important to keep in mind that the plastic waste fraction is very heterogeneous as the number of plastic types is significant. Some plastic types and their application are reported below:

Table 23 Some plastic types and their applications

	Type	Use
Thermoplastics	PET	bottles, carpets and food packaging
	HDPE	bottles for detergents, food products, pipes and toys
	LDPE	cling-film, bin liners and flexible containers
	PP	yoghurt and margarine pots, auto motive parts, fibres, milk crates
	PVC	window frames, flooring, pipes, wallpaper, bottles, medical products
Thermoset	PU	coatings, finishes, mattresses and vehicule seating
	Epoxy	adhesives, sports equipement, electrical and automotive components
	Phenolic	ovens, toaster, automotive parts and circuit boards

According to the APME, high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP) and polyethylene terephthalate (PET) represent 86% of all plastics packaging (APME, 2001). Due to their important volumes in MSW and recyclability, PE/PP and PET are the main focus of specific collection and recycling programmes. In most European countries, the use of polyvinyl chloride (PVC) in bottling applications has been progressively replaced by PET. PVC continues to be used and recycled widely in other applications.

In order to compare the various end-of-life alternatives for plastics, a total of eight publications have been selected and are presented in the following table. The types of plastics assessed are polyethylene [PE], sometimes divided into high density polyethylene [HDPE] and low density polyethylene [LDPE], polyethylene terephthalate [PET], polypropylene [PP], polystyrene [PS] and polyvinyl chloride [PVC]. Some scenarios also consider a mix of plastics types [MIX].

Table 24 Presentation of the selected studies for plastics

Study number	Title	Main author	Year	Geographical scope
1	Bilan environnemental de filières de traitement de plastiques de différentes origines (*Environmental assessment of treatment channels of plastics of different origins*)	BIOIS	2006	France
2	LCA of management options for mixed waste plastics	Shonfield	2008	UK
3	Life Cycle Assessment of energy from solid waste	Finnveden	2000	Sweden
4	A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes	Perugini	2005	Italy
5	LCA: a tool for evaluating and comparing different treatment options for plastic wastes from old television sets	Dodbiba	2007	Japan
6	Solid Waste Management and Greenhouse Gases	US EPA	2006	USA
7	Report for Life Cycle Assessment for paper and packaging waste management scenarios in Victoria	Grant	2001	Australia
8	Kunststoffe aus nachwachsenden Rohstoffen: Vergleichende Ökobilanz für Loose-fill-Packmittel aus Stärke bzw. Polystyrol (*Plastics from renewable resources: Comparative LCA for loose-fill packaging materials made from starch and polystyrene*)	BIfA/IFEU/ Flo-Pak	2006	Germany

It can be seen from this table that the LCAs analyzed covered a variety of countries. 6 out of the 8 studies have been published since 2006. The two studies from 2000 and 2001 have been included despite their age since they were considered as high quality LCAs and had not been used in the previous edition of the report for plastics.

The system diagram below shows the plastics life cycle and the steps where key system boundary issues arise. All studies except study n°5 and n°8 focus on the disposal and recovery stage.

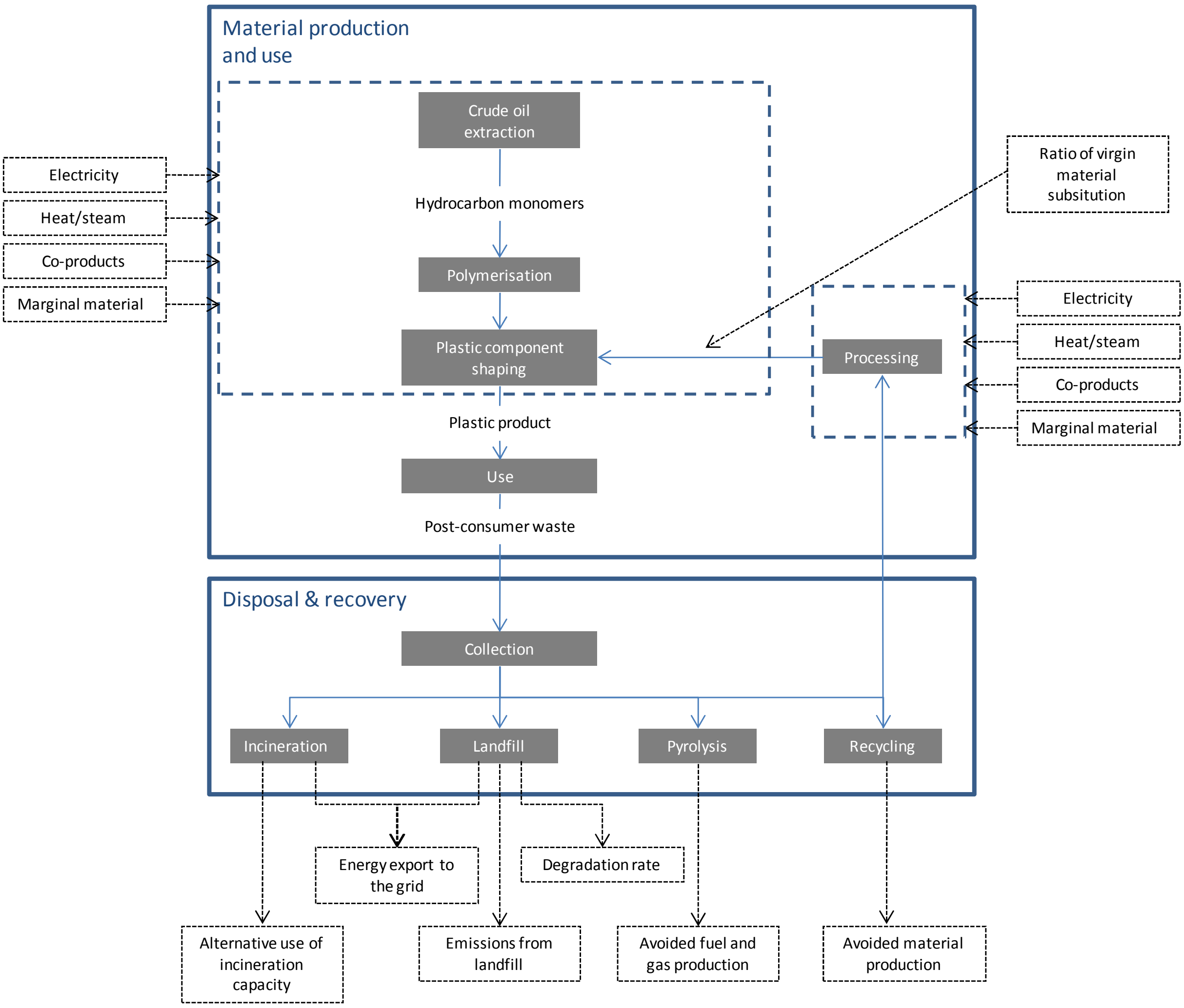

Figure 12 The plastics system and key parameters

3.3.2 Comparison between the various end-of-life options

Alternatives compared

The end-of-life options covered by the selected studies are:

- Recycling
- Incineration with energy recovery
- Landfill
- Pyrolysis

The table below gives an overview of the alternatives that are compared within each case. It also illustrates how often each end-of-life option is represented. It can be seen that 22 cases have been assessed, representing a total of 64 scenarios. The table also highlights that pyrolysis is analyzed in two studies. This end-of-life option is still in early development and the scenarios refer to site-specific processes or pilot plants and use proprietary technologies. The results presented here are thus not considered to be sufficient to draw up conclusions regarding the environmental performances of this end-of-life option compared to other alternatives. However, it still provides information concerning the key parameters that can affect the benefits of this technology. It should also be noted that recycling encompasses both mechanical and feedstock recycling. In the case of mechanical recycling, plastics are shredded into pellets or granulates and serve as new raw materials. Feedstock recycling refers to a change in the chemical structure of the material, where the resulting chemicals can be used to manufacture a range of products, potentially including plastics. An example of feedstock recycling is the use of plastics waste as reducing agents in blast furnaces where it replaces coke for instance. It can be discussed whether this end-of-life option should be classified as recycling since it is a form of energy recovery. However, it is not only the energy content of the material that is used but also its ability to reduce iron oxides. It has thus been decided to consider this alternative as a form of recycling. However, to avoid confusion, this scenario is differentiated from the other scenarios in the results tables.

Table 25 Overview of the end-of-life alternatives compared within each case for plastics

Case	Recycling	Composting	Incineration with electricity recovery only	Incineration with heat or combined heat/ electricity recovery	Landfill	Anaerobic digestion	Pyrolysis	Gasification
1[PE]	x			x	x			
1[PET]	x			x	x			
2[MIX1]	x		x		x		x	
2[MIX2]	x		x		x		x	
2[MIX3]	x		x		x		x	
2[MIX4]	x		x		x		x	
3[PE]	x			x	x			
3[PP]	x			x	x			
3[PS]	x			x	x			
3[PET]	x			x	x			
3[PVC]	x			x	x			
4[MIX]	x		x		x		x	
5[MIX]	x		x					
6[HDPE]	x		x		x			
6[LDPE]	x		x		x			
6[PET]	x		x		x			
7[PET]	x				x			
7[PE]	x				x			
7[PVC]	x				x			
8[PS1]	x*			x				
8[PS2]	x			x				
8[PS3]	x			x				
Total number of cases	**22**	**0**	**9**	**10**	**18**	**0**	**5**	**0**

* Feedstock recycling scenario

Ranking between the various end-of-life options within each scenario

Table 26 compares the end-of-life options compared within each scenario. When the indicator is not taken into account in a given case the line is coloured in grey. This table should be interpreted with care. It shows the relative ranking of the end-of-life solutions within a given case study for specific assumptions and system boundaries. It does not provide sufficient information to be able to give an overall conclusion regarding which alternatives are the best.

Study no 1

In study no 1, recycling, landfill and incineration with energy recovery are compared for PE and PET. For depletion of natural resources and energy demand, landfill appears as the least preferable option for both products. However, for climate change, landfill performs better than incineration with energy recovery. Indeed, the contribution to global warming is assessed over a 100-year period while plastic is assumed not to decompose over this time period, thus there are no emissions of gases contributing to climate change. Recycling appears as the best option for all three indicators.

Study no 2

This study compares a range of mechanical recycling technologies, two technologies for pyrolysis, landfill and incineration with energy recovery for domestic mixed plastic wastes (PE, PET, PP, PS, PVC). Some of the technologies assessed are operated on a large scale while some others still at the pilot stage. This study compares nine different recycling scenarios that differed in terms of sorting and recycling technologies are compared. Depending on the scenario, the sorting technology is either near-infrared (NIR) sorting or density separation. The recycling technologies are similar in all scenarios since the plastic is always first shredded and then extruded to form recycled granulate. As a consequence of these similarities between the various recycling scenarios, the results are of a similar magnitude. To reflect the range of values, it has been decided to use the highest and lowest results for each indicator.

Regarding pyrolysis, the two technologies assessed are feedstock recycling (leading to products substituting naphtha, paraffin and refinery gas) and conversion to diesel. Feedstock recycling and conversion to diesel is suitable for polyolefins[2] (i.e. PE and PP) and polystyrene. PET and nylon have also been processed through feedstock recycling on a semi-commercial basis. It should be also be noted that pyrolysis is not yet considered as a mature technology and that relatively poor data is available on pyrolysis technologies. Thus, the two pyrolysis scenarios assessed are not sufficient to draw general conclusions on the overall environmental performance of pyrolysis.

The results from this study show that recycling performs better than the other alternatives for the impacts on depletion of natural resources and climate change while pyrolysis is the preferred alternative for energy demand. This can be explained by the fact that the avoided impacts associated with displacing production of fuels exceed the credits gained by avoiding the use of gas to produce electricity. The least favourable alternative is landfill for depletion of natural resources and energy demand but landfill performs better than incineration regarding climate change. As for the previous study, the explanation lays in the choice of a 100-year time horizon to assess the global warming potential.

Study no 3

In study no 3, recycling, incineration with energy recovery and landfill are compared over a large range of plastics: PE, PP, PS, PET and PVC. The study highlights that recycling is the preferred alternative for all types of plastics for climate change, energy demand and depletion of natural resources. Landfill is the worst alternative for all materials for those three indicators including climate change. This result thus differs from both previous studies but can be explained by the choice of the time period. In this study, the authors have chosen a hypothetical infinite time period when inventorying emissions which implies that complete degradation of landfilled material is assumed.

Study no 4

This study assesses the environmental performances of recycling, incineration with energy recovery, landfill and pyrolysis for a mix of PE and PET. For the pyrolysis scenario, low-temperature pyrolysis is applied to the polyolefins fraction while the PET fraction not suitable for pyrolysis goes to mechanical recycling.

Unlike the previously mentioned studies, contribution to depletion of natural resources is not analysed but water consumption is. Recycling appears as the preferred alternative for the three indicators. Landfill is the worst option regarding energy demand and water consumption but performs better than incineration regarding climate change. The limited impacts on climate change from landfills are again explained by the choice of a time period of 100 years during which very little degradation takes place.

[2] *A **polyolefin** is a polymer produced from a simple olefin as a monomer. For example, polyethylene is the polyolefin produced by polymerizing the olefin ethylene. Polypropylene is another common polyolefin which is made from the olefin propylene.*

Study no 5

This study consists of an LCA of two treatment options for plastics wastes from discarded TV sets. All steps starting from the extraction of the resources required for the plastics production and up to the incineration or recycling into new TV sets are included. At the disposal stage, incineration with energy recovery and recycling are compared for a mix of PE, PS and PVC regarding depletion of natural resources and climate change. Recycling is found to be preferable to incineration for both indicators.

Study no 6

This study compares recycling, incineration with energy recovery and landfill for HDPE, LDPE and PET regarding only two indicators: climate change and energy demand. Once again, recycling appears as the best alternative. Thanks to the energy credit, incineration performs better than landfill in terms of energy demand. However, landfill is preferred to incineration for climate change since no emissions are accounted for during the 100-year time period considered.

Study no 7

This study compares recycling and landfill for PET, HDPE and PVC. For climate change and energy demand, recycling performs better. For water consumption, the picture is less clear since recycling is preferred for PVC but not for PET and HDPE. It is indeed assumed in the study that no water is consumed in the event the material is landfilled and that for PET and HDPE recycling water use (due to washing the collected plastics) is higher than water use in avoided virgin plastic production.

Study no 8

This LCA looks at the complete end-of-life of different types of plastics and bioplastics packaging. For plastics, three different recycling scenarios are compared to incineration with energy recovery for recycled PS packaging (made from polystyrene production wastes). Two of the three recycling scenarios correspond to mechanical recycling scenarios in which the PS is regranulated into similar material. The difference between both scenarios is that the recycling scenario from case 8[PS2] includes the avoided material production within the system boundaries while the other one from case 8[PS3] does not. In this latter case, the recycled material is assumed to be sold on the market with a large range of possible applications that have not been modelled. The remaining recycling scenario, from case 8[PS1], is a feedstock recycling scenario in which the PS is recovered in blast furnaces and used as a replacement for coke. Feedstock recycling which, as already mentioned, can be defined as a change in the chemical structure of the material, where the resulting chemicals are used for another purpose than producing the original material. The use of PS as a reducing agent in blast furnaces is usually considered to fall under this definition. It is debatable whether the scenario should be classified as recycling rather than energy recovery but the choice has been made in this review to refer to it as a recycling scenario as argued above.

Regarding climate change, the three recycling scenarios perform better than incineration with energy recovery. Concerning the energy demand, the mechanical scenarios are more advantageous than incineration but incineration is preferable to feedstock recycling.

Table 26 Ranking of end-of-life options within each scenario for plastics (to be continued)

	Case	Recycling	Incineration with energy recovery	Landfill	Pyrolysis
Climate change (kg CO2 eq)	1[PE]	+++	+	++	
	1[PET]	+++	+	++	
	2[MIX1]	+++	+	++	++
	2[MIX2]	+++	+	++	++
	2[MIX3]	+++	+	++	++
	2[MIX4]	+++	+	++	++
	3[PE]	+++	++	+	
	3[PP]	+++	++	+	
	3[PS]	+++	++	+	
	3[PET]	+++	++	+	
	3[PVC]	+++	+++	+	
	4[MIX]	+++	+	++	++
	5[MIX]	+++	+		
	6[HDPE]	+++	+	++	
	6[LDPE]	+++	+	++	
	6[PET]	+++	+	++	
	7[PET]	+++		+	
	7[PE]	+++		+	
	7[PVC]	+++		+	
	8[PS1] *	+++ *	+		
	8[PS2]	+++	+		
	8[PS3]	+++	+		
Depletion of abiotic sources (kg Sb eq)	1[PE]	+++	++	+	
	1[PET]	+++	++	+	
	2[MIX1]	+++	++	+	++
	2[MIX2]	+++	++	+	++
	2[MIX3]	+++	++	+	++
	2[MIX4]	+++	++	+	++
	3[PE]	+++	++	+	
	3[PP]	+++	++	+	
	3[PS]	+++	++	+	
	3[PET]	+++	+	++	
	3[PVC]	+++	+	++	
	5[MIX]	+++	+		
	Studies n°4, 6, 7 and 8 do not include this indicator				

* Feedstock recycling scenario

+++	best option
++	intermediary option
+	worst option
	option not assessed

	Case	Recycling	Incineration with energy recovery	Landfill	Pyrolysis
Energy demand (MJ)	1[PE]	+++	++	+	
	1[PET]	+++	++	+	
	2[MIX1]	++	++	+	+++
	2[MIX2]	++	++	+	+++
	2[MIX3]	++	++	+	+++
	2[MIX4]	++	++	+	+++
	3[PE]	+++	++	+	
	3[PP]	+++	++	+	
	3[PS]	+++	++	+	
	3[PET]	+++	++	+	
	3[PVC]	+++	++	+	
	4[MIX]	+++	++	+	++
	6[HDPE]	+++	++	+	
	6[LDPE]	+++	++	+	
	6[PET]	+++	++	+	
	7[PET]	+++		+	
	7[PE]	+++		+	
	7[PVC]	+++		+	
	8[PS1] *	+ *	+++		
	8[PS2]	+++	+		
	8[PS3]	+++	+		
	Study n°5 does not include this indicator				
Water consumption (m3)	4[MIX]	+++	++	+	++
	7[PET]	+		+++	
	7[PE]	+		+++	
	7[PVC]	+++		+	
	Studies n°1, 2, 3, 5, 6 and 8 do not include this indicator				

* Feedstock recycling scenario

+++	best option
++	intermediary option
+	worst option
	option not assessed

3.3.3 Detailed comparison between the various treatment options

This section focuses on the comparison of the various treatment options indicator by indicator. The alternatives serving as a reference for comparison are recycling and incineration with energy recovery.

For each indicator, the differences resulting from the comparison of the various end-of-life options compared to recycling and to incineration with energy recovery are first presented in tables (values rounded up to the nearest ten in the tables). The results are then grouped by range of 25% difference on the following graphs that follow in order to highlight the main tendencies.

Climate change

Figure 13 clearly shows that recycling is preferable to the other end-of-life alternatives in all cases. Recycling presents an unambiguous advantage to incineration since for 63% of the cases (12 cases out of 19), the difference between both alternatives exceeds 150%. The low recycling benefits for case 3[PVC] are explained by the fact that PVC is hard to recycle compared to the other plastics. In case 8[PS1], the recycling option assessed is material recovery via blast furnaces, which explains the low advantage of recycling over incineration in this specific case. When recycling is compared to landfill, recycling is at least 100% better for 89% of the cases (16 cases out of 18). The studies comparing recycling and pyrolysis also conclude that recycling is better for this indicator, with recycling being 80% to 110% better for study no2 and 26% better for study no 4.

Figure 14 compares the various alternatives to incineration with energy recovery. It highlights that incineration is globally a worse option regarding climate change. For instance, landfill performs better than incineration in 67% of the cases (10 cases out of 15). Indeed, the contribution to climate change is usually assessed over a 100-year period, while plastic decomposes over a much longer time period. Degradation has thus not been taken into account in most studies, resulting in a low contribution to climate change for the landfill scenarios. This is confirmed by the results from study no 3. In this study, a hypothetical infinite time period is assumed and incineration appears preferable to landfill. In addition, the superiority of pyrolysis compared to incineration shows that the credits gained from the avoided production of petrochemical products are superior to the energy credits obtained with incineration (credits based on the UK electricity mix for study no 2 and Italian mix for study no 4).

Table 27 Relative difference between the impacts from the different end-of-life options vs. recycling for climate change for plastics. A positive value means that recycling is preferable to the other end-of-life option. A negative value means that recycling causes more environmental impact than the other end-of-life option.

	Recycling versus other alternatives										
N° case	1[PE]	1[PET]	2[MIX1]	2[MIX2]	2[MIX3]	2[MIX4]	3[PE]	3[PP]	3[PS]	3[PET]	3[PVC]
Incineration with energy recovery	310%	200%	390%	710%	390%	710%	990%	50%	100%	210%	0%
Landfill	100%	100%	130%	150%	130%	150%	1080%	60%	130%	220%	10%
Pyrolysis			100%	110%	90%	80%					

	Recycling versus other alternatives										
N° case	4[MIX]	5[MIX]	6[HDPE]	6[LDPE]	6[PET]	7[PET]	7[PE]	7[PVC]	8[PS1]*	8[PS2]	8[PS3]
Incineration with energy recovery	430%	40%	170%	150%	170%				10%*	60%	100%
Landfill	290%		100%	100%	100%	130%	160%	110%			
Pyrolysis	30%										

* Feedstock recycling scenario

Table 28 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for climate change for plastics. A positive value means that incineration is preferable to the other end-of-life option. A negative value means that incineration causes more environmental impact than the other end-of-life option.

	Incineration with energy recovery versus other alternatives										
N° case	1[PE]	1[PET]	2[MIX1]	2[MIX2]	2[MIX3]	2[MIX4]	3[PE]	3[PP]	3[PS]	3[PET]	3[PVC]
Recycling	-150%	-200%	-130%	-120%	-130%	-120%	-90%	-30%	-50%	-190%	0%
Landfill	-100%	-100%	-90%	-90%	-90%	-90%	10%	10%	20%	10%	10%
Pyrolysis			-100%	-100%	-100%	-100%					

	Incineration with energy recovery versus other alternatives							
N° case	4[MIX]	5[MIX]	6[HDPE]	6[LDPE]	6[PET]	8[PS1]*	8[PS2]	8[PS3]
Recycling	-80%	-30%	-250%	-280%	-240%	-10%*	-40%	-50%
Landfill	-30%		-100%	-100%	-100%			
Pyrolysis	-80%							
Study n°7 does not include a comparison with incineration with energy recovery for this indicator and thus is not included in this table								

* Feedstock recycling scenario

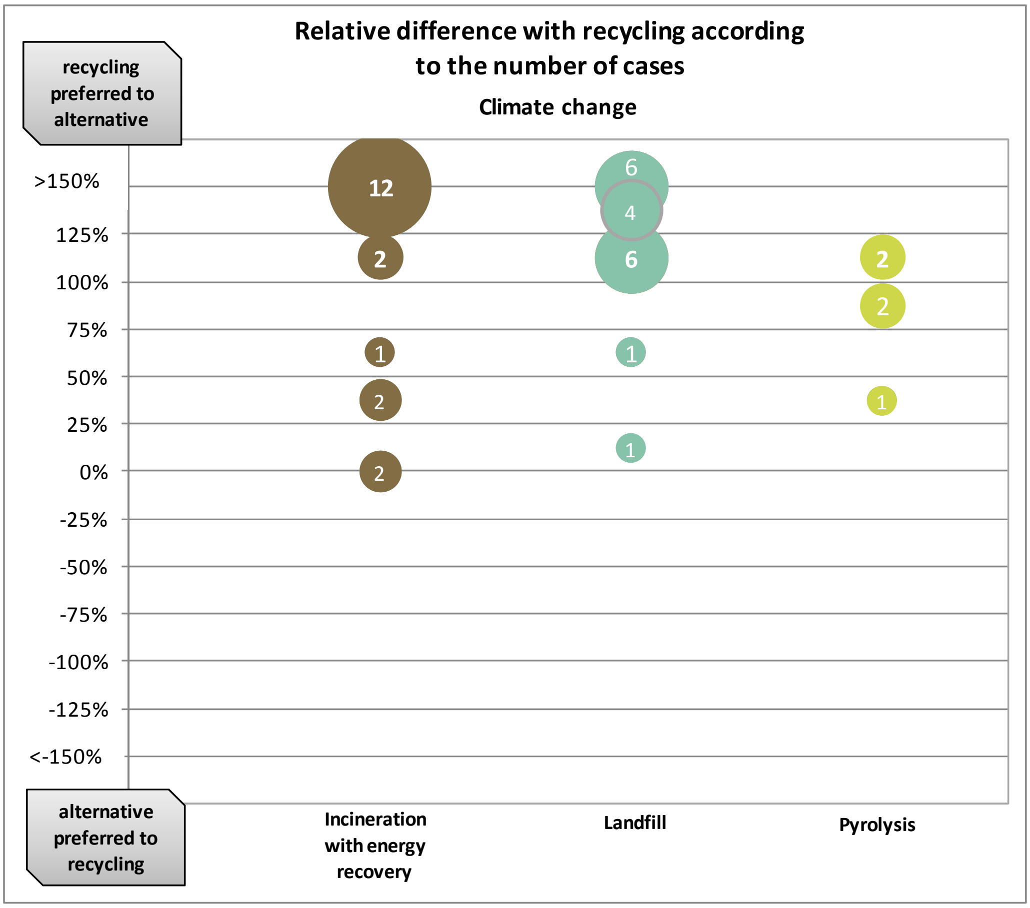

Figure 13 Relative difference between the impacts from the different end-of-life options vs. recycling for climate change for plastics. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

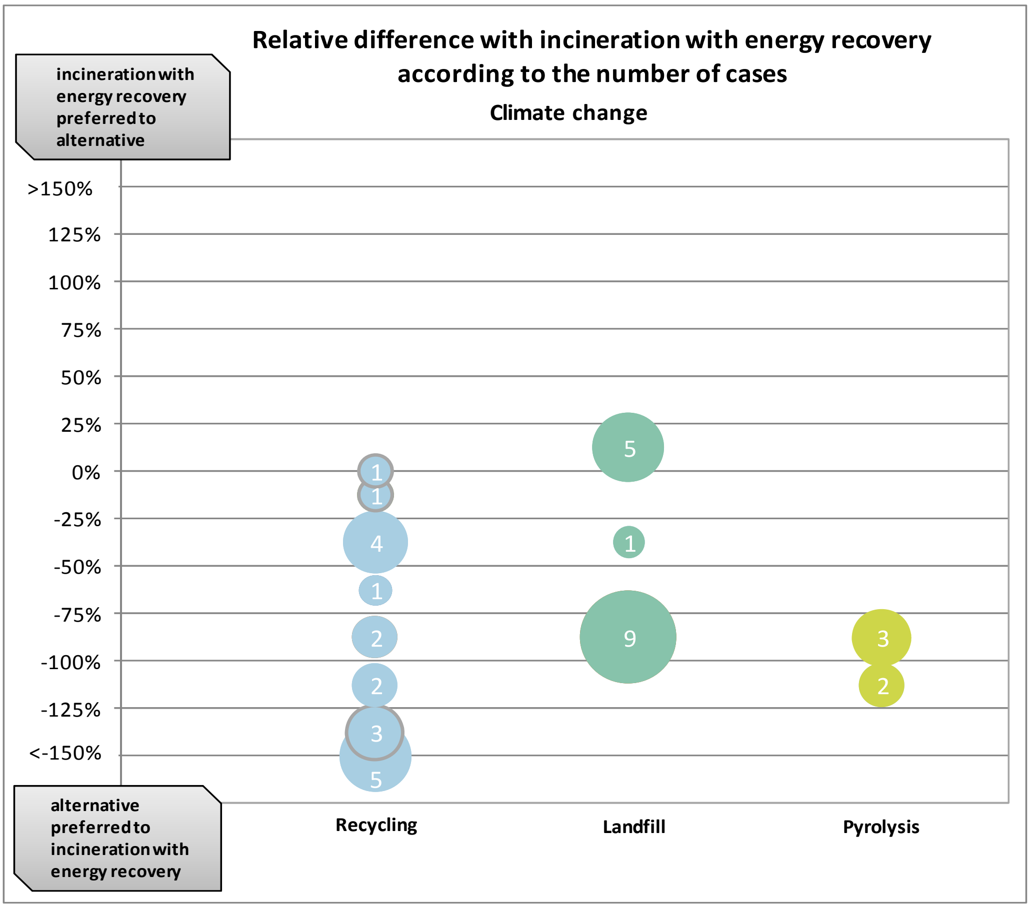

Figure 14 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for climate change for plastics. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Depletion of natural resources

Figure 15 shows that recycling is more favourable than the other alternatives regarding depletion of natural resources. The difference is the highest for landfill while the benefits of recycling over pyrolysis are lower, remaining in the range 0-50%.

Figure 16 illustrates the comparison between incineration with energy recovery and the other alternatives. For the four cases, pyrolysis appears more advantageous than incineration. On the contrary, landfill is on average worse than incineration. However, in two cases from study no 3, landfill presents more benefits than incineration. These cases concern PET and PVC which are assumed to have a lower heating value of 29 and 21 MJ/ton, respectively compared to heating values above 40 MJ/ton for the other types of plastics analysed in study no 4. As a result, the energy gain is lower.

Table 29 Relative difference between the impacts from the different end-of-life options vs. recycling for depletion of natural resources for plastics. A positive value means that recycling is preferable to the other end-of-life option. A negative value means that recycling causes more environmental impact than the other end-of-life option.

	Recycling versus other alternatives											
N° case	1[PE]	1[PET]	2[MIX1]	2[MIX2]	2[MIX3]	2[MIX4]	3[PE]	3[PP]	3[PS]	3[PET]	3[PVC]	5[MIX]
Incineration with energy recovery	70%	80%	70%	60%	70%	60%	100%	100%	100%	100%	100%	60%
Landfill	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	
Pyrolysis			40%	20%	40%	20%						
Studies n°4, 6, 7 and 8 do not include a comparison with recycling for this indicator and thus are not included in this table												

Table 30 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for depletion of natural resources for plastics. A positive value means that incineration is preferable to the other end-of-life option. A negative value means that incineration causes more environmental impact than the other end-of-life option.

	Incineration with energy recovery versus other alternatives											
N° case	1[PE]	1[PET]	2[MIX1]	2[MIX2]	2[MIX3]	2[MIX4]	3[PE]	3[PP]	3[PS]	3[PET]	3[PVC]	5[MIX]
Recycling	-190%	-430%	-200%	-130%	-200%	-130%	-10690%	-6080%	-13490%	-51770%	-4330%	-40%
Landfill	100%	100%	100%	100%	100%	100%	60%	50%	40%	-80%	-80%	
Pyrolysis			-80%	-80%	-90%	-90%						
Studies n°4, 6, 7 and 8 do not include a comparison with incineration with energy recovery for this indicator and thus are not included in this table												

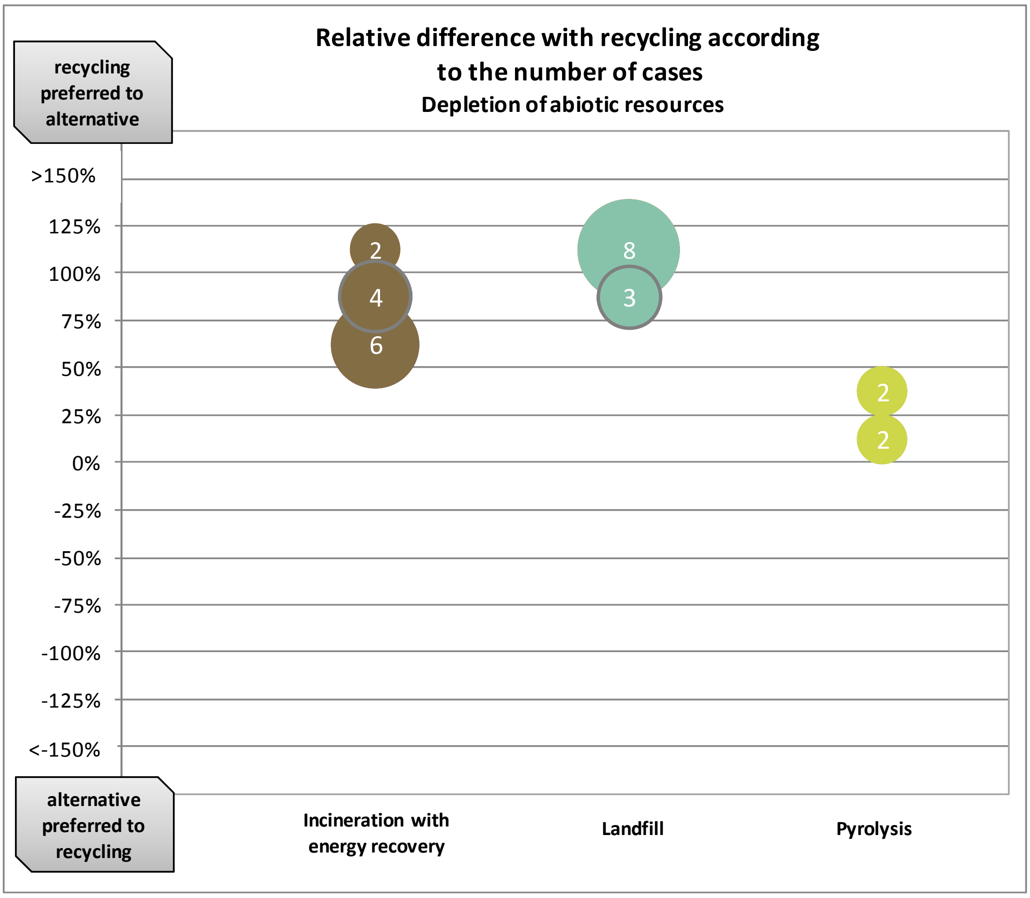

Figure 15 Relative difference between the impacts from the different end-of-life options vs. recycling for depletion of natural resources for plastics. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

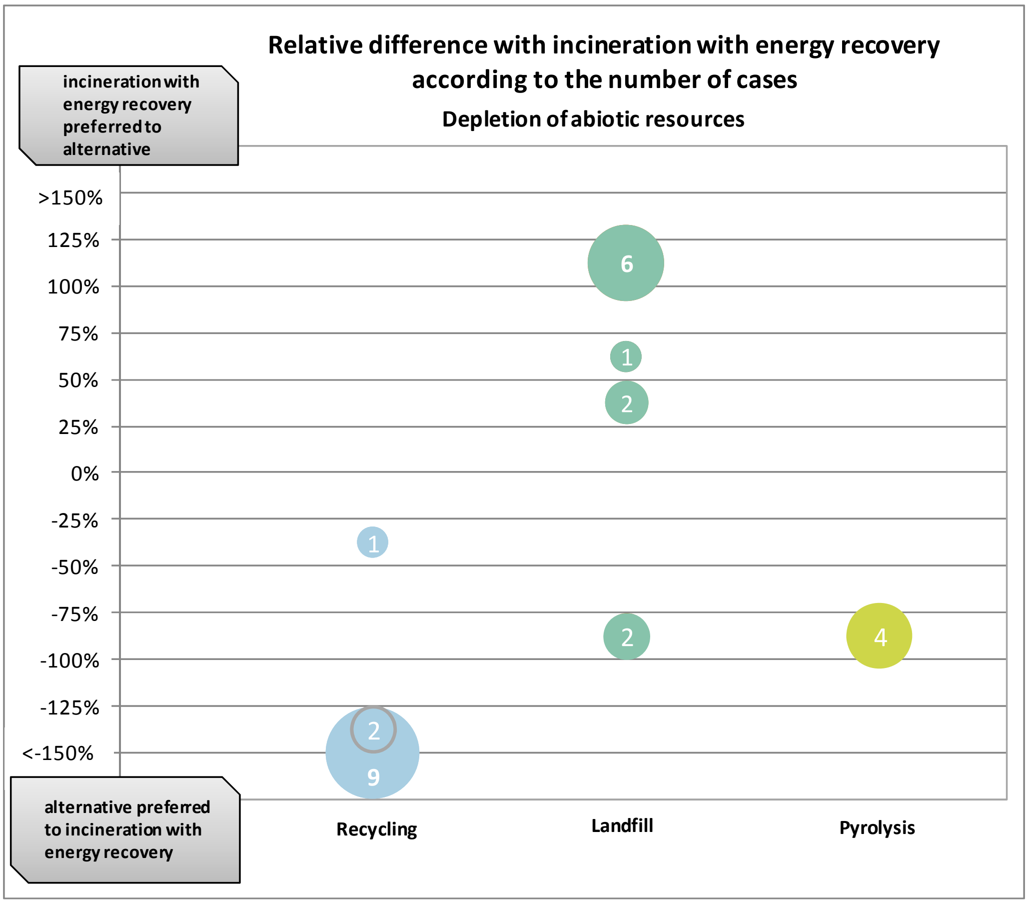

Figure 16 Relative difference between the impacts from the different end-of-life options vs. incineration for depletion of natural resources for plastics. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Energy demand

As shown in Figure 17, recycling appears more favourable than landfill in all the cases. Regarding the comparison between recycling and incineration, though the majority of analysed scenarios are in favour of recycling, three cases attribute an advantage to incineration. Two cases belong to study no 2 and the explanation is that the sorting and recycling technologies used in these cases require more energy. The last case corresponds to the feedstock recycling scenario from study no 8 (case 8[PS1]) and should anyway not be compared with the other recycling scenarios since the process is completely different. In this specific case, the PS waste is not recycled into new plastics products but is instead used as a reducing agent in blast furnaces. The results from this scenario show that this form of recycling brings fewer benefits than mechanical recycling. The four cases for which pyrolysis are analysed suggest that pyrolysis is less energy-demanding than recycling. These scenarios receive large primary energy benefits from avoiding the production of petrochemical products.

Figure 18 unambiguously highlights that incineration performs better than landfill but worse than pyrolysis. Indeed, landfill has low energy requirements but receives fewer credits for avoided impacts. Some studies do not assume any energy production from biogas (studies no 2 and 4). This explains why incineration performs 700% better than landfill for case 4[MIX].

Table 31 Relative difference between the impacts from the different end-of-life options vs. recycling for energy demand for plastics. A positive value means that recycling is preferable to the other end-of-life option. A negative value means that recycling causes more environmental impact than the other end-of-life option

	Recycling versus other alternatives										
N° case	1[PE]	1[PET]	2[MIX1]	2[MIX2]	2[MIX3]	2[MIX4]	3[PE]	3[PP]	3[PS]	3[PET]	3[PVC]
Incineration with energy recovery	60%	80%	10%	-100%	10%	-100%	30%	10%	20%	70%	30%
Landfill	100%	100%	100%	110%	100%	110%	70%	100%	100%	100%	100%
Pyrolysis			-40%	-200%	-50%	-210%					

	Recycling versus other alternatives									
N° case	4[MIX]	6[HDPE]	6[LDPE]	6[PET]	7[PET]	7[PE]	7[PVC]	8[PS1]*	8[PS2]	8[PS3]
Incineration with energy recovery	220%	90%	90%	90%				-10%*	60%	150%
Landfill	1050%	100%	100%	100%	110%	110%	120%			
Pyrolysis										
Study n°5 does not include a comparison with recycling for this indicator and thus is not included in this table										

* Feedstock recycling scenario

Table 32 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for energy demand for plastics. A positive value means that incineration is preferable to the other end-of-life option. A negative value means that incineration causes more environmental impact than the other end-of-life option.

	Incineration with energy recovery versus other alternatives										
N° case	1[PE]	1[PET]	2[MIX1]	2[MIX2]	2[MIX3]	2[MIX4]	3[PE]	3[PP]	3[PS]	3[PET]	3[PVC]
Recycling	-130%	-360%	-10%	50%	-10%	50%	-40%	-10%	-30%	-210%	-40%
Landfill	100%	100%	100%	100%	100%	100%	60%	100%	100%	100%	100%
Pyrolysis			-50%	-50%	-60%	-60%					

	Incineration versus other alternatives						
N° case	4[MIX]	6[HDPE]	6[LDPE]	6[PET]	8[PS1]*	8[PS2]	8[PS3]
Recycling	-180%	-700%	-780%	-1570%	10%*	-40%	-60%
Landfill	700%	110%	110%	120%			
Pyrolysis							
Studies n°5 and 7 do not include a comparison with incineration with energy recovery for this indicator and thus are not included in this table							

* Feedstock recycling scenario

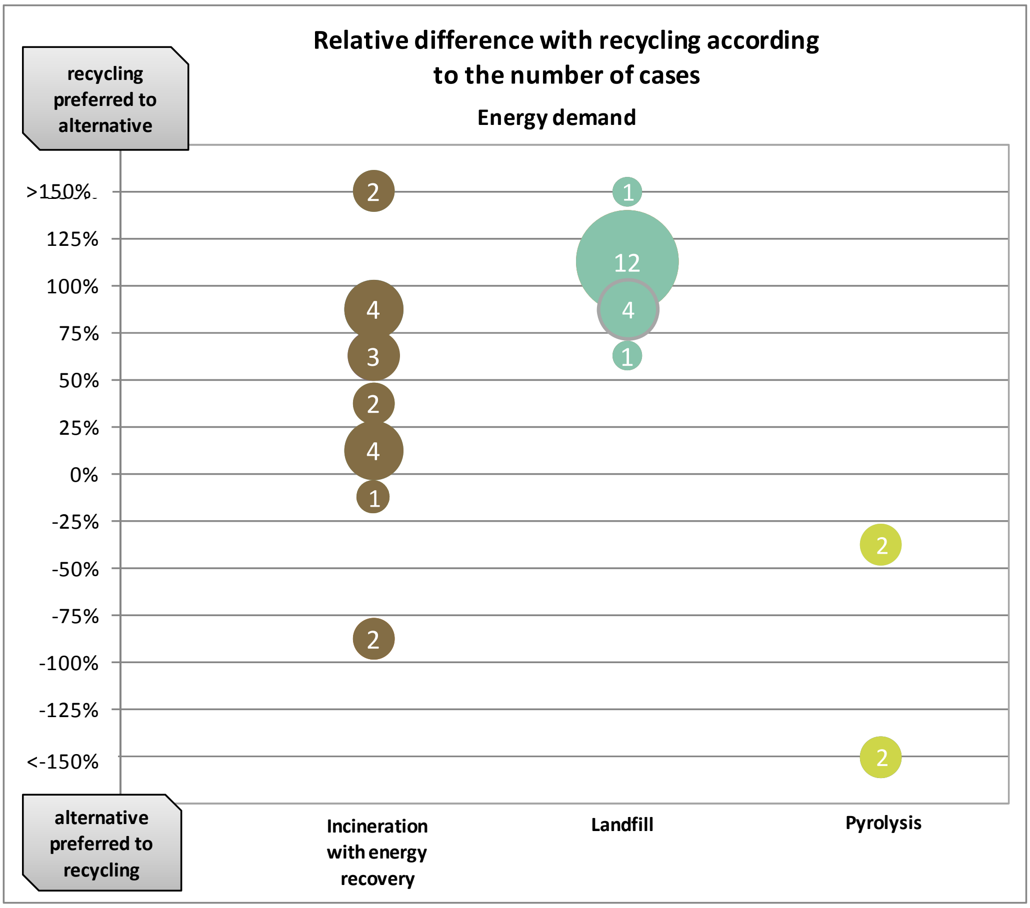

Figure 17 Relative difference between the impacts from the different end-of-life options vs. recycling for energy demand for plastics. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

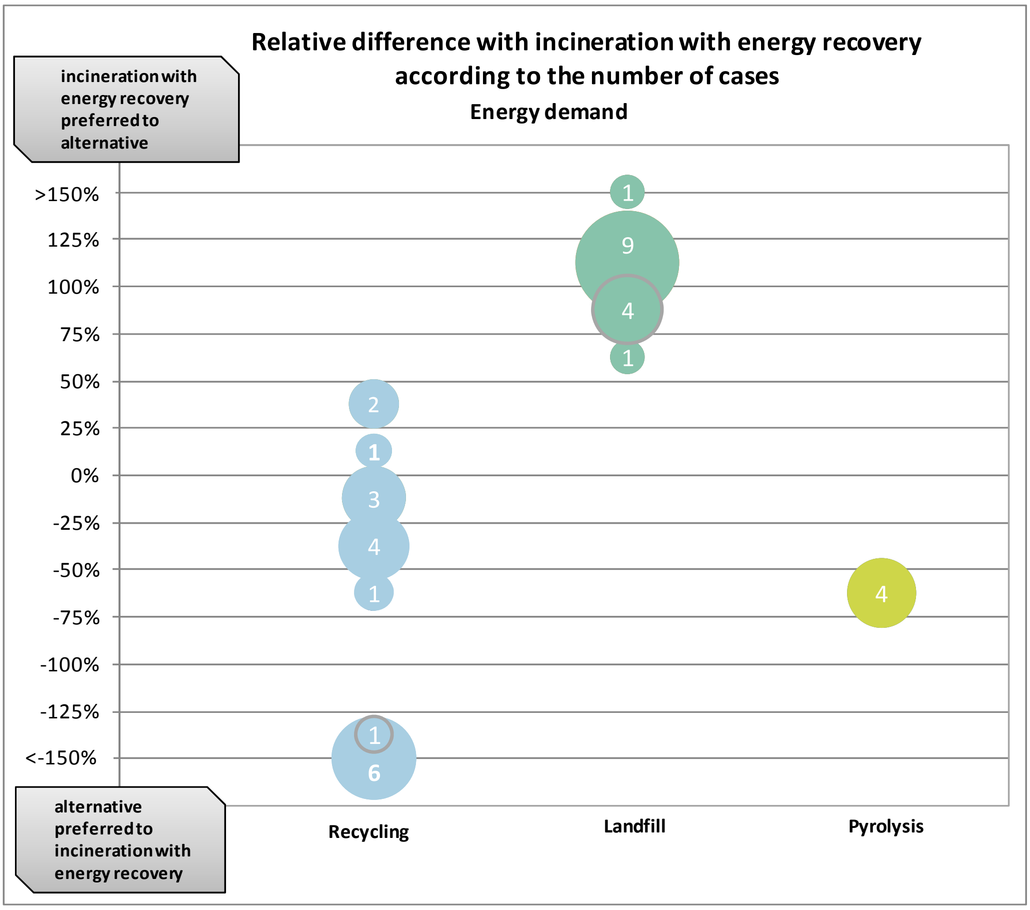

Figure 18 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for energy demand for plastics. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Water consumption

Only studies no 4 and 7 include the indicator water consumption and study no 7 only compares recycling and landfill. The general conclusion from study no 4 is that recycling is preferable by far to incineration, landfill and pyrolysis. The results from study no 7 differ depending on the material. Recycling appears better for PVC but not for PET and PE. For PET and PE recycling, water use, due to washing of the collected plastics, is higher than water use in avoided virgin plastic production. This is not the case for PVC, which requires more water to be produced.

The comparison of landfill and pyrolysis versus incineration is conducted only in study no 4. It points out that recycling and pyrolysis consume less water than incineration while the water consumed for landfill and incineration is similar.

Table 33 Relative difference between the impacts from the different end-of-life options vs. recycling for water consumption for plastics. A positive value means that recycling is preferable to the other end-of-life option. A negative value means that recycling causes more environmental impact than the other end-of-life option

	Recycling versus other alternatives			
N° case	4[MIX]	7[PET]	7[PE]	7[PVC]
Incineration with energy recovery	1220%			
Landfill	1250%	-100%	-100%	100%
Pyrolysis	300%			
Only studies n°4 and 7 include a comparison with recycling for this indicator				

Table 34 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for water consumption for plastics. A positive value means that incineration is preferable to the other end-of-life option. A negative value means that incineration causes more environmental impact than the other end-of-life option.

	Incineration versus other alternatives
N° case	4[MIX]
Recycling	-90%
Landfill	0%
Pyrolysis	-70%
Only study n°4 includes a comparison with incineration with energy recovery for this indicator	

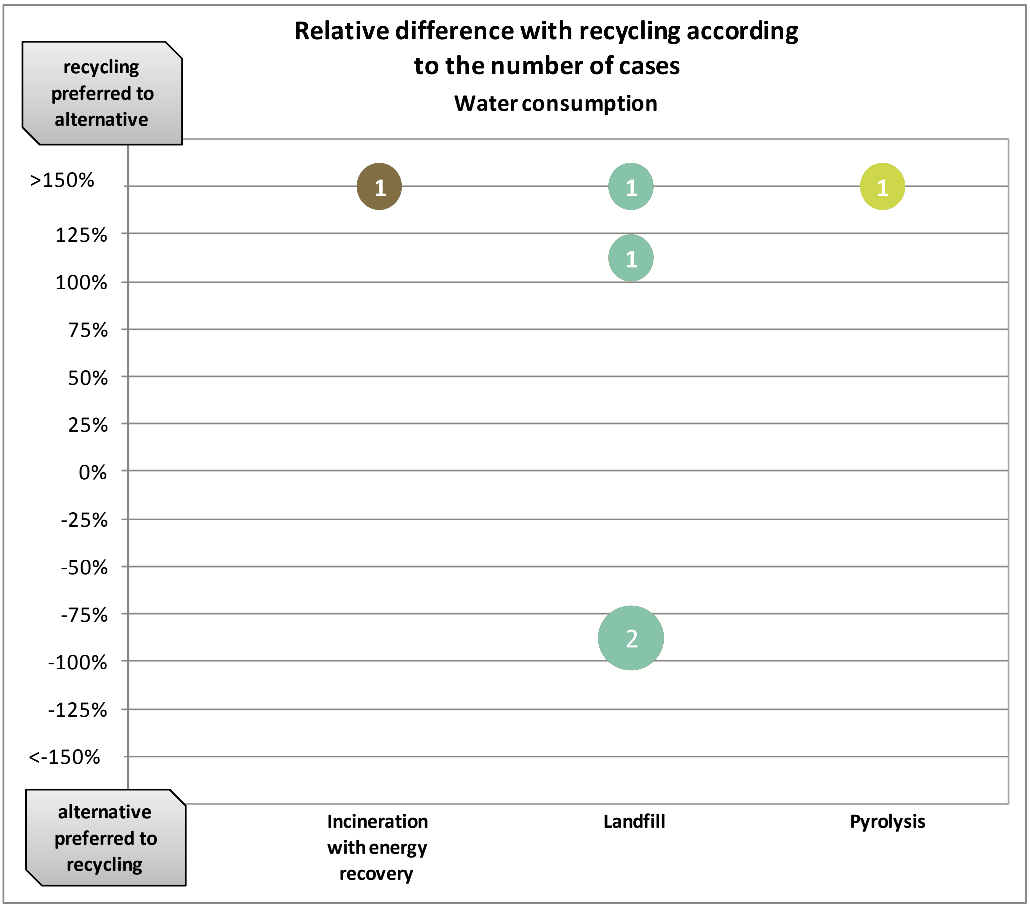

Figure 19 Relative difference between the impacts from the different end-of-life options vs. recycling for water consumption for plastics. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

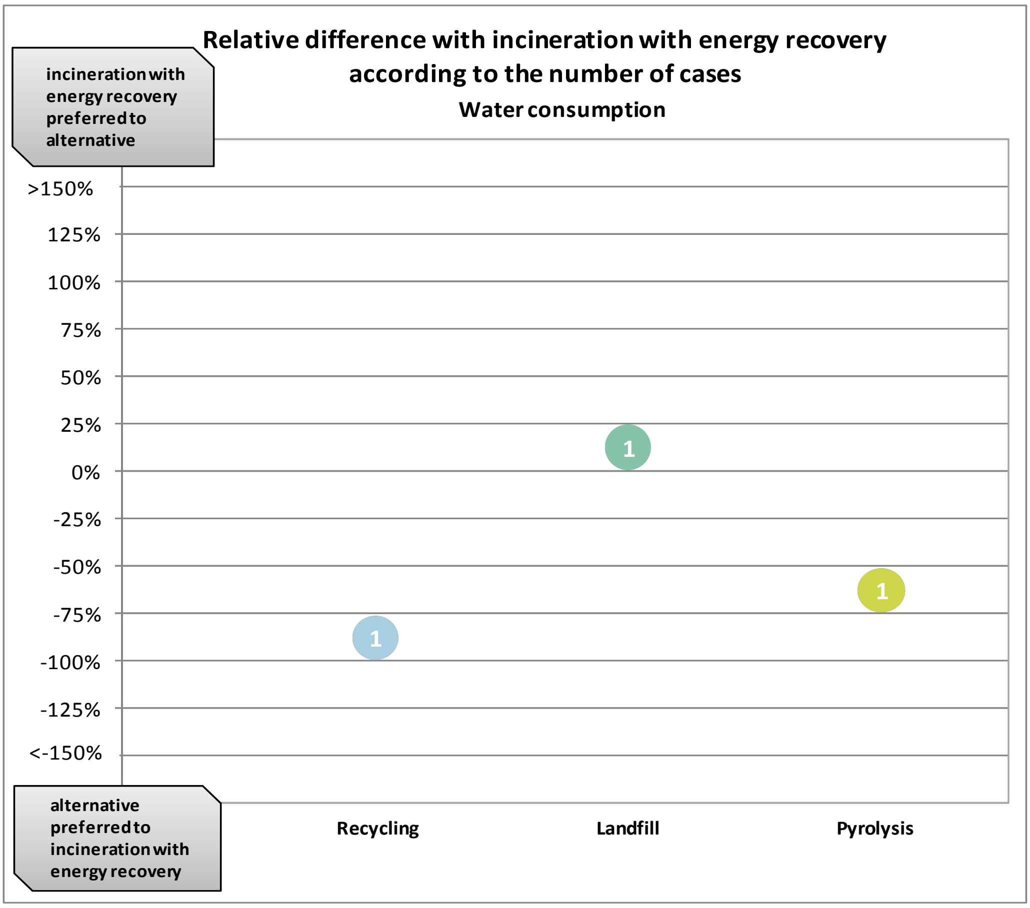

Figure 20 Relative difference between the impacts from the different end-of-life options vs. incineration for water consumption for plastics. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Other indicators

Acidification

Recycling appears as the preferable option in most cases while landfill is the least preferable option. The feedstock recycling (case 8[PS1]) appears again as an exception in that it is less advantageous than incineration.

Table 35 Ranking of end-of-life options within each scenario for acidification for plastics

	Case	Recycling	Incineration with energy recovery	Landfill	Pyrolysis
Acidification (kg SO2 eq)	1[PE]	+++	++	+	
	1[PET]	+++	++	+	
	2[MIX1]	+++	++	+	++
	2[MIX2]	+++	++	+	++
	2[MIX3]	+++	++	+	++
	2[MIX4]	+++	++	+	++
	3[PE]	++	+++	+	
	3[PP]	+++	++	+	
	3[PS]	+++	++	+	
	3[PET]	+++	++	+	
	3[PVC]	+++	++	+	
	8[PS1] *	+ *	+++		
	8[PS2]	+++	+		
	8[PS3]	+++	+		
	Studies n°4, 5, 6 and 7 do not include this indicator				

+++	best option
++	intermediary option
+	worst option
	option not assessed

* Feedstock recycling scenario

Photochemical oxidation

The majority of cases points out that recycling is the preferred option and landfill the worst option regarding this indicator. However, in the case of PVC recycling, only assessed in case 7[PVC], landfill is preferable to recycling.

Table 36 Ranking of end-of-life options within each scenario for photochemical oxidation for plastics

	Case	Recycling	Incineration with energy recovery	Landfill	Pyrolysis
Photochemical oxidation (kg ethylene eq)	1[PE]	+++	+	++	
	1[PET]	+++	+	++	
	2[MIX1]	+++	++	+	++
	2[MIX2]	+++	++	+	++
	2[MIX3]	+++	++	+	++
	2[MIX4]	+++	++	+	++
	3[PE]	++	+++	+	
	3[PP]	+++	++	+	
	3[PS]	+++	++	+	
	3[PET]	+++	++	+	
	3[PVC]	+++	++	+	
	7[PET]	+++		+	
	7[PE]	+++		+	
	7[PVC]	+		+++	
	8[PS1] *	++ *	++		
	8[PS2]	+++	+		
	8[PS3]	+++	+		
	Studies n°4, 5 and 6 do not include this indicator				

+++	best option
++	intermediary option
+	worst option
	option not assessed

* Feedstock recycling scenario

Eutrophication

No clear conclusion can be draw up for this indicator but still recycling and pyrolysis both emerge as the options bringing more benefits. Landfill is in most cases the worst option.

Table 37 Ranking of end-of-life options within each scenario for eutrophication for plastics

	Case	Recycling	Incineration with energy recovery	Landfill	Pyrolysis
Eutrophication (kg PO4 eq)	1[PE]	+++	+	++	
	1[PET]	+++	+	++	
	2[MIX1]	+++	++	+	++
	2[MIX2]	++	++	+	+++
	2[MIX3]	++	++	+	+++
	2[MIX4]	++	++	+	+++
	3[PE]	+	++	+++	
	3[PP]	+++	++	+	
	3[PS]	++	+++	+	
	3[PET]	+++	++	+	
	3[PVC]	+++	++	+	
	8[PS1] *	+ *	+++		
	8[PS2]	+++	+		
	8[PS3]	+++	+		
	Studies n°4, 5, 6 and 7 do not include this indicator				

+++	best option
++	intermediary option
+	worst option
	option not assessed

* Feedstock recycling scenario

Human toxicity

Once again, recycling and pyrolysis are the preferable options while landfill clearly appears as the worst option.

Table 38 Ranking of end-of-life options within each scenario for human toxicity for plastics

	Case	Recycling	Incineration with energy recovery	Landfill	Pyrolysis
Human toxicity (kg 1,4-DB eq)	1[PE]	+++	++	+	
	1[PET]	+++	++	+	
	2[MIX1]	+++	++	+	++
	2[MIX2]	++	++	+	+++
	2[MIX3]	+++	++	+	++
	2[MIX4]	++	++	+	+++
	3[PE]	+++	++	+	
	3[PP]	+++	++	+	
	3[PS]	++	+++	+	
	3[PET]	+++	++	+	
	3[PVC]	+++	++	+	
	Studies n°4, 5, 6, 7 and 8 do not include this indicator				

+++	best option
++	intermediary option
+	worst option
	option not assessed

Key parameters

The assumptions that have been identified as potential key parameters are:

- the time perspective taken into account for the plastics degradation in landfills
- the avoided material production and substitution ratio
- the type of energy recovery
- the efficiency of the sorting process and the “default” disposal option

The role and influence of each of these parameters are investigated below.

Time perspective

A specificity of landfill is the **time frame** since emissions from landfills can spread over very long time periods, often thousands of years or longer. The potential emissions thus need to be integrated over a certain time period.

A 100-year period is chosen in most LCAs but there is a debate around this issue among LCA experts. It can for instance be noted that SETAC recommends infinite emissions consideration (Thomas & McDougall, 2005). **This choice of the time period mainly affects the climate change potential since emissions of GHG are directly affected by this parameter**. This issue is critical, especially for plastics, since as they are made of fossil carbon their degradation is very slow, so that emissions take place over a time horizon that largely exceeds 100 years. Among the studies assessed, study no 3 assumes an infinite time period while the other studies stick to the usual 100-year time span.

To illustrate the importance of this parameter, a sensitivity analysis is conducted in study no 3 (Finnveden, 2000). The results are compared for an infinite time period versus a 100-year time horizon. Under the 100-year assumption, it is considered that only 3% of the carbon contained in plastics is released while full degradation is assumed in the case of an infinite time horizon. The results obtained show that this change induces a new ranking between the various alternatives because, unlike in the base case, **landfill becomes a more favourable option than incineration for a 100-year time period** as illustrated below.

Table 39 Analysis of the influence of the time perspective on the performances of landfill in Finnveden et al., 2000

Time perspective	Ranking between alternatives for the potential impact on climate change
Infinite	recycling < ***incineration*** < **landfill**
100 years	recycling < **landfill** < ***incineration***

This conclusion points out that this parameter should be given special attention and it is thus interesting to check how this parameter can explain the differences between the various cases analysed in this study. It should first be noted that cases from study no 3 are the only cases for which landfill is the worst alternative regarding the climate change potential as illustrated on Figure 21. For all the other cases, landfill appears to be preferable to incineration for this indicator. This observation therefore tends to confirm that the time perspective is a key assumption that significantly affects the assessment of the environmental performance of landfill. It can also be noted that in studies 1, 2 and 6 the results from the comparison between incineration and landfill are very homogenous, as landfill performs from 90 to 100% better in the nine cases concerned.

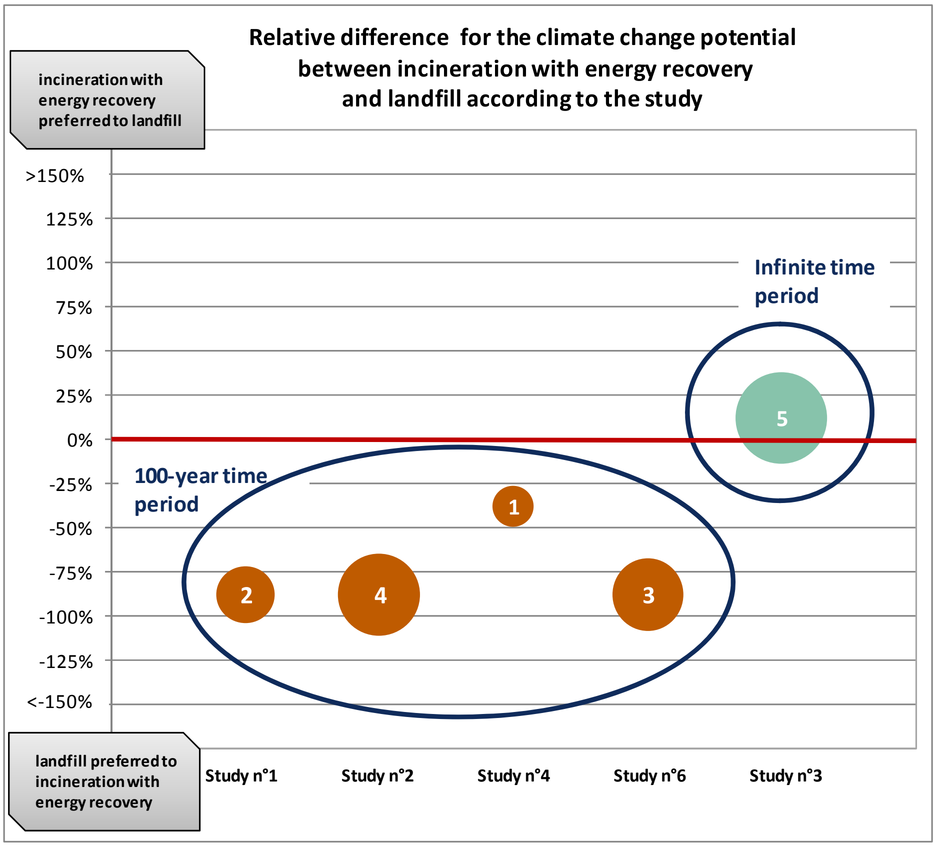

Figure 21 Influence of the time perspective on the relative comparison between incineration and landfill for climate change

Avoided material production and substitution ratio

The good environmental performance of recycling and pyrolysis that was highlighted previously is mostly explained by the **credits brought by the avoided material production**. However, **the choice of possible assumptions around this issue is very broad and is possibly a source of disparities between the different cases**. For example, pyrolysis leads to the production of various products that can potentially replace petrochemical products, such as naphtha and paraffin, or replace fuels such as diesel oils. In the case of open-loop recycling, recycled products can also be used for a large range of applications. For example, in study no 1 (BIOIS, 2006), PET recyclate is assumed to replace resin and fibres.

Table 40 Overview of the assumptions regarding the avoided material production for recycling and pyrolysis

Study number	Avoided material production
Recycling	
1	Virgin HDPE bottles for PE recycling Virgin resin, virgin PET fibres and virgin PET flakes for PET recycling
2	Virgin plastics similar to the ones being recycled
3	Virgin plastics similar to the ones being recycled
4	Virgin plastics similar to the ones being recycled
5	Virgin plastics similar to the ones being recycled
6	Virgin plastics similar to the ones being recycled
7	Virgin plastics similar to the ones being recycled
8	Virgin plastics similar to the ones being recycled for closed-loop recycling (case 8[PS2])
Pyrolysis	
2	Naphta, paraffin and refinery gas OR diesel oil
4	Atmospheric residues, C3/C4 compounds, naphta

In addition to the **choice of the substituted material**, the question that also arises is what is the **ratio of substitution. In most current LCAs it is assumed that recycled plastic will substitute directly for virgin plastic on a 1:1 basis** (i.e. 1 kg of recycled plastic is equivalent to 1 kg of virgin plastic). However, this implies that high quality recycled products are obtained.

The sensitivity of the results with regard to the material that is substituted was looked at in study no 2 (Shonfield, 2008) for two recycling scenarios. The base scenario, for which a degree of virgin plastic displaced by recycled plastic of 100% is assumed, is compared to a scenario in which only 20% of the recyclate replaces virgin plastic (the remainder being evenly split between substituting for concrete and wood). **The consequences of this change on the global warming potential** (see Table 41) **are huge**. **The two recycling scenarios switch from saving impacts to contributing to net emissions.** This means that under the assumption of a degree of virgin plastic substitution of 20%, the impacts from the recycling process are no longer offset by the benefits from the avoided material production. Under this assumption, the ranking is (the best alternative being the one on the left):

pyrolysis < landfill < recycling <incineration

Table 41 Influence of the choice of material substitution for recycling in study n°2 (Shonfield, 2008)

	Recycling scenario 1		Recycling scenario 2	
	Substitutes 100% virgin plastic	Substitutes 20% virgin plastic, 40% wood, 40% concrete	Substitutes 100% virgin plastic	Substitutes 20% virgin plastic, 40% wood, 40% concrete
Global warming potential (kg eq CO_2/ton)	-620	439	-464	415
Depletion of abiotic resources (kg eq Sb/ton)	-14 667	-2 547	-13 735	-2496
Energy demand (MJ/ton)	-12 897	-7 363	-9 753	-1457

The choice of the displaced material and substitution ratio are therefore crucial but do not play a role in the comparison across the studies analysed here since all the studies have assumed a substitution of virgin plastic with a ratio of 1 in the case of closed-loop recycling (See Table 40), i.e. recycled products replace same plastic products produced from virgin raw materials. In study no 1(BIOIS, 2006), open-loop recycling is taken into account. The PET recycling scenario represents an aggregation of the three main PET recycling channels: recycling into filling fibres (50%), recycling into PET resin (25%) and regeneration (25%). However, when compared with the results of the other PET recycling scenarios (from studies 3, 6 and 7), this different choice of substituted material does not appear to have a strong influence on the conclusions.

Energy valorisation

Energy recovery is mainly associated with incineration but is also often assumed for landfill for the cases assuming biogas capture. **Energy recovery can potentially offset the impacts resulting from the waste treatment processes and is therefore a parameter that requires special attention.**

First, in the case of incineration, **the electric and/or thermal conversion efficiency of municipal incinerators determines to what degree the need to produce electricity or heat from primary fuels is avoided**. The 2006 BAT standard for waste incineration gives efficiencies of 15-30% for incineration plants generating electricity only. The efficiencies assumed in the selected studies stick to this range as shown in Table 42.

Table 42 Overview of the incinerator efficiencies assumed in the selected studies for plastics. The efficiency figures are based on gross calorific values (GCV) or net calorific values (NCV). When it is not clear whether the figure is based on GCV or NCV a question mark is added.

Study number	Energy produced with incineration	Efficiency
5	electricity	15% (?)
6	electricity	17,8% (?)
2	electricity	23% (NCV)
4	electricity	25% (?)
1	electricity + heat	32% (GCV)
8	electricity + heat	65% (?)
3	heat	90% (NCV)

In study no 2 (Shonfield, 2008) a sensitivity analysis was conducted to test the potential influence of this parameter. A comparison was conducted between a 30% and a 23% efficient plant. The results showed a 13% decrease for the contribution to global warming when switching to 30% efficiency but this difference was not sufficient to change the ranking of incineration compared to the other scenarios. **The study therefore concluded that this parameter is not expected to significantly influence the conclusions.**

The second issue that arises is the **choice of substituted power or heat** which depends on the country considered as illustrated in Table 43. This issue was also dealt with in study no 2 for incineration. Additional scenarios for which power production from incineration substitutes for average production from the UK grid (mainly based on natural gas (39.9%), coal (32.6%) and nuclear (19.1%)), and for production from a coal-fired power plant were compared to the reference scenario for which the power produced substitutes production from a combined-cycle gas plant. **The global warming potential was found not to be particularly sensitive to a switch of substitution from gas to UK average grid mix. The difference was more significant in the case of the switch to coal power substitution but was not sufficient to change the overall ranking compared to the other technologies.**

An analysis on this parameter was also conducted in study no 3 in which the base case assumes that the heat produced by incineration or landfill waste replaces heat from forest residues. A sensitivity analysis was conducted for PET to analyse the effect of a switch to natural gas for heat production. Under this assumption, an avoided non-renewable fuel consumption is credited to the system. The results showed that the global energy balance is very slightly affected. For depletion of natural resources, this change induces a change in the ranking between the alternatives. Incineration appears as a better alternative than landfill in the natural gas scenario while in the base case landfill performed better. The global warming potential decreased by 60% for the natural gas scenario but the ranking is not affected, i.e. recycling remains the best option while landfill is still the worst one. For the acidification impact, the effect is the other way around and landfill becomes a better alternative than incineration.

Table 43 Choice of substituted power in the selected studies by order of importance

	Choice of substituted power in the selected studies (only energy sources representing for than 15% of the country mix are indicated)							
	Study n°1	Study n°2	Study n°3	Study n°4	Study n°5	Study n°6	Study n°7	Study n°8
Country electricity mix susbtituted	France	UK	/	Italy	Japan	USA	Australia	Germany
Main energy sources constituting the mix								
1	Nuclear	Natural gas	Coal	Natural gas	Nuclear	Coal	Coal	Coal
2		Coal		Coal	Coal	Natural gas		Nuclear
3		Nuclear			Natural gas	Nuclear		
Source of information for the identification of the energy sources constituting the mix	*IEA*	*Study*	*Study*	*IEA*	*IEA*	*IEA*	*Study*	*Study*

Sorting process efficiency and "default" disposal option

In the case of recycling and pyrolysis, the pre-treatment process and especially the sorting stage are important when the input is a mix of plastics because the processes can differ according to the plastic types. For instance, it has been mentioned that in study no 2, one of the pyrolysis scenarios is only suitable for the polyolefin fraction while some recycling technologies are specific to PE or PP. In addition, sorting is also necessary to remove impurities prior to recycling. The scraps from the sorting process are then discarded via a default option that can differ from one study to another. Table 44 presents the assumptions that have been chosen in the selected studies for which the information was available regarding the sorting efficiencies and the default disposal option.

Table 44 Overview of the sorting processes efficiencies and "default" disposal options in the selected studies.

Study number	Material percentage retained in the sorting stage (loss rate)	Disposal option
1	0% (sorting excluded)	/
6	10%	Outside system boundaries
7	10%	Landfill
4	25% for the recycling scenario 5% for the pyrolysis scenario	Incineration with energy recovery
5	33%	Incineration with energy recovery
3	40%	Incineration with energy recovery
2	46%-55% for recycling scenarios 49%-54% for pyrolysis scenarios	85% landfill 15% incineration with energy recovery

Table 44 points out the diversity of assumptions in the selected studies. The influence of the sorting efficiency is analysed in Figure 22 in which the studies are classified according to their loss rate during production. The figure thus illustrates the relative difference between incineration and recycling for energy demand according to the loss rate during sorting. **The overall trend observed suggests that the impacts of recycling increase as the sorting losses increase.**

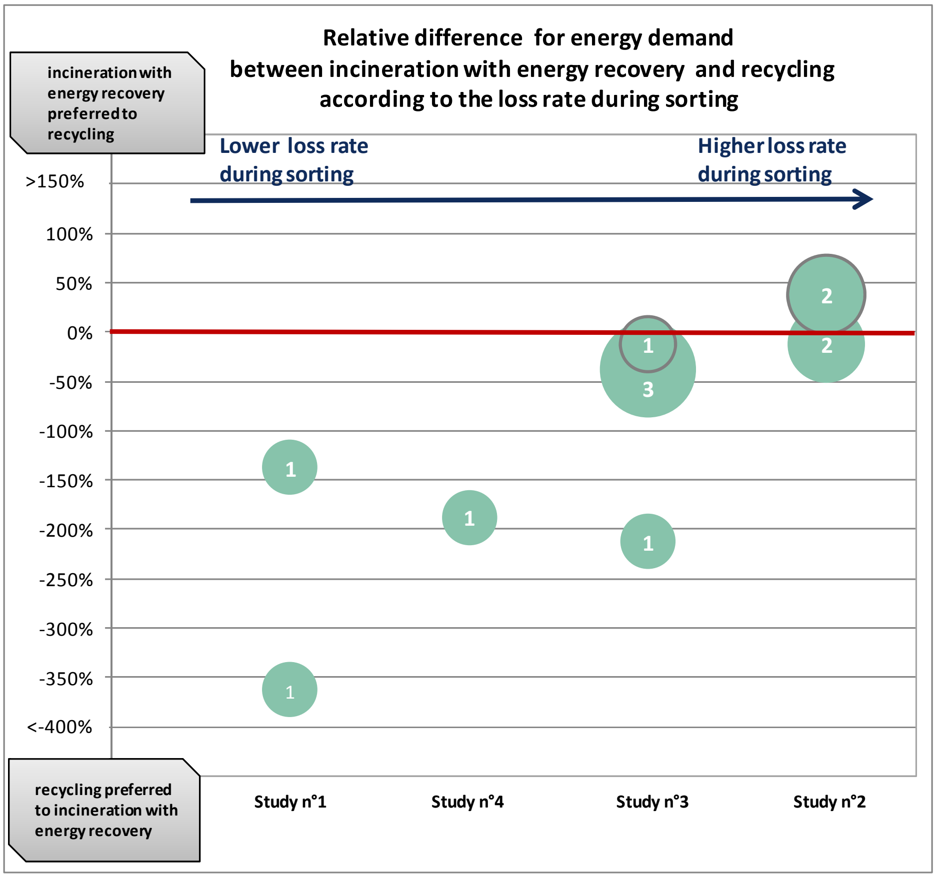

Figure 22 Influence of the loss rate during sorting on the relative comparison between incineration and recycling for energy demand

3.3.4 Conclusion

The results show that **mechanical recycling is the best alternative regarding the climate change potential, depletion of natural resources and energy demand**.

It also comes out that **incineration with energy recovery performs quite poorly regarding GHG emissions**. **Pyrolysis is still in early development** and is included in only two studies, but the results suggest that it could be a **promising option** regarding all indicators assessed. Unsurprisingly, **landfill turns out to be the option with the greater environmental burden** in the large majority of cases.

However, **for the assessment of the performances of landfill regarding the climate change potential, the choice of the time perspective is essential**. Indeed, as plastics degrade very slowly, a time frame of several hundred years should, in theory, be taken into account to include the emissions resulting from degradation. Most studies consider a 100-year time frame and therefore underestimate the contribution to global warming as highlighted in the analysis. However, there is no consensus among LCA experts regarding the approach that should be chosen. This issue is currently under discussion.

In the case of recycling, the analysis has highlighted that the environmental benefits are mainly brought by the avoided material production. In order to maximise the benefits, emphasis should be put on recovering good quality material with high purity (to limit the rejected fraction) that once recycled can replace virgin plastics on a high ratio (1 to 1).

3.3.5 Comparison with the results from the previous report edition

The review conducted in 2006 covered 60 scenarios and compared recycling, incineration and landfill. The plastic types studied were the same than in the present study (PVC, PP, LDPE, HDPE and PET), except for PS (which as not included in the 2006 review).

Among the selected scenarios in this 2006 edition, the choice of the ratio of material substitution for recycling differed from one scenario to another, and thus the influence of this parameter could be analysed. For scenarios that anticipated recovered material to substitute virgin material of the same kind in the weight/weight ratio of 1:1 (assumptions chosen by the studies selected in the present review), closed-loop recycling was found to be environmentally better than both incineration and landfill on all environmental impact categories, with recycling being 50% better on average. This is thus in line with the results obtained here. In addition, the authors could demonstrate that a ratio of 1:0.5 (1 kg of recycled plastics replace 0.5 kg of virgin plastics) was about the break-even point at which recycling and incineration with energy recovery were environmentally equal.

The previous study also pointed out that the possible needs for washing or cleaning prior to recycling of plastics containing organic contaminants may lead to incineration being environmentally preferable to recycling. Among the studies selected for the present review, this issue was only investigated in study no 2. However the results did not highlight the influence of this specific parameter.

3.3.6 Data gaps/further research

Key parameters

As the possible washing and cleaning needs prior to recycling were only considered in study no 2, this issue could not be specifically investigated in the present study. However, as highlighted in the previous report edition, the recycling environmental performances can be affected by the need for cleaning, for example in the case of plastic packaging containing residues such as shampoo or ketchup. As the residues are mainly organic, the washing step can give rise to a significant COD (Chemical Oxygen Demand) load in wastewater. The energy requirements to treat the COD reduce the environmental benefits from recycling. Conversely, the organic content is an advantage for incineration thanks to the heating value of the contaminants.

Coverage of the various end-of-life alternatives

The comparison between recycling, incineration and landfill has been conducted on a significant number of cases, since on average 20 cases were included for each of these alternatives. On the other hand, pyrolysis was included in only two studies and in view of the obtained results, it would be interesting to be able to confirm the environmental benefits of this option by other studies.

Environmental indicators

As in the case of paper, the climate change potential clearly stands out as the indicator that draws more attention. The number of cases including water consumption is too restricted to be able to make general conclusions. The lack of interest in the water consumption indicator is probably linked to the fact that washing and cleaning was not included in the studies. However, it would be advisable to include this issue in the assessment.

3.4 Biopolymers

3.4.1 Presentation

Biopolymers are polymers produced from biomass and are therefore made of renewable resources. Biopolymers can be:

- natural polymers directly formed from natural biomass, e.g. cellulose
- synthetic polymers made from biomass monomers, e.g. Polylactic Acid (PLA)
- synthetic polymers made from synthetic monomers derived from biomass, e.g. polythene derived from bioethanol

In the end-of-life stage, the available options differ depending on the biopolymer properties. Some biopolymers are biodegradable meaning that they can be broken down into CO_2 and water by microorganisms. However, biopolymers such as polyethylene made from renewable resources will not biodegrade. Additionally, some biopolymers are also compostable. In the EU, the criteria for compostability for packaging material are defined in the standard EN 13432. The criteria used in the standard are linked to the performances of the material regarding biodegradability and disintegration, the quality of the compost obtained and the absence of any negative effect on the composting process.

Biopolymers should not be confused with degradable plastics such as UV or Oxo-degradable plastics that break down when exposed to light or air respectively but that are still primarily oil-based.

Biopolymers can be divided into two main types:

- *Pure biopolymers*
  Cellulose, the main component of plants, is the most common biopolymer. Polylactic acid (PLA) is also commonly used. PLA is made from the polymerisation of lactic acid derived from starch.

- *Biopolymer complexes*
  Biopolymers are often used as blends, either with other biopolymers or most commonly with fossil-based polymers. It is for example the case of the biopolymer Biolice results from the association between polyester and cereals. Biolice is produced by ULICE, a member of the Limagrain group. Another example is Mater-Bi which is a blend between starch and polycaprolactone (based on crude oil) produced by Novamont.

Renewable base	Manufacturer (trade name)	Application
Starch-based polymers	Novamont (MaterBi) Rodenburg (Solanyl) Plantic Technologies Bioplast (Biotec) Biop and other	films, moulding, extrusion
Polyhydroxy-alkanoates (PHA)	Kaneka Metabolix Telles PHB Industrial	moulding, films
Polylactic acid (PLA)	NatureWorks PLA Pyramid Bioplastics Synbra Technologies	films, moulding, fibers
Cellulose-derivatives	Innovia Films (NatureFlex) FKuR	films, injection moulding

Figure 23 Overview of the different types of biopolymers (Source: European Bioplastics)

In order to compare the various end-of-life alternatives for biopolymers, a total of seven publications have been selected and are presented in the Table 45. The biopolymers assessed are PLA [PLA], cellulose [CE], maize starch [MAS], Mater-Bi [MB], Octopus [OCT] (blend between PLA and Ecofoil), Biolice [BIO] and Multi-bio [MUB] (blend between starch with polycaprolactone (PCL) and PLA).

Table 45 Presentation of the selected studies for biopolymers

Study number	Title	Main author	Year	Geographical scope
1	Life Cycle Assessment (LCA) of Biopolymers for single-use carrier bags	Murphy	2008	UK
2	Bilan environnemental de filières de traitement de plastiques de différentes origines (*Environmental assessment of treatment channels of plastics of different origins*)	BIOIS	2006	France
3	Life Cycle Assessment pf polylactide (PLA)	IFEU	2006	Germany
4	Environmental assessment of biodegradable multilayer film derived from carbohydrate polymers	Vidal	2007	Spain
5	Assessment of the environmental profile of PLA, PET and PES clamshell containers using LCA methodology	Madival	2009	USA
6	Miljøvurdering af alternative bortskaffelsesveje for bionedbrydelig emballage (*Environmental assessment of alternative disposal routes for biodegradable packaging*)	Nielsen	2002	Denmark
7	Kunststoffe aus nachwachsenden Rohstoffen: Vergleichende Ökobilanz für Loose-fill-Packmittel aus Stärke bzw. Polystyrol (*Plastics from renewable resources: Comparative LCA for loose-fill packaging materials made from starch and polystyrene*)	BIfA/IFEU/ Flo-Pak	2006	Germany

The system diagram below shows the biopolymers life cycle and the steps where key system boundary issues arise. Studies n° 1, 3;5 and 7 analyse the full life cycle, while studies 2, 4 and 6 focus on the disposal and recovery stage.

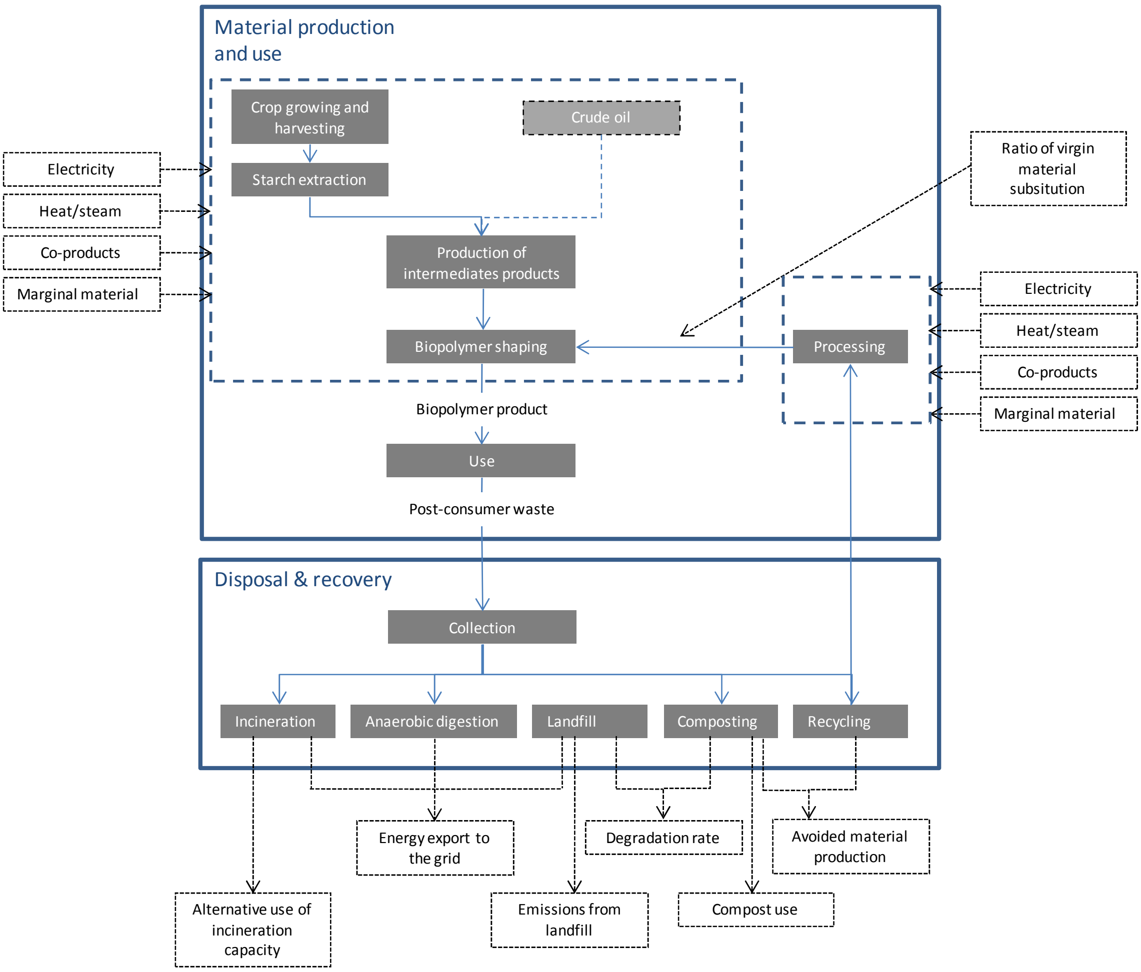

Figure 24 The biopolymers system and key parameters

3.4.2 Comparison between the various end-of-life options

Alternatives compared

The end-of-life options covered by the selected studies are:

- Recycling
- Composting
- Incineration with energy recovery
- Incineration without energy recovery
- Anaerobic digestion

Table 46 gives an overview of the alternatives that are compared within each case. It also illustrates how often each end-of-life option is represented. It can be seen that incineration without energy recovery and anaerobic digestion are analysed in one and two studies, respectively. In fact, incineration without energy recovery is no longer common and will inevitably disappear in the near future. As anaerobic digestion is not a fully mature option for biopolymers, very few studies could be found since little data is available about the technology. The results obtained should thus be interpreted with care, especially as the number of cases is not sufficient to assess the validity of the results. It should also be noted that in this chapter recycling refers to three types of recycling:

- mechanical recycling, where plastics are shredded into pellets or granulates and serve as new raw materials. This corresponds to the usual definition for recycling;
- feedstock recycling, which is defined as a change in the chemical structure of the material, where the resulting chemicals are used for a purpose other than producing the original material; and
- chemical recycling, which implies a change in the chemical structure of the material, but in such a way that the resulting chemicals can be used to produce the original material again (monomer recovery).

Table 46 Overview of the end-of-life alternatives compared within each case for biopolymers

Case	Recycling	Composting	Incineration with electricity recovery only	Incineration with heat or combined heat/ electricity recovery	Incineration without energy recovery	Landfill	Anaerobic digestion	Pyrolysis	Gasification
1[MB]		x	x			x			
1[OCT]		x	x			x			
2[PLA]		x		x		x			
2[MB]	x	x		x		x			
2[BIO]		x		x		x			
3[PLA1]	x[1]	x					x		
3[PLA2]	x[2]	x					x		
4[MUB1]		x			x	x			
4[MUB2]		x			x	x			
5[PLA]	x		x	x		x			
6[PLA]		x		x					
6[CE]		x		x					
7[MAS]	x[1]	x		x			x		
Total number of cases	**5**	**12**	**3**	**7**	**2**	**8**	**3**	**0**	**0**

[1] Feedstock recycling scenario
[2] Chemical recycling scenario

Ranking between the various end-of-life options within each scenario

Table 47 compares the end-of-life options compared within each scenario. When the indicator is not taken into account in a given case the line is coloured in grey. This table should be interpreted with care. It shows the relative ranking of the end-of-life solutions within a given case study for specific assumptions and system boundaries. It does not provide sufficient information to be able to give an overall conclusion regarding which alternatives are the best.

Study no 1

In study no 1, composting, landfill and incineration with energy recovery are compared. The biopolymers under study (Mater-Bi and Octopus) satisfy the biodegradability and compostability requirements of EN 13432. For depletion of natural resources and climate change, composting appears as the least preferable option. However, regarding eutrophication, it is the landfill alternative that has the most impacts. For acidification, composting and landfill present similar potential impacts and are less preferable than incineration with energy recovery. The high impacts for composting can be explained by the high degradation rate (90%) assumed for the carbon content.

Study no 2

Study no 2 compares the same alternatives but also includes a prospective recycling scenario for Mater-Bi. Whenever taken into account, recycling appears as the preferable option. In the other cases, incineration with energy recovery is the best option regarding energy consumption and depletion of natural resources. This is due to the avoided production of electricity. Composting and landfill are more favourable regarding climate change. This is explained by the fact that the sequestration of the carbon contained in the material is taken into account and thus some CO_2 emissions are avoided. The degradation rate is assumed to be higher for landfill thus the rate of sequestered carbon is higher for composting. Nevertheless, for Mater-Bi and Biolice, landfill is more beneficial than incineration with energy recovery for this indicator. This is because some methane and CO2 emissions are emitted during composting, while in the case of landfill methane emissions and energy production are avoided thanks to the valorisation of the biogas produced. Incineration with energy recovery appears more favourable for PLA than for the other polymers as PLA contains a higher rate of carbon from biomass thus incineration of PLA leads to the production of CO_2 neutral energy that replaces fossil fuel energy.

Study no 3

In study no 3, composting, anaerobic digestion and recycling of PLA are compared. Two types of recycling are considered, i.e. feedstock recycling and chemical recycling. When PLA undergoes feedstock recycling (case 3[PLA1]), it is mainly recovered in blast furnaces where it used as a reducing agent or processed into methanol. This type of recycling thus does not allow the production of secondary plastics products. However it is still considered as a type of recycling since it is a form of material recovery since it leads to the production of methanol. For the part that is used in blast furnaces, it can be discussed whether this end-of-life option should be classified as recycling since it is a form of energy recovery. However, it is not only the energy content of the material that is used but also its ability to reduce iron oxides. It has thus been decided to consider this alternative as a form of recycling. However, to avoid confusion, this scenario is differentiated from the other scenarios in the results tables.

In the case of chemical recycling, PLA waste goes though a hydrolysis process and is then repolymerised as PLA. Chemical recycling (case 3[PLA2]) appears as the preferable option for all the indicators assessed thanks to savings in virgin PLA polymer demand and thanks to a low energy consumption for the recycling process. Anaerobic digestion also performs better than composting because some electricity is generated with the obtained biogas and replaces grid electricity. The feedstock recycling scenario has performances similar to the anaerobic digestion scenario, except for energy demand where feedstock recycling is more beneficial.

Study no 4

In study no 4, incineration without energy recovery is compared with composting and landfill for Multibio multilayer film. Case [MUB1] corresponds to a degradation rate for the carbon content of 30% for composting and landfill while case [MUB2] corresponds to a degradation rate for the carbon content of 50%. The only indicator in this study is climate change and the results show that composting is the most beneficial alternative whereas landfill is the worst option. This is due to the methane emissions occurring when the material is disposed of in landfills. Incineration has little impact since the incineration of biobased materials is assumed to be neutral regarding climate change (taking into account that the CO_2 content of the PLA-based biopolymer is mainly based on biogenic CO_2).

Study no 5

Study no 5 assesses the performances of recycling, landfill and incineration with energy recovery regarding climate change and energy demand for PLA. Once again, recycling appears as the best option. Landfill performs better than incineration for climate change, although some energy is recovered from incineration. This may be due to the fact that it is assumed that PLA does not degrade in landfill, thus reducing the impacts from the process. This assumption is justified by the quotation of two recent studies of the same author.

Study no 6

In study no 6, composting and incineration with energy recovery are compared for PLA and cellulose. The materials satisfy the biodegradability and compostability requirements of EN 13432. For climate change, incineration appears as a better option thanks to the production of electricity and steam, which replaces energy produced from natural gas and oil, which corresponds to the Danish electricity mix mainly based on fossil resources. However, for the other indicators included in the study, i.e. acidification, photochemical oxidation and toxicity, composting performs better for both materials.

Study no 7

This LCA looks at the complete end-of-life of different types of plastics and bioplastics packaging. For bioplastics, this study compares incineration with energy recovery, composting, anaerobic digestion and feedstock recycling for a packaging made of maize starch. In the feedstock recycling scenario, the maize starch packaging is used as a reducing agent in blast furnaces.

Regarding climate change, anaerobic digestion and incineration appear as the best alternatives thanks to the recovery of the energy produced. On the contrary, composting is the least preferable because of emissions due to the CO_2 and CH_4 emissions accompanying the biopolymer degradation. Composting is also the end-of-life option with the highest energy consumption. This can be explained by the absence of energy recovery. Incineration with energy recovery is the preferable option regarding energy demand.

Table 47 Ranking of end-of-life options within each scenario for biopolymers

	Case	Composting	Recycling	Incineration with energy recovery	Incineration without energy recovery	Landfill	Anaerobic digestion
Climate change (kg CO2 eq)	1[MB]	+		++		+++	
	1[OCT]	+		++		+++	
	2[PLA]	+++		++		+	
	2[MB]	++	+++	+		++	
	2[BIO]	++		+		+++	
	3[PLA1] [1]	+	++ [1]				+++
	3[PLA1] [2]	+	+++ [2]				++
	4[MUB1]	+++			++	+	
	4[MUB2]	+++			++	+	
	5[PLA]		+++	+		++	
	6[PLA]	+		+++			
	6[CE]	+		+++			
	7[MAS] [1]	+	++ [1]	++			+++
Depletion of natural resources (kg Sb eq)	1[MB]	+		+++		++	
	1[OCT]	+		+++		++	
	2[PLA]	+		+++		++	
	2[MB]	+	+++	++		+	
	2[BIO]	+		+++		++	
	Studies n°3, 4, 5, 6 and 7 do not include this indicator						
Energy demand (MJ)	2[PLA]	+		+++		++	
	2[MB]	+	+++	++		+	
	2[BIO]	+		+++		++	
	3[PLA1] [1]	+	+++ [1]				++
	3[PLA1] [2]	+	+++ [2]				++
	5[PLA]		+++	+		+	
	7[MAS] [1]	+	++ [1]	+++			++
	Studies n°1, 4 and 6 do not include this indicator						
Water consumption (m^3)	No study includes this indicator						

[1] Feedstock recycling scenario

[2] Chemical recycling scenario

+++	best option
++	intermediary option
+	worst option
	option not assessed

3.4.3 Detailed comparison between the various treatment options

This chapter focuses on the comparison of the various treatment options indicator by indicator. The alternatives serving as a reference for comparison are composting and incineration with energy recovery.

For each indicator, the differences resulting from the comparison of the various end-of-life options compared to composting and to incineration with energy recovery are first presented in tables (values rounded up to the nearest ten in the tables). The results are then grouped by range of 25% difference on the following graphs in order to highlight the main tendencies.

The results highlight large differences between the different cases. This is partly due to the fact that the studies do not all include the same steps. As mentioned previously, some studies only focus on the end-of-life stage while others include the whole life cycle without giving the details of the various steps. In addition, some system boundary issues and key assumptions also have considerable influence on the results discussed below.

Climate change

Figure 25 illustrates that recycling and anaerobic digestion are more favourable than composting regarding climate change. However it should be noted that the number of cases is limited for these end-of-life alternatives: five cases for recycling and three for anaerobic digestion.

The picture is less clear regarding composting vs. landfill and incineration since the results differ between the various studies (see Table 48). This seems to be mainly due to the assumptions chosen regarding the degradation rate:

- Composting performs better than incineration for the cases assuming a low degradation rate of 30 or 50%
- Incineration performs better than composting for the cases assuming a degradation rate above 90%

The comparison between the results from cases 4[MUB1] and 4[MUB2] for composting vs. landfill illustrates the influence of the degradation rate. Although placed on the same line on the graph, composting presents an environmental improvement of 600% for a degradation rate of 30% and of 1700% for a degradation of 50%.

Figure 26 shows that recycling is the most favourable option even versus incineration with energy recovery in 2 cases out of three. When comparing landfill and incineration with energy recovery, it is interesting to notice that landfill tends to perform better. This can be due to:

- the valorisation of the biogas produced (cases 2[MB] and 2[BIO])
- the choice of a low degradation rate (cases 1[MB]; 1[OCT], 5[PLA]).

In addition, it can be observed from Table 48 and Table 49 that the different Mater-Bi cases do not lead to the same conclusions. For cases from study no 2, composting appears better than incineration with energy recovery because the compost produced avoids the production of inorganic fertilisers. On the contrary in study no 1 the compost produced is not assumed to replace fertilisers and thus composting does not appear as a better alternative than incineration.

Table 48 Relative difference between the impacts from the different end-of-life options vs. composting for climate change for biopolymers. A positive value means that composting is preferable to the other end-of-life option. A negative value means that composting causes more environmental impact than the other end-of-life option.

	Composting versus other alternatives											
N° case	1[MB]	1[OCT]	2[PLA]	2[MB]	2[BIO]	3[PLA1][1]	3[PLA2][2]	4[MUB1]	4[MUB2]	6[PLA]	6[CE]	7[MAS][1]
Recycling				-9270%		-20% [1]	-40%[2]					-50% [1]
Incineration with energy recovery	-10%	-20%	60%	2060%	2090%					-60%	-60%	-60%
Incineration without energy recovery								110%	110%			
Landfill	-40%	-50%	60%	-650%	-10%			590%	1720%			
Anaerobic digestion						-20%						-60%
Study n°5 does not include a comparison with composting for this indicator and thus is not included in this table												

[1] Feedstock recycling scenario

[2] Chemical recycling scenario

Table 49 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for climate change for biopolymers. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes more environmental impact than the other end-of-life option.

	Incineration with energy recovery versus other alternatives								
N° case	1[MB]	1[OCT]	2[PLA]	2[MB]	2[BIO]	5[PLA]	6[PLA]	6[CE]	7[MAS][1]
Recycling				-520%		-50%			20% [1]
Composting	20%	20%	-130%	-100%	-110%		160%	160%	130%
Incineration without energy recovery									
Landfill	-40%	-40%	20%	-130%	-110%	-30%			
Anaerobic digestion									-10%
Studies n°3 and 4 do not include a comparison with incineration with energy recovery for this indicator and thus are not included in this table									

[1] Feedstock recycling scenario

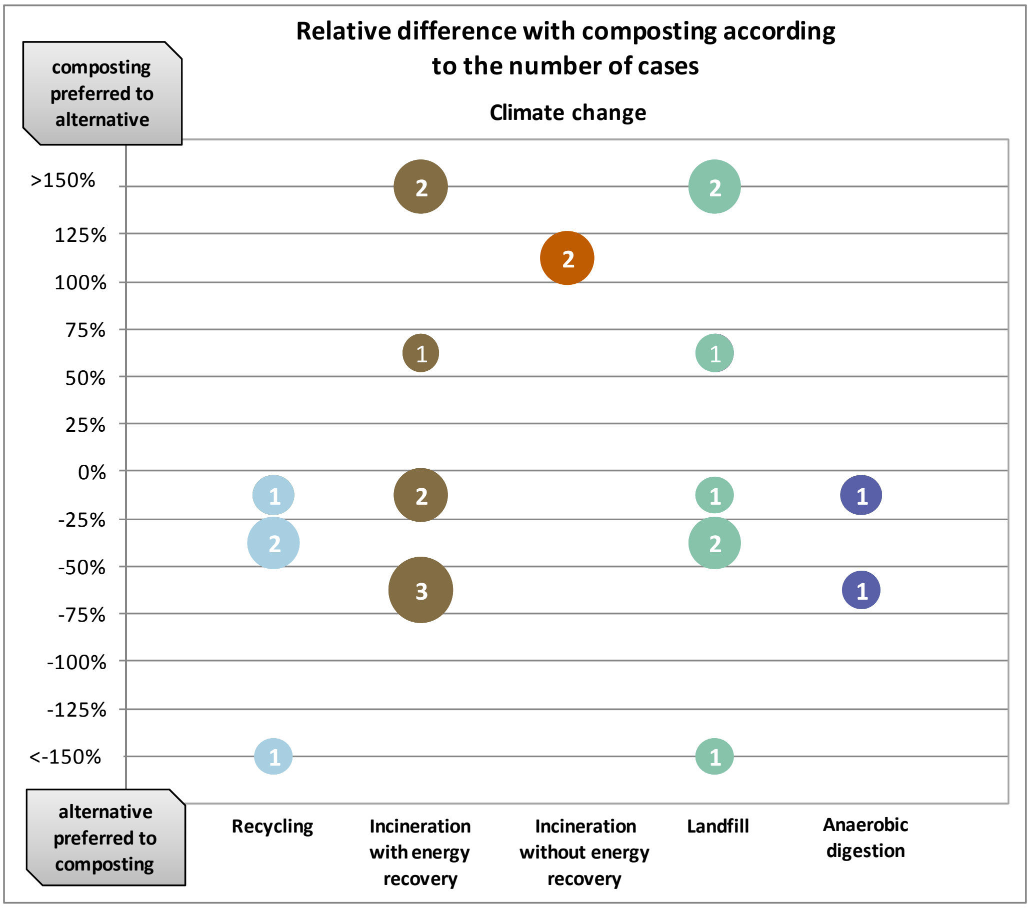

Figure 25 Relative difference between the impacts from the different end-of-life options vs. composting for climate change for biopolymers. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

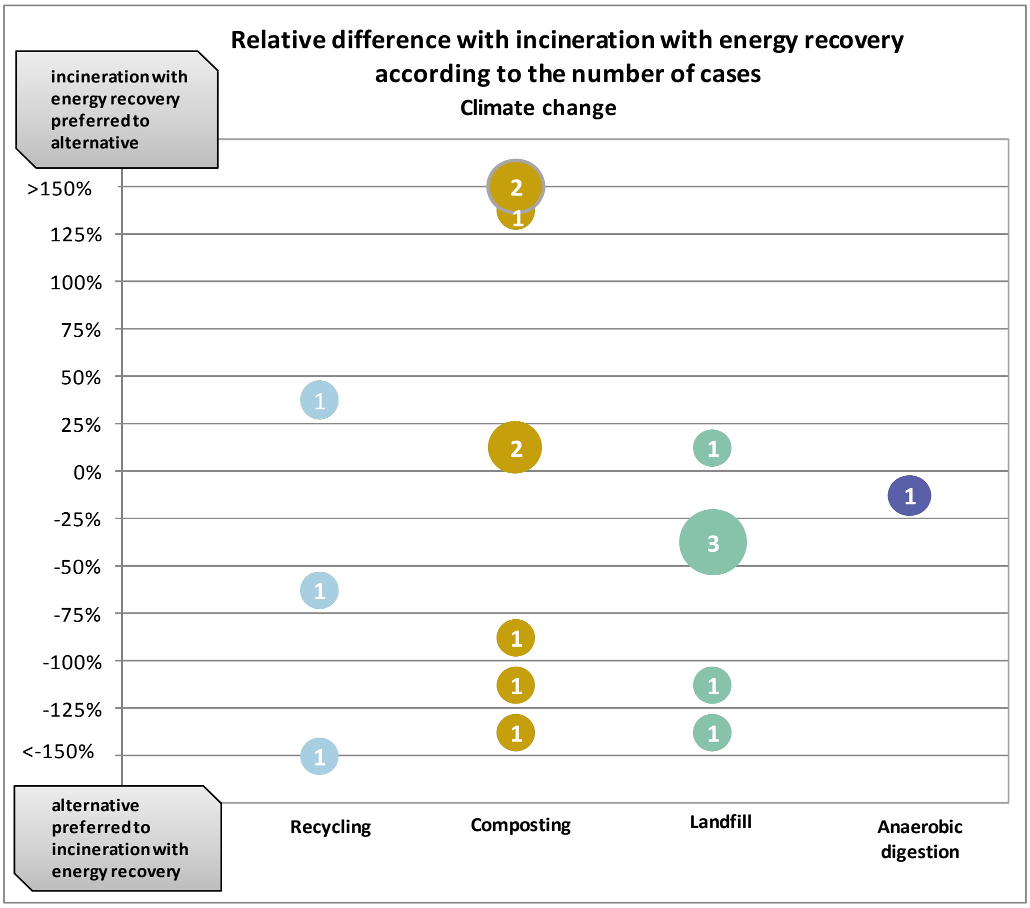

Figure 26: Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for climate change for biopolymers. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Depletion of natural resources

Compared to climate change, fewer cases take this indicator into account (five cases compared to 13 cases). Figure 27 suggests that for this indicator composting is the least preferable option compared to recycling, incineration with energy recovery and landfill. However, landfill presents an environmental improvement of only 0-25% compared to composting, for all cases assessed. Thus, given the uncertainties associated with the indicator, this difference cannot be considered significant. The good performance of incineration with energy recovery for study no 2 (see Table 50 and Table 51) is due to the energy credits while the benefits of incineration over composting are lower for study no 1. This is probably linked to the fact that in study n°1 only electricity is recovered whereas both electricity and heat are generated in study no 2. For recycling, the high benefits come from the material recovery that avoids the production of virgin material. Figure 28 illustrates that recycling seems to be the only alternative that performs better than incineration with energy recovery.

Table 50 Relative difference between the impacts from the different end-of-life options vs. composting for depletion of natural resources for biopolymers. A positive value means that composting is preferable to the other end-of-life option. A negative value means that composting causes more environmental impact than the other end-of-life option.

	Composting versus other alternatives				
N° case	1[MB]	1[OCT]	2[PLA]	2[MB]	2[BIO]
Recycling				-67520%	
Incineration with energy recovery	-10%	-10%	-6480%	-7860%	-6700%
Incineration without energy recovery					
Landfill	0%	0%	-20%	-20%	-20%
Anaerobic digestion					
Studies n°3, 4, 5, 6 and 7 do not include a comparison with composting for this indicator and thus are not included in this table					

Table 51 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for depletion of natural resources for biopolymers. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes more environmental impact than the other end-of-life option.

	Incineration with energy recovery versus other alternatives				
N° case	1[MB]	1[OCT]	2[PLA]	2[MB]	2[BIO]
Recycling				-770%	
Composting	10%	10%	100%	100%	100%
Incineration without energy recovery					
Landfill	10%	10%	100%	100%	100%
Anaerobic digestion					
Studies n°3, 4, 5, 6 and 7 do not include a comparison with incineration with energy recovery for this indicator and thus are not included in this table					

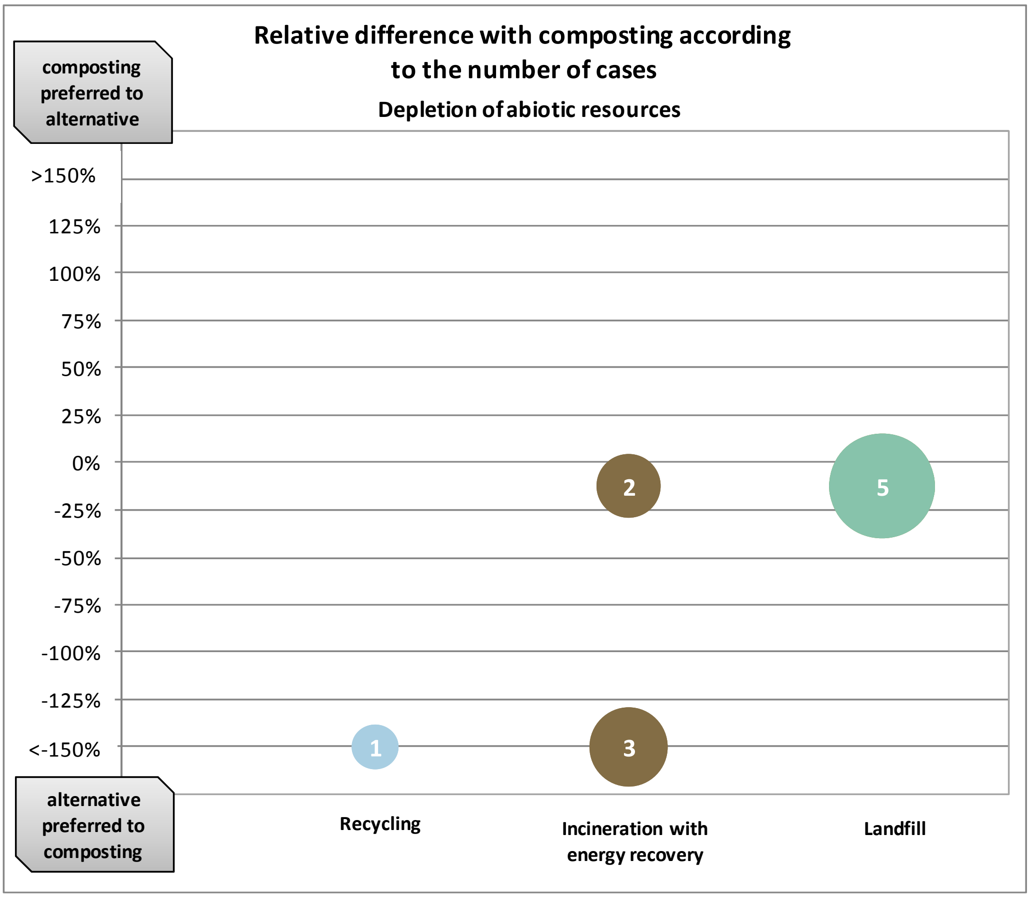

Figure 27 Relative difference between the impacts from the different end-of-life options vs. composting for depletion of natural resources for biopolymers. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

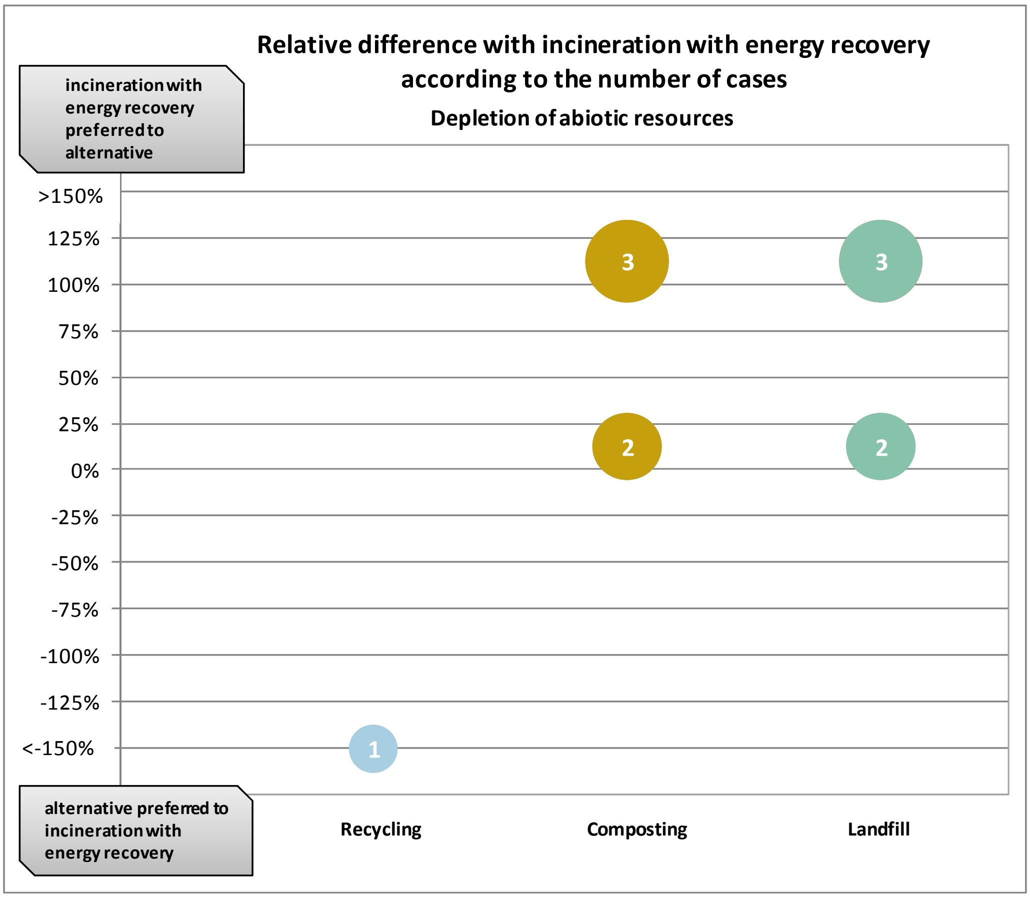

Figure 28 Relative difference between the impacts from the different end-of-life options vs. incineration for depletion of natural resources for biopolymers. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Energy demand

Figure 29 shows that all cases assessed tend towards the similar conclusion, i.e. composting is the least preferable option for this indicator. For landfill and anaerobic digestion the energy demand is reduced up to 50% compared to composting. In study n°2 that focuses on the end of life stage only, recycling and incineration with energy recovery both appear largely better than composting.

The comparison between recycling and incineration with energy recovery on Figure 30 highlights that incineration with energy recovery appears as the second preferable option after recycling. The only case for which incineration is preferable to recycling is case 7[MAS]. Indeed, in this case, the biopolymer waste is used as a reducing agent in blast furnaces (open loop recycling), which is less advantageous than replacing virgin biopolymer material.

Table 52 Relative difference between the impacts from the different end-of-life options vs. composting for energy demand for biopolymers. A positive value means that composting is preferable to the other end-of-life option. A negative value means that composting causes more environmental impact than the other end-of-life option.

	Composting versus other alternatives					
N° case	2[PLA]	2[MB]	2[BIO]	3[PLA1][1]	3[PLA2][2]	7[MAS][1]
Recycling		-36800%		-40%[1]	-30%[2]	-40%[1]
Incineration with energy recovery	-4380%	-5360%	-4750%			-50%
Incineration without energy recovery						
Landfill	-50%	-50%	-50%			
Anaerobic digestion				-10%		-40%
Studies n°1, 4, 5 and 6 do not include a comparison with composting for this indicator and thus are not included in this table						

[1] Feedstock recycling scenario

[2] Chemical recycling scenario

Table 53 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for energy demand for biopolymers. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes more environmental impact than the other end-of-life option.

	Incineration with energy recovery versus other alternatives				
N° case	2[PLA]	2[MB]	2[BIO]	5[PLA]	7[MAS][1]
Recycling		-600%		-60%	20%[1]
Composting	100%	100%	100%		110%
Incineration without energy recovery					
Landfill	100%	100%	100%	0%	
Anaerobic digestion					20%
Studies n°1, 3, 4 and 6 do not include a comparison with incineration with energy recovery for this indicator and thus are not included in this table					

[1] Feedstock recycling scenario

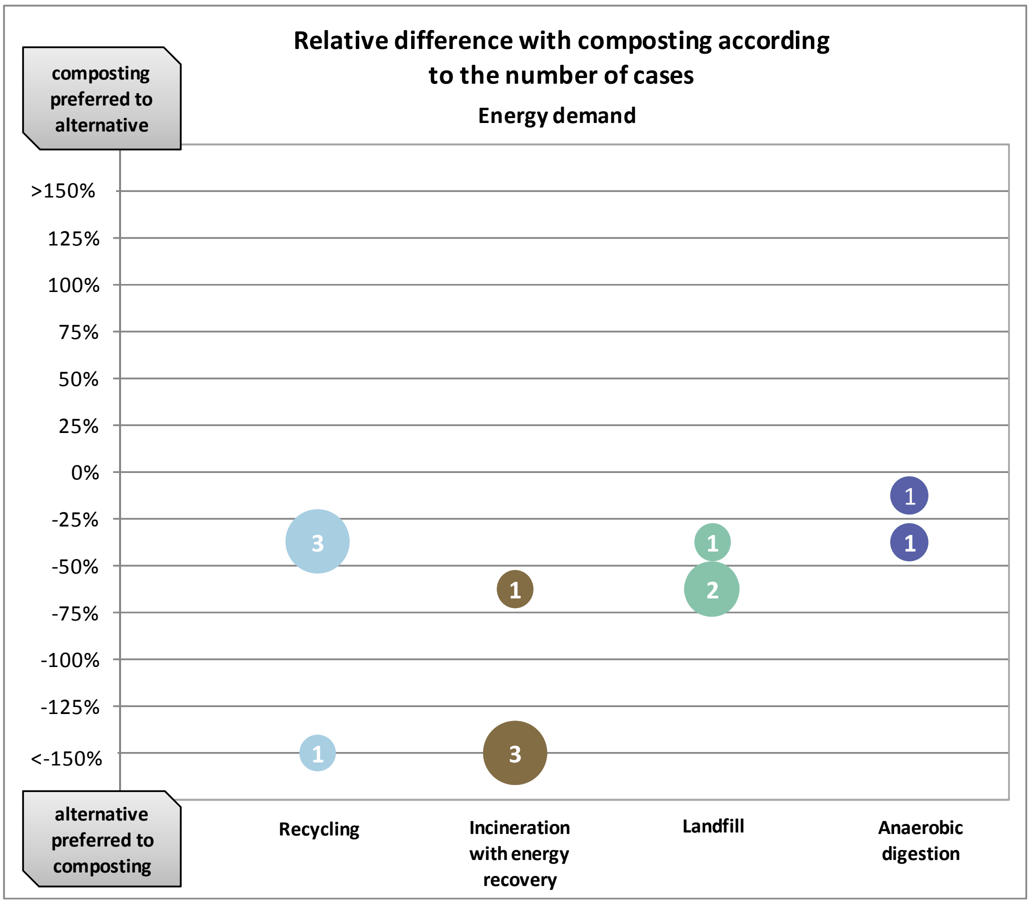

Figure 29 Relative difference between the impacts from the different end-of-life options vs. composting for energy demand for biopolymers. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

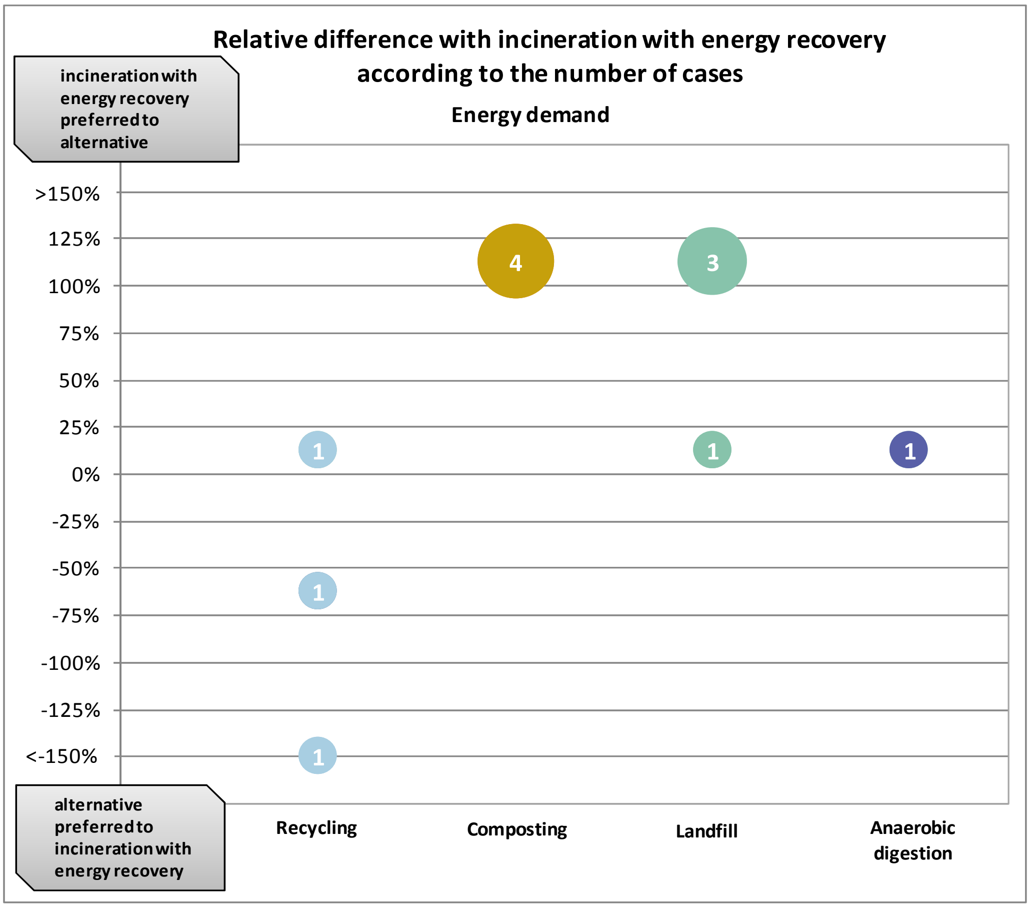

Figure 30 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for energy demand for biopolymers. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Other indicators

Acidification

Recycling when assessed appears as the best option, except in study no 7. Indeed, the recycling scenario in study no 7 corresponds to a **feedstock recycling** scenario in which the biopolymer waste is used as a reducing agent in blast furnaces, which is less advantageous than replacing virgin biopolymer material. Composting and landfill have more impacts than the other alternatives regarding this indicator.

Table 54 Ranking of end-of-life options within each scenario for acidification

	Case	Composting	Recycling	Incineration with energy recovery	Landfill	Anaerobic digestion
Acidification (kg SO2 eq)	1[MB]	+		+++	+	
	1[OCT]	+		+++	+	
	2[PLA]	+		+++	+	
	2[MB]	+	+++	++	+	
	2[BIO]	+		+++	++	
	3[PLA1] [1]	+	+++ [1]			+++
	3[PLA1] [2]	+	+++ [2]			++
	6[PLA]	+		+++		
	6[CE]	+		+++		
	7[MAS] [1]	+	++ [1]	+++		++
	Studies n°4 and 5 do not include this indicator					

+++	best option
++	intermediary option
+	worst option
	option not assessed

[1] Feedstock recycling scenario
[2] Chemical recycling scenario

Photochemical oxidation

According to the studies analysed, incineration with energy recovery seems to be the worst alternative. This is not the case in study n°7 but the ranking for this study should be moderated since all the alternatives are very close to each other regarding this indicator.

Table 55 Ranking of end-of-life options within each scenario for photochemical oxidation

	Case	Composting	Recycling	Incineration with energy recovery	Landfill	Anaerobic digestion
Photochemical oxydation (kg ethylene eq)	2[PLA]	++		+	+++	
	2[MB]	++	+++	+	++	
	2[BIO]	++		+	+++	
	3[PLA1] [1]	+	+++ [1]			++
	3[PLA1] [2]	+	+++ [2]			++
	6[PLA]	+++		+		
	6[CE]	+++		+		
	7[MAS] [1]	+	++ [1]	+++		++
	Studies n°1, 4 and 5 do not include this indicator					

+++	best option
++	intermediary option
+	worst option
	option not assessed

[1] Feedstock recycling scenario
[2] Chemical recycling scenario

Eutrophication

Composting appears as the preferable option when recycling is not analyzed. This is due to the avoided production of fertilizers. In study no 2, landfill seems to be a good end-of-life option regarding this indicator.

Table 56 Ranking of end-of-life options within each scenario for eutrophication

	Case	Composting	Recycling	Incineration with energy recovery	Landfill	Anaerobic digestion
Eutrophication (kg PO4 eq)	1[MB]	+++		+++	+	
	1[OCT]	+++		+++	+	
	2[PLA]	+++		+	+++	
	2[MB]	++	+++	+	++	
	2[BIO]	++		+	+++	
	3[PLA1] [1]	+	+++ [1]			+++
	3[PLA1] [2]	+	+++ [2]			++
	7[MAS] [1]	++	+ [1]	+++		++
	Studies n°4, 5 and 6 do not include this indicator					

+++	best option
++	intermediary option
+	worst option
	option not assessed

[1] Feedstock recycling scenario
[2] Chemical recycling scenario

Human toxicity

Recycling and incineration are the preferable options. The degradation processes occurring in the case of composting, landfill and anaerobic digestion lead to a higher contribution to this indicator.

Table 57 Ranking of end-of-life options within each scenario for human toxicity

	Case	Composting	Recycling	Incineration with energy recovery	Landfill	Anaerobic digestion
Human toxicity (kg 1,4-DB eq)	2[PLA]	+		+++	++	
	2[MB]	+	+++	++	++	
	2[BIO]	+		+++	++	
	3[PLA1] [1]	+	+++ [1]			++
	3[PLA1] [2]	+	+++ [2]			++
	Studies n°1, 4, 5, 6 and 7 do not include this indicator					

+++	best option
++	intermediary option
+	worst option
(grey)	option not assessed

[1] Feedstock recycling scenario

[2] Chemical recycling scenario

Key parameters

The assumptions that were found to have the highest influence on the results were:

- the degradation rate of the biopolymer in landfills and during composting and the inclusion or exclusion of biogenic carbon
- the type of energy valorisation included
- the avoided production of material considered

The role and influence of each of these parameters are investigated below.

Degradation rate and biogenic carbon

The issue of the degradation rate is of key importance in assessing the environmental performances of composting and landfill as illustrated in Table 58 and Figure 31. As mentioned previously, the specificity of biopolymers is to be biodegradable but however **the degradation rate varies between the different types of biopolymers**. For instance, the degradation rate is lower for biopolymers resulting from a blend between oil-based polymers and organic compounds. **There seems to be considerable uncertainty around this issue since the degradation rate chosen for PLA in the various cases varies from 0% to 98%.** The carbon that is not degraded is sequestered and will thus not be degraded into, for instance, methane.

Table 58 Degradation rates assumed for composting and landfill for biopolymers

Study number	Degradation rate: Composting	Degradation rate: Landfill
1	90%	32%
2	30%	80%
3	95%	/
4	30%/50%	30%/50%
5	/	0%
6	98%	/
7	83%	/

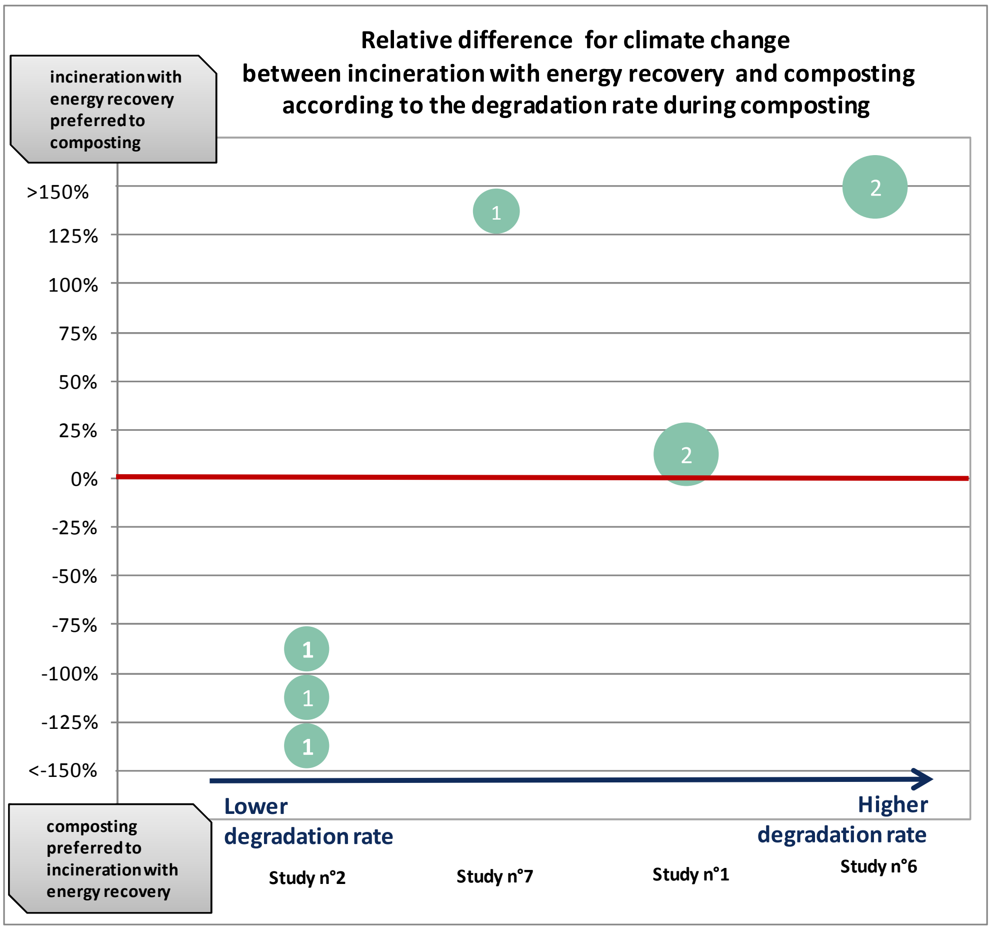

Figure 31 Influence of the degradation rate on the environmental assessment of composting and landfill regarding climate change

The comparison between cases 4[MUB1] and 4[MUB2] confirm the importance of this parameter because when the degradation rate changes from 30% to 50%, the environmental contribution to climate change of landfill increases by 83% and that of composting by 14% (See Table 59). The impact on landfill is greater since the authors have assumed that the material (PLA-compound-PLA) is degraded into methane during the landfill process, while no methane emissions occur during the composting process.

Table 59 Influence of the degradation rate on the performances of landfill and composting regarding the climate change potential in study no 4

		Climate change potential (kg CO2 eq/t)	
Case	Degradation rate	Landfill	Composting
4[MUB1]	30%	1209	-248
4[MUB2]	50%	3452	-213

In study no 2, a sensitivity analysis was conducted to check the influence of carbon sequestration on the environmental performances of composting and landfill regarding climate change. It showed that the results were extremely dependent on this parameter and that it could completely change the conclusions as shown in Table 60. For example for PLA, while composting was the worst option when carbon sequestration was not taken into account, it became the best option once a 30% degradation rate was assumed (i.e. 70% sequestrated).

Table 60 Influence of the carbon sequestration issue on the performances of landfill and composting regarding the climate change potential in study n°2

Assumption	Climate change potential (kg CO2 eq/t) Landfill	Composting	Relative ranking
No carbon sequestration	1	234	**landfill** < composting
Carbon sequestration	-355	-1009	composting < **landfill**

The issue of the degradation rate and carbon sequestration is also linked to the inclusion or exclusion of the biogenic CO_2 which influences the climate change potential. When biogenic CO_2 is taken into consideration, it means that the CO_2 that is emitted due to the degradation of biomass-based substances is assumed not to contribute to global warming since it was taken from the atmosphere during the growth of the plant. In addition, following this approach, the biogenic carbon that is not emitted in landfills or in compost can be considered to have been removed from the natural cycle, thus reducing CO_2 emissions when looking at the full life cycle, as explained in the following:

- Growing phase: X kg of CO_2 absorbed
- End-of-life phase:

  In case of incineration: X kg of CO_2 emitted ⇨ 0 kg of CO_2 for the whole life cycle

  In case of landfill or composting: 0 kg of CO_2 emitted ⇨ X kg of CO_2 **absorbed** for the whole life cycle

Among the studies selected, studies no 2 and 4 clearly indicate that biogenic CO_2 has been taken into account. Study no 1 also refers to biogenic carbon but it is not clear how it has been taken into account in the calculations. The influence of this parameter can be seen on Table 61 which presents the influence of the inclusion of biogenic CO_2 for study no 4. When biogenic CO_2 is excluded, it means that the emissions of biogenic CO_2 are assumed to contribute to global warming as fossil CO_2 and the sequestered carbon is not assumed to save any emissions. The results show that the inclusion of biogenic CO_2 has a very significant influence on the results and affect the ranking between the different options:

- Ranking with biogenic CO2

  Composting < Incineration without energy recovery < Landfill

- Ranking without biogenic CO2

  Incineration without energy recovery < *Composting* < Landfill

The choice of assumptions regarding how carbon issues (degradation, sequestration, biogenic CO_2) should be taken into account is thus of major importance and should be clearly presented.

Table 61 Influence of the inclusion of biogenic CO_2 on the performances of landfill and composting regarding the climate change potential in study n°4

	Climate change potential (kg CO_2 eq) Composting		Landfilling	
	With biogenic CO_2	Without biogenic CO_2	With biogenic CO_2	Without biogenic CO_2
[MUB1]	-0.248	1.92	1.21	3.05
[MUB2]	-0.213	1.95	3.46	5.08

Energy recovery

In the case where some energy is recovered during the waste management stage, the production of energy from other sources is avoided and these benefits are included in the system boundaries. The extent of the credits that can be attributed depends on the type of energy that is replaced. The electricity produced is usually assumed to be average national grid electricity. Although the electricity mix varies from one country to another, the electricity production is still based mainly on fossil fuel resources; thus the credits for avoiding energy use significantly improve the environmental performances.

Energy recovery is very often associated with incineration, which explains why incineration with energy recovery often performs better than composting and landfill. The biogas from landfill can also be collected to produce electricity, as in study no 2. For Biolice and Mater-Bi, landfill then emerges as a better alternative than incineration with energy recovery. The explanation may lie in the fact that the degradation of the material in methane releases more energy than the incineration process. The other studies assessing landfill disposal (studies 1, 4 and 5) do not assume energy recovery from landfill. Therefore, the influence of this parameter cannot be analysed further.

Some biogas is also produced in the case of anaerobic digestion in studies n°3 and 7 and the assumptions around the recovery of the biogas are presented in the Table 62. The two studies differ in terms of biogas production rate and type of energy recovery. It is also interesting to note that both studies take place in Germany and follow an attributional approach, thus assuming that the energy produced replaces average grid energy.

Table 62 Overview of the assumptions regarding anaerobic digestion in the selected studies for biopolymers

Study number	Material	Biogas production	Biogas valorisation
3	PLA	0.84 m^3/kg PLA	electricity only
7	Maize starch	0.4 m^3/kg organic matter	33% electricity/56% heat

The assumptions around energy recovery for incineration (See Table 63) also explain why in studies no 2 and 4 composting performs better than incineration for climate change as illustrated on Figure 32. Indeed, study no 2 is a French study and the electricity is thus mainly comes from nuclear power which is CO_2 free. Thus the energy generated by incineration does not give any credit to the system regarding GHG emissions. In study no 4, no energy recovery is associated with incineration or landfill and composting thus results in a better option. The type of energy recovered and the efficiencies assumed for incineration in the selected studies are shown in Table 63.

Table 63 Overview of the incinerator efficiencies assumed in the selected studies for biopolymers. The efficiency figures are based on gross calorific values (GCV) or net calorific values (NCV). When it is not clear whether the figure is based on GCV or NCV a question mark is inserted.

Study number	Energy produced with incineration	Efficiency
4	No energy	/
5	n.a.	n.a.
1	electricity	n.a.
2	electricity + heat	32% (GCV)
7	electricity + heat	65% (?)
6	electricity + heat	n.a.

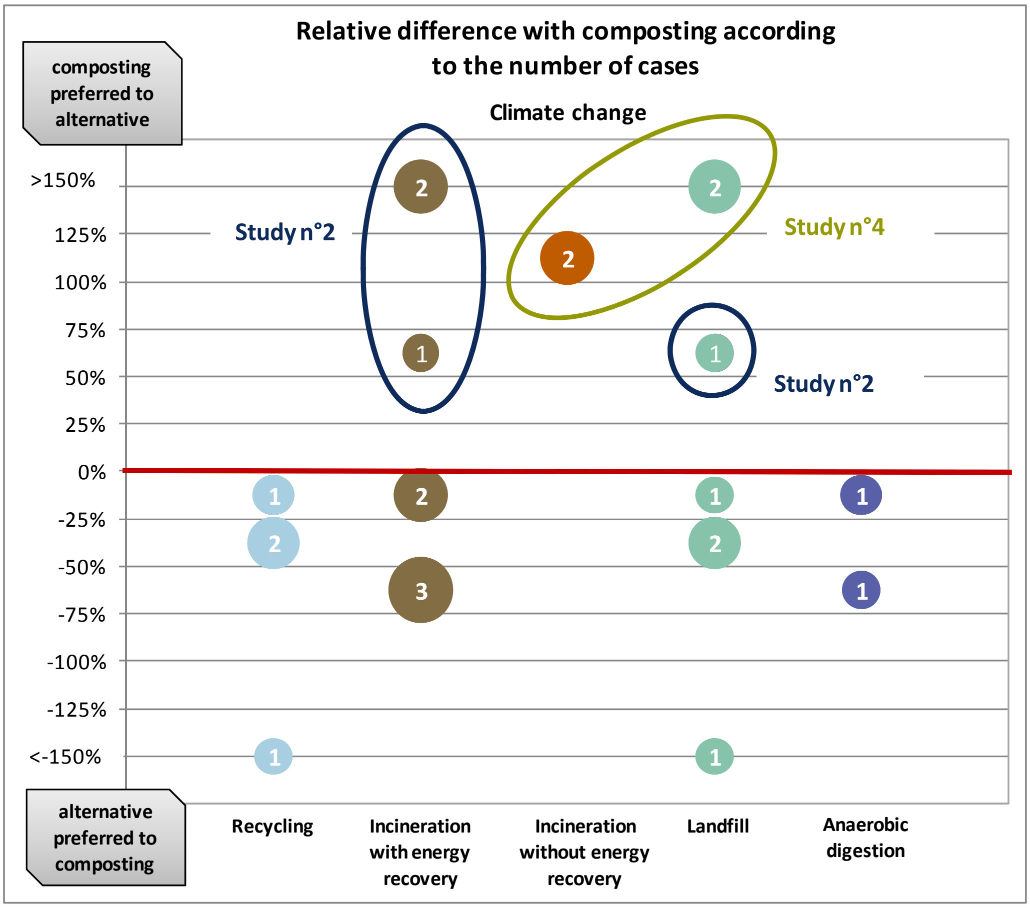

Figure 32 Influence of the assumptions regarding energy recovery on the composting performances in studies n°2 and 4

Avoided production/use of material

Some end-of-life alternatives lead to the production of secondary products that bring credits to the system. For example, in studies 2, 3 and 4, the compost is used as soil conditioner and plant growing medium instead of peat or inorganic fertilisers as shown in Table 64. On the contrary, in the composting scenarios in studies 1, 6 and 7, there is no product substitution assumed for the compost produced. For anaerobic digestion, assessed in studies 3 and 7, the digestate that is produced can also be valorised. This is the case for study no 3 in which the digestate is assumed to replace both mineral fertilisers and peat. However, there is no clear evidence of the influence of these parameters on the results for anaerobic digestion and composting. It is instead the assumptions around the degradation rates or energy recovery that predominate.

Table 64 Substituted products for composting and anaerobic digestion for biopolymers

Study number	Substituted material by compost	Substituted material by digestate
1	No substitution	/
2	Inorganic fertilisers	/
3	mineral fertilisers and peat	mineral fertilisers and peat
4	peat	/
5	/	/
6	No substitution	/
7	No substitution	No substitution

The good performance of recycling is also explained by this parameter. For instance, in scenario 2 [MB] for recycling, the relative difference between recycling and composting exceeds 9000% in favour of recycling for climate change. This can be explained by the fact that in this scenario, the recycling of the biopolymer (Mater-Bi) avoids some production of virgin Mater-Bi which is responsible for high greenhouse gases emissions.

3.4.4 Conclusion

Composting, landfill and incineration with energy recovery are well covered by the selected scenarios with on average ten cases assessed while recycling and anaerobic digestion are represented in five and three cases, respectively.

The results highlight the **good environmental performances of mechanical and chemical recycling** regarding energy demand, depletion of natural resources and climate change potential. On the contrary, the use of biopolymer waste as a reducing agent in blast furnaces in the feedstock recycling scenarios does not bring substantial benefits and incineration and anaerobic digestion are preferable.

Composting does not appear to be advantageous for energy demand and depletion of natural resources compared to the other alternatives. However, **composting presents an advantage over incineration with energy recovery regarding GHG emissions, under the condition of a low degradation rate** (<50%).

Anaerobic digestion is only assessed in studies 3 and 7, for PLA and maize starch respectively and performs better than composting regarding both indicators analysed, i.e. climate change and energy demand. **The advantage of anaerobic digestion over composting comes from the recovery of the biogas produced via electricity and heat production.**

3.4.5 Data gaps/further research

Key parameters

The importance of the **degradation rate** has been highlighted for the evaluation of composting and landfill, thus there is a real need for evidence based information regarding this parameter.

Coverage of the various end-of-life alternatives

Anaerobic digestion has been assessed in only two scenarios and seems a more promising option than composting. However, it should be noted that there is still a lot of uncertainty about the behaviour of biopolymers when undergoing anaerobic digestion. It would also be beneficial to investigate further the impacts of **recycling** since there seems to be some real potential for environmental benefits. There is a need for reliable scientific information to determine whether it would be beneficial to develop a recycling channel for biopolymers. In addition, no study assessing **pyrolysis** or **gasification** has been found so this could be another area for further research.

Environmental indicators

It should also be noted that **water consumption** has not been taken into consideration in any of the selected publications. As biopolymers are based on crops, water consumption may be of significant importance. It would also be interesting if more studies took into consideration a large panel of indicators. Many studies give priority to climate change. The risk of focusing on a single indicator is that an improvement regarding this indicator might lead to an increased environmental burden for another indicator.

3.5 Food and garden waste

3.5.1 Presentation

The definition of 'municipal food and garden waste' is quite vague. It refers to the waste containing carbon compounds, generated in households and similar sources. In the waste industry, the term 'organic' usually refers to waste deriving from animal and plant materials. Various waste fractions are included in this stream, but two main categories can be defined: food or kitchen waste and garden waste.

In LCA studies, the scope of the study determines the genre of waste included. Therefore, there might be studies that focus on a very specific waste streams, such as branches in garden waste or on a very general grouping such as the entire organic part of municipal waste (i.e. kitchen, garden, paper and wood waste). Paper and wood are usually excluded from this category and examined separately, but there are cases in which these fractions are included in the organic part, especially if an appropriate technology is examined (e.g. central compost) or a collection scheme is simulated.

In this report, seven studies were located that fulfil all the preconditions and qualify for further analysis. Some of these studies refer to the same waste stream, but some others only examine a part of organic waste, according to their scope as it is expressed in the corresponding functional unit. There are two studies (studies 6 and 7) investigating organic waste, two (3 and 4) focusing on food waste, one on garden waste (no 2), one (no 5) for mixed organic waste (defined as a weighted average of food discards and yard trimmings) and study no 1 refers to bio-waste from households (thought as a mix of household organic waste and garden/wood waste). The selected publications are presented in Table 65 below and the materials they examine in Table 66.

Table 65 Presentation of the selected studies

Study number	Title	Main author	Year	Geographical scope
1	Using LCA to evaluate impacts and resources conservation potential of composting: A case study of the Asti District in Italy	Blengini	2008	Italy
2	Environmental assessment of garden waste management in Århus Kommune	Boldrin	2009	Denmark
3	Life cycle assessment of food waste management options	Lundie	2005	Australia
4	Life cycle assessment of energy from solid waste	Finnveden	2000	Sweden
5	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks	US EPA	2006	USA
6	Klimaregnskap for avfallshåndtering (*Climate accounting for waste management*)	Raandal	2009	Norway
7	Environmental assessment of waste systems for municipal waste in Århus Kommune	Kikerby	2004	Denmark

Table 66 Materials included in the selected LCA studies

Study	Case	Material
1	1[OR]	Organic municipal waste
2	2[GW1]	Garden waste
	2[GW2]	Garden waste
3	3[FW1]	Food waste
	3[FW2]	Food waste
	3[FW3]	Food waste
4	4[FW1]	Food waste
	4[FW2]	Food waste
5	5[OR]	Organic municipal waste
6	6[OR]	Organic municipal waste
7	7[OR]	Organic municipal waste

Besides these seven studies, an Australian study was located focusing on comparisons between different types of composting (Recycled Organics Unit, 2007). Although it is a valuable study that penetrates the compost systems quite comprehensively, it was decided not to analyse it further since it includes no other treatment options and thus relative conclusions.

The clear definition of the system boundaries when performing an LCA is essential for appreciating the assumptions and methodologies included, as well as for understanding the type of comparisons among treatment routes. The system boundaries are unique for each study and all particularities should be taken into account when reviewing. A general framework of a typical (usual) system boundaries diagram is illustrated below in Figure 33.

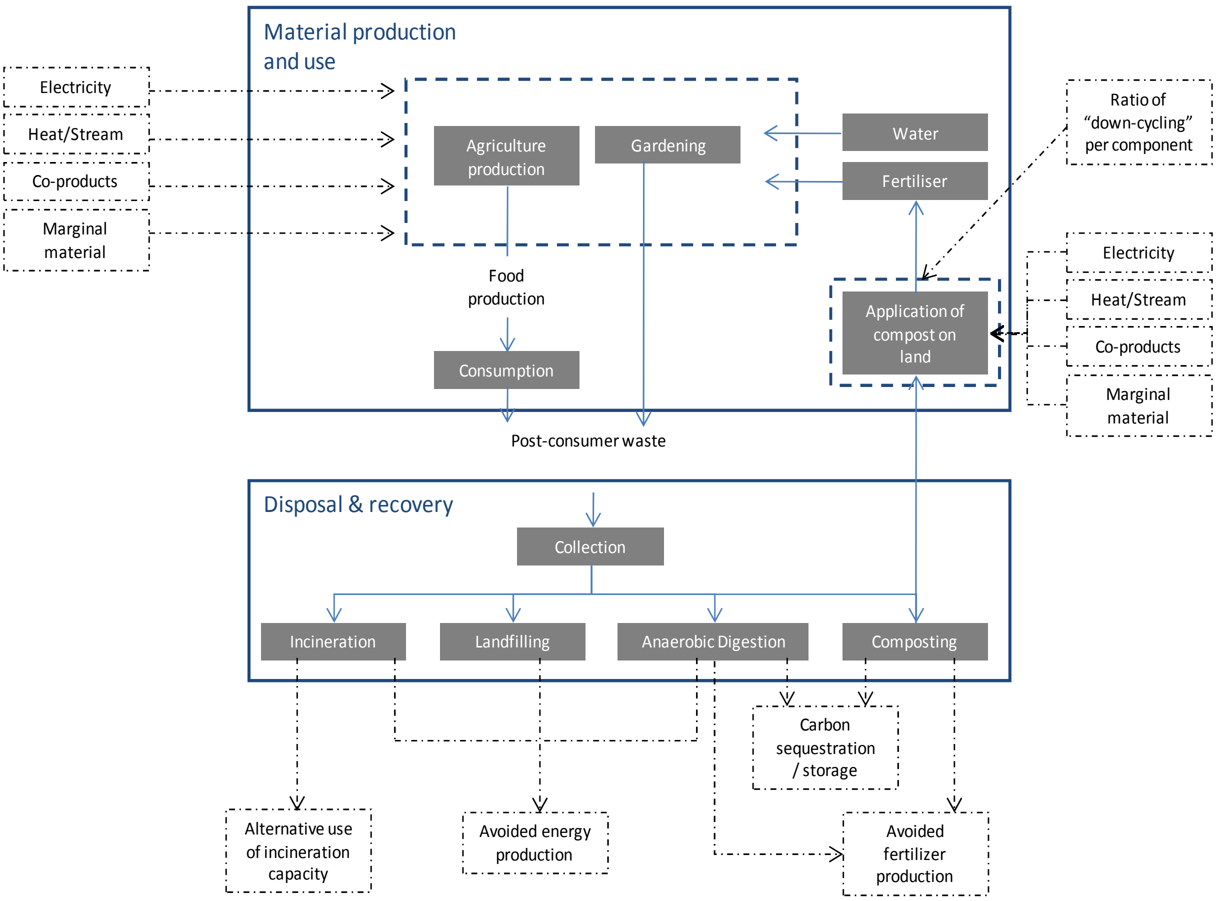

Figure 33 The food and garden waste system and key parameters

3.5.2 Comparison between the various end-of-life options

The end-of-life options covered by the selected studies are:

- Various types of composting
- Incineration with energy recovery
- Landfill
- Anaerobic digestion

Table 67 lists all the treatment options analysed. The traditional options are given clearly given more weight (incineration, landfill and mainly composting), but anaerobic digestion is also studied as a newly popular route. Unfortunately, no reliable studies have been carried out so far regarding two prominent but not well established methods, pyrolysis and gasification.

All selected studies focus on the end-of-life stage of food and garden waste; in other words none of the studies examines the full life cycle of food and gardening.

Table 67 Overview of the end-of-life alternatives compared within each case for food and garden waste

Case	Recycling	Composting	Incineration with electricity recovery only	Incineration with heat or combined heat/ electricity recovery	Landfill	Anaerobic digestion	Pyrolysis	Gasification
1[OR]		X			X			
2[GW1]		X		X				
2[GW2]		X		X				
3[FW1]		X			X			
3[FW2]		X			X			
3[FW3]		X*			X			
4[FW1]		X		X	X	X		
4[FW2]		X		X	X	X		
5[OR]		X	X		X			
6[OR]		X		X	X	X		
7[OR]				X		X		
Total number of cases	**0**	**10**	**1**	**6**	**8**	**4**	**0**	**0**

* Scenario assuming total anaerobic degradation

Ranking between the various end-of-life options within each scenario

Study no 1

The first study compared composting to landfill only. Of the four most important indicators chosen, composting is better according to global warming potential and landfill is bettering terms of primary energy demand. In fact, landfill is the worst option for all the other included impact categories, except for ozone depletion, where the difference is only marginal. The fact that the simulated chosen landfill is assumed not to have installed any energy recovery technologies is decisive for the climate change contribution, since no benefits are attributed to the landfill option. Therefore, this particular landfill appears a much less attractive option than composting.

Study no 2

The second study compares windrow or home composting to incineration for garden waste and it provides results for global warming only, out of the basic indicators. Carbon binding is taken into account in this study. In this impact category, incineration has a better performance than both types of composting. According to the remaining indicators (eutrophication, acidification, photochemical oxidation, ecotoxicity in water, ecotoxicity in soil and human toxicity via soil, water and air), incineration is preferable for all but two cases (two for eutrophication and one case in human toxicity via air). However, the increased energy potential of the garden waste compared to food waste (due to the presence of wood), combined with the lower water content in garden waste, results in a higher heating value of garden waste than the average heating value for food and garden waste. Thus, incineration is favoured compared to composting and the conclusions should not be interpreted with reference to all organic waste.

Study no 3

This study compares two types of home composting and centralised composting to disposal in a landfill. The results for the two types of home composting are identical except for climate change, where the most important parameter is the form of degradation assumed. The study takes into account two 'extreme' artificial cases in order to provide a range of values according to the degree of aerobic conditions operating. This range varies from a value based on an assumption of total aerobic conditions (case 3[FW2]) and a value for assumed total anaerobic conditions (case 3[FW3]). For the remaining impact categories, study no 3 uses average values for home composting. According to the results, composting is preferable for climate change except for the anaerobic version. Home composting is the best regarding primary energy demand and all types of compost are better than landfill regarding water consumption. Generally, home composting is the best option, followed by centralised composting even in the rest of the impact categories. In this study also, no energy recovery is assumed to take place in the landfill.

Study no 4

This study compares the traditional disposal options (incineration, landfill and composting) to two types of anaerobic digestion. Anaerobic digestion is the best option regarding resource depletion and climate change, but behind incineration when examining primary energy demand. The better efficiencies achieved in a modern incineration plant are primarily responsible for this outcome. Composting, on the other hand, is the worst option for resource consumption and primary energy, while landfill takes its place for climate change. When the rest of indicators are examined the classification of options becomes more complicated.

Study No 5

This US study produces results only for climate change and energy demand, while comparing composting to incineration and landfill. Carbon binding is taken into account when examining the composting option. Energy recovery is assumed for both incineration and landfill. Incineration is the best option for both categories, although composting presents equivalent results for climate change. Landfill is the worst option for climate change and the second regarding energy use.

Study no 6

Only climate change is included in this study as an environmental indicator. All well established options are analysed in this study: landfill with energy recovery, incineration with energy recovery, composting and anaerobic digestion. Anaerobic digestion appears to be preferable, but it is closely followed by composting. On the other hand, landfill is the worst option and the one (together with incineration) that has a net positive contribution to global warming. It should also be mentioned that carbon binding is taken into account in this study.

Study no 7

This Danish study compares incineration to anaerobic digestion in a strictly Danish context. Among the basic indicators, only climate change is included, in spite of this being a full LCA. Incineration prevails in terms of global warming, but it should be noted that incineration is favoured by the assumptions chosen. Indeed, the state-of-the-art dedicated combustion plant examined produces energy on a quite high efficiency and the substituted electricity is assumed to be produced in a coal-fired power plant (the same assumption is applied for the energy recovered through anaerobic digestion).

Table 68 Ranking of end-of-life options within each scenario for food and garden waste

	Case	Composting	Incineration with energy recovery	Landfill	Anaerobic digestion
Climate change (kg CO_2 eq)	1[OR]	+++		+	
	2[GW1]	+	+++		
	2[GW2]	+	+++		
	3[FW1]	+++		+	
	3[FW2]	+++		+	
	3[FW3]*	+ *		+++	
	4[FW1]	++	++	+	+++
	4[FW2]	++	++	+	+++
	5[OR]	+++	+++	+	
	6[OR]	++	++	+	+++
	7[OR]		+++		+
Depletion of natural resources (kg Sb eq)	4[FW1]	+	++	++	+++
	4[FW2]	+	++	++	+++
	Only study n°4 includes this indicator				
Energy demand (MJ)	1[OR]	+		+++	
	3[FW1]	+		+++	
	3[FW2]	+++		+	
	3[FW3]*	+++ *		+	
	4[FW1]	+	+++	++	++
	4[FW2]	+	+++	++	++
	5[OR]	+	+++	++	
	Studies n°2, 6 and 7 do not include this indicator				
Water consumption (m^3)	3[FW1]	+++		+	
	3[FW2]	+++		+	
	3[FW3]*	+++ *		+	
	Only study n°3 includes this indicator				

* Composting scenario assuming total anaerobic degradation

+++	best option
++	intermediary option
+	worst option
	option not assessed

3.5.3 Detailed comparison between the various treatment options

Climate change

The diagrams below indicate the relative difference of composting or incineration with energy recovery and the rest of the treatment options.

One point regarding anaerobic digestion should be explained. The configuration of anaerobic digestion in all three studies that include it shows quite high methane recovery efficiencies (methane capture is above 90-95%) and conversion to energy. These numbers reveal the assumption that the anaerobic digestion plant is state-of-the-art, which influences the results greatly and renders the comparisons to other treatment plants relatively unfair.

Moreover, it should be noted that study no 3 contains two cases of home composting. The first case assumes fully aerobic conditions (case 3[FW2]), while the second assumes fully anaerobic conditions (case 3[FW3]). These artificial conditions aim at providing a range of values for global warming. Exclusively aerobic conditions are impossible to obtain in home composting and anaerobic conditions are likely to arise if the compost is not often aerated properly. This virtual 'anaerobic' case attempts to demonstrate the (rather large) effect that the aeration assumption has regarding the contribution to climate change. For the rest of impact categories, study no 3 presents identical figures for both cases of home composting.

Figure 34 illustrates where composting stands compared to the other routes in terms of global warming contribution only. It instantly becomes clear that anaerobic digestion is absolutely better, in the sense that there is relative consensus among studies (three out of four cases). The situation is not as clear for incineration. There are studies that classify compost as a better option and one that supports the opposite statement. Study no 2 includes two cases of composting from which incineration is superior. In this study, state-of-the-art technologies are assumed for a Danish context. Therefore, it is safe to say that a high-standards incinerator provides more advantages for climate change than composting, despite the low heating value of wet organic waste. The rest of the cases are in favour of composting, but in two cases the results are very close. Composting is clearly better than landfill according to the diagram below. The only case where composting is worse is contained in study no3 where artificial anaerobic conditions are assumed for composting resulting in the release of high concentrations of methane - which is particularly harmful for climate change. The rest of the studies agree that composting is better.

Figure 35 illustrates the relative superiority of incineration with energy recovery to other treatment options. It is also quite clear that incineration is superior to landfill with respect to climate change. All four cases support this statement and they even belong to the upper side of the positive axis (above 150%) which means that the figures for the two options differ greatly. As mentioned above, the results of the comparison to composting are not that clear.

As a general rule of thumb, from all comparisons among options, landfill appears to be the worst option, while anaerobic digestion is the best.

Table 69 Relative difference between the impacts from the different end-of-life options vs. composting for climate change for food and garden waste. A positive value means that composting is preferable to the other end-of-life option. A negative value means that composting causes a larger environmental burden than the other end-of-life option.

	Composting versus other alternatives									
N° case	1[OR]	2[GW1]	2[GW2]	3[FW1]	3[FW2]	3[FW3]*	4[FW1]	4[FW2]	5[OR]	6[OR]
Incineration with energy recovery		-1320%	-410%				20%	20%	0%	150%
Landfill	630%			60%	2720%	-70%	1980%	1980%	220%	4550%
Anaerobic digestion							-740%	-790%		-350%
Study n°7 does not include a comparison with incineration with energy recovery for this indicator and thus is not included in this table										

* Composting scenario assuming total anaerobic degradation

Table 70 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for climate change for food and garden waste. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes a larger environmental burden than the other end-of-life option.

	Incineration with energy recovery versus other alternatives						
N° case	2[GW1]	2[GW2]	4[FW1]	4[FW2]	5[OR]	6[OR]	7[OR]
Composting	90%	80%	-20%	-20%	0%	-300%	
Landfill			1600%	1600%	220%	8800%	
Anaerobic digestion			-620%	-670%		-1000%	40%
Studies n°1 and 3 do not include a comparison with incineration with energy recovery for this indicator and thus are not included in this table							

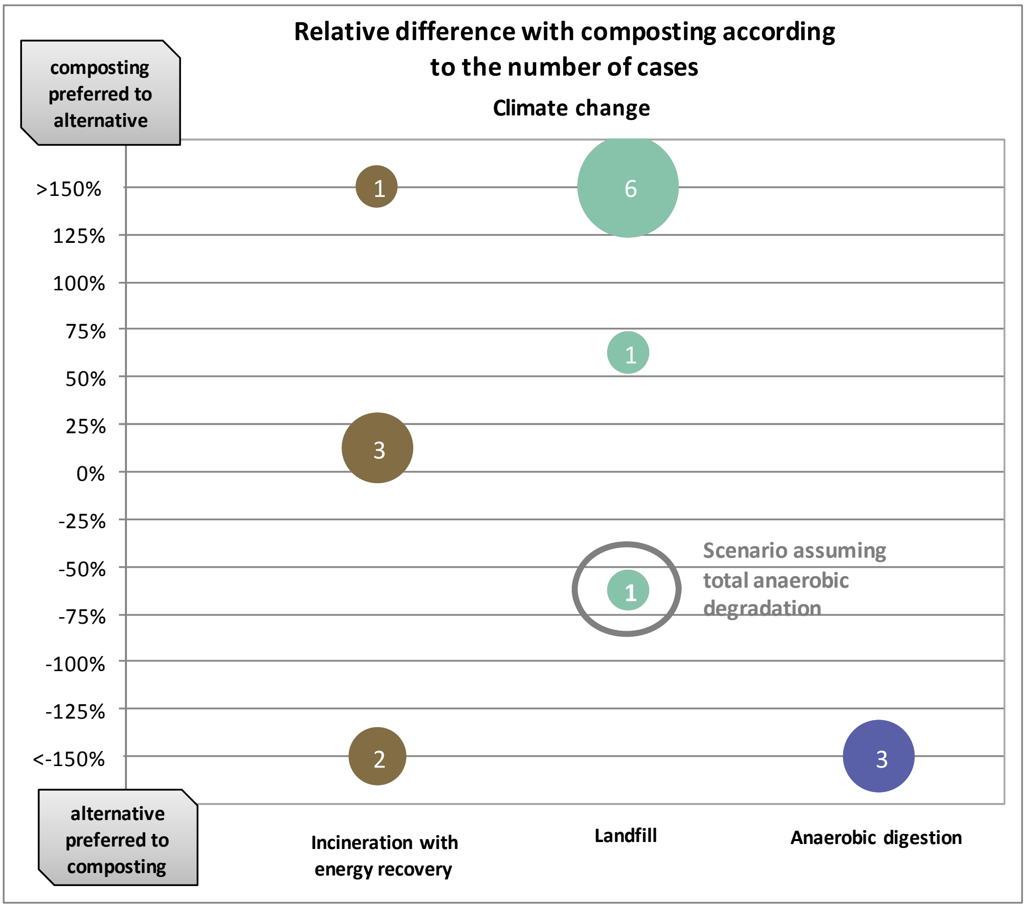

Figure 34 Relative difference between the impacts from the different end-of-life options vs. composting for climate change for food and garden waste. The size of the “bubble” is proportional to the number of cases coming up with a value within the same range as another.

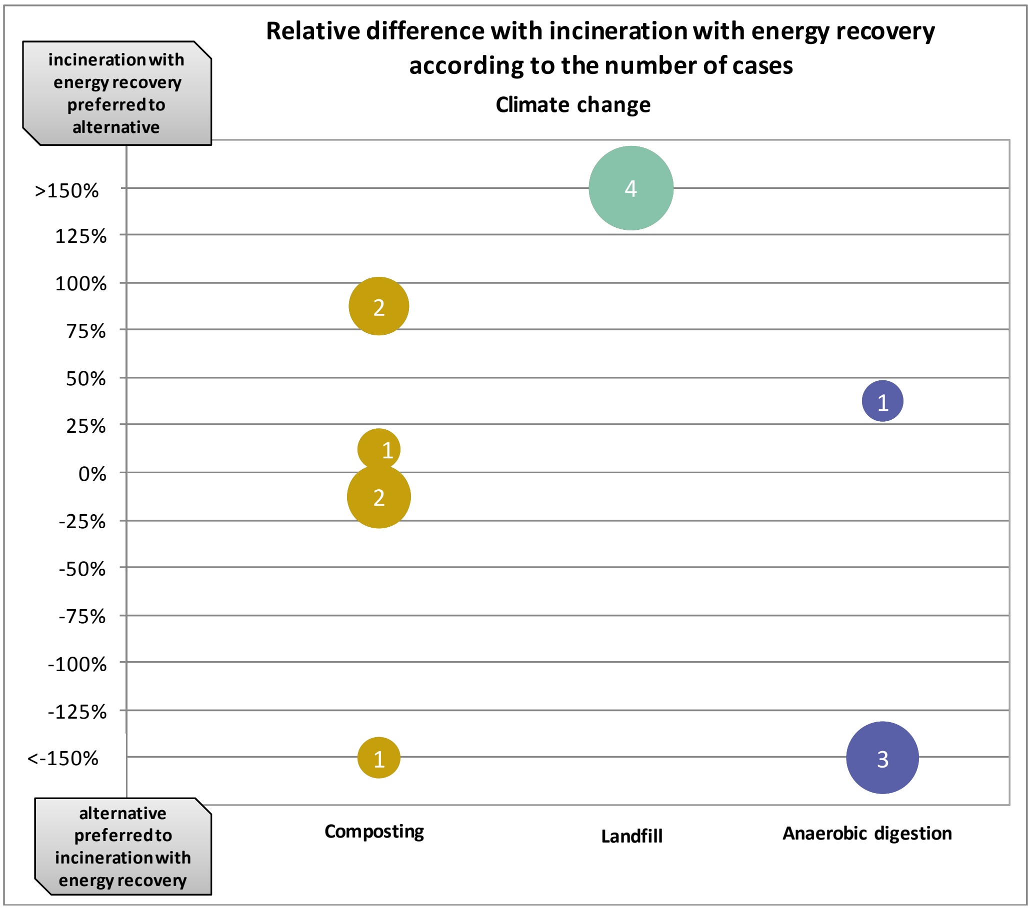

Figure 35 Relative difference between the impacts from the different end-of-life options vs. incineration for climate change for food and garden waste. The size of the “bubble” is proportional to the number of cases coming up with a value within the same range as another.

Depletion of natural resources

Unfortunately, only study no 4 includes this indicator in its impact assessment. Both cases examined are quite consistent with one another and they produce a clear classification of alternatives. Anaerobic digestion takes the first place mainly because of the large benefits it brings to the system. Anaerobic digestion recovers both material (fertiliser) and energy, saving at the same time the resources required for the primary production of both.

On the other hand, since composting is considered to be the worst option in this study, it appears that it is the energy recovered by anaerobic digestion that brings the most benefits. Moreover, the differences in the results are so great that it highlights that energy recovery (which in this study leads to the avoidance of fossil fuel depletion) is much more beneficial than material recovery (fertiliser substitution). The reason for this observation is that fossil fuels in an LCA context are considered to be a limited resource, while fertiliser is not. Landfill appears to be performing better than composting, which is rather surprising. The explanation given in the study is that, for this system, this impact category is greatly dependent on energy consumption and the consumed resources are approached as energy carriers. Therefore the energy recovery of the landfill manages to overcome the benefits from material recovery in composting.

In this study and for this impact category, anaerobic digestion is the most efficient method for recovering energy, since incineration has much worse figures. Obviously, the additional function in anaerobic digestion of producing a secondary material also plays a part in the results obtained.

The following tables and graphs confirm the superiority of anaerobic digestion. In Figure 37, incineration is proved to be the worst option except for composting.

Table 71 Relative difference between the impacts from the different end-of-life options vs. composting for depletion of natural resources for food and garden waste. A positive value means that composting is preferable to the other end-of-life option. A negative value means that composting causes a larger environmental burden than the other end-of-life option.

	Composting versus other alternatives	
N° case	4[FW1]	4[FW2]
Incineration with energy recovery	-70%	-70%
Landfill	-300%	-300%
Anaerobic digestion	-420%	-460%
Only sudy n°4 includes a comparison with composting for this indicator		

Table 72 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for depletion of natural resources for food and garden waste. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes a larger environmental burden than the other end-of-life option.

	Incineration with energy recovery versus other alternatives	
N° case	4[FW1]	4[FW2]
Composting	230%	230%
Landfill	-770%	-770%
Anaerobic digestion	-1160%	-1270%
Only sudy n°4 includes a comparison with incineration with energy recovery for this indicator		

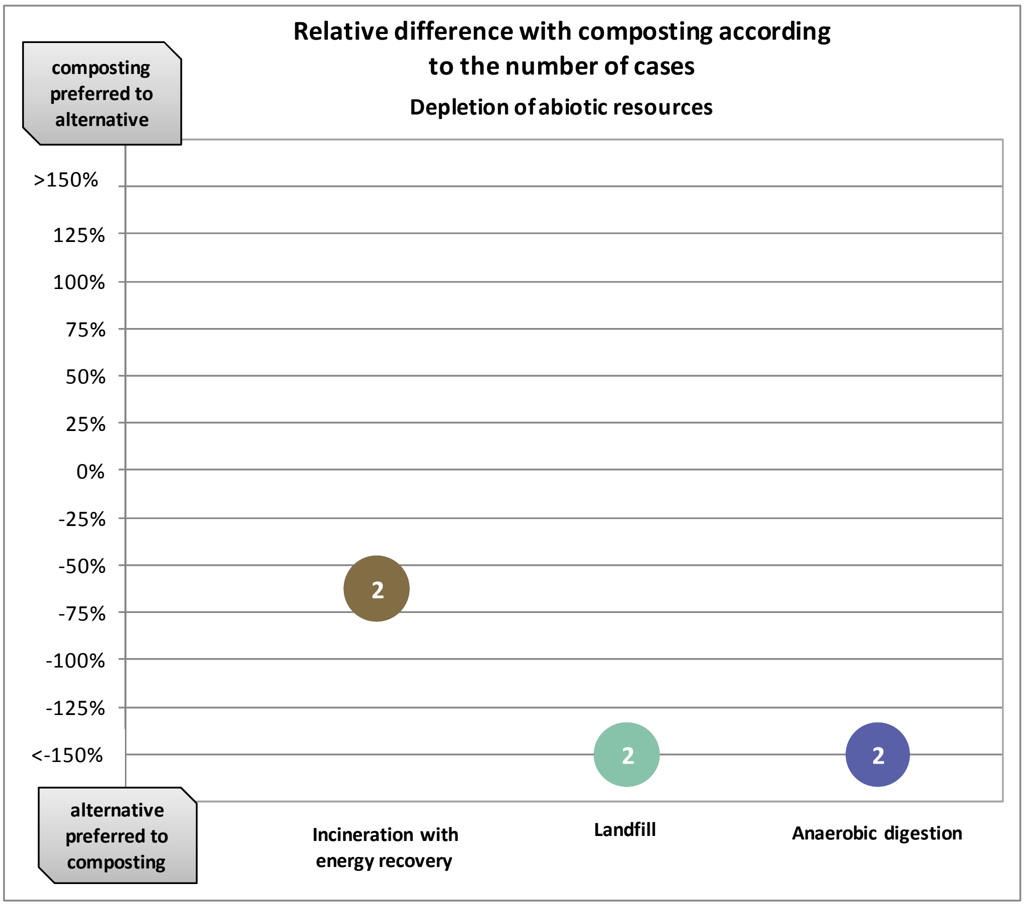

Figure 36 Relative difference between the impacts from the different end-of-life options vs. composting for depletion of natural resources for food and garden waste. The size of the “bubble” is proportional to the number of cases coming up with a value within the same range as another.

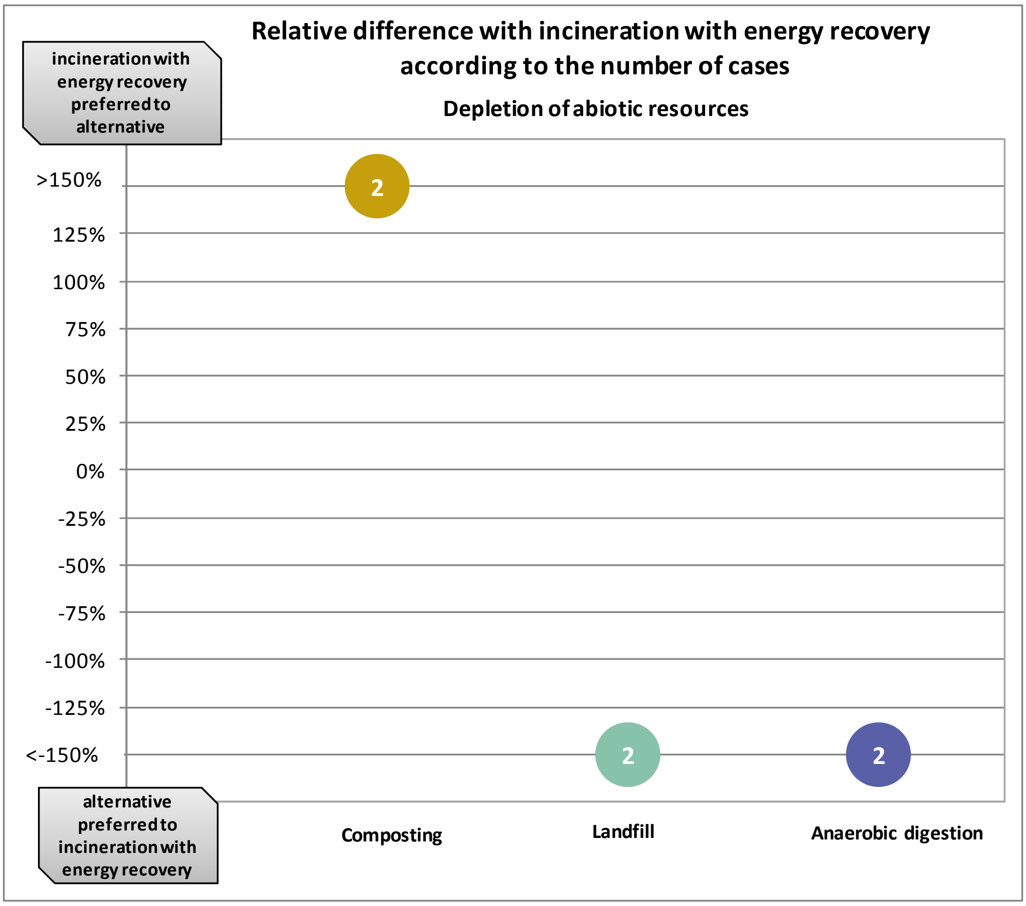

Figure 37 Relative difference between the impacts from the different end-of-life options vs. incineration for depletion of natural resources for food and garden waste. The size of the “bubble” is proportional to the number of cases coming up with a value within the same range as another.

Energy demand

The tables and graphs below depict the relative difference of composting and incineration with energy recovery towards the other treatment options. Figure 38 shows that in terms of energy budgets, incineration and anaerobic digestion are clearly better options than composting. The landfill route is also better in most cases except for two. Those two cases are included in study no 3, where the simulated landfill does not contain any energy recovery from waste. This absence of benefits in these cases is responsible for the landfill's shortcomings. Generally, since composting is an option that does not recover any energy, it is difficult to compete against the other alternatives in this impact category. However, study no 1 does not include any energy recovery from the landfill either, but performs better than composting-

On Figure 39, shows a self-evident and clear classification of alternatives. Incineration appears to be the best option in this category. However, this statement is only based on two studies (4 and 5) that included this comparison for this indicator. According to them, incineration is much better than composting and landfill and slightly better than anaerobic digestion. The last comparison, in terms of energy budget, means that in a life-cycle perspective, the overall energy efficiencies for incineration and anaerobic digestion lean towards the former. Technological advancements in the anaerobic digestion field might, however, improve the overall efficiencies of energy recovery for this option. So far, the best alternative for using the potential energy in organic waste has been incineration, but this analysis of recent LCAs shows that anaerobic digestion can result in similar energy credits to incineration and certainly better ones than landfill (see study no 4).

Table 73 Relative difference between the impacts from the different end-of-life options vs. composting for energy demand for food and garden waste. A positive value means that composting is preferable to the other end-of-life option. A negative value means that composting causes a larger environmental burden than the other end-of-life option.

	Composting versus other alternatives						
N° case	1[OR]	3[FW1]	3[FW2]	3[FW3]*	4[FW1]	4[FW2]	5[OR]
Incineration with energy recovery					-730%	-730%	-200%
Landfill	-20%	-70%	440%	440%	-380%	-380%	-40%
Anaerobic digestion					-610%	-450%	
Studies n°2,6 and 7 do not include a comparison with composting for this indicator and thus are not included in this table							

* Composting scenario assuming total anaerobic degradation

Table 74 Relative difference between the impacts from the different end-of-life options vs. incineration with energy recovery for energy demand for food and garden waste. A positive value means that incineration with energy recovery is preferable to the other end-of-life option. A negative value means that incineration with energy recovery causes a larger environmental burden than the other end-of-life option.

	Incineration with energy recovery versus other alternatives		
N° case	4[FW1]	4[FW2]	5[OR]
Composting	120%	120%	200%
Landfill	60%	60%	160%
Anaerobic digestion	20%	40%	
Only sudies n°4 and 5 include a comparison with incineration with energy recovery for this indicator			

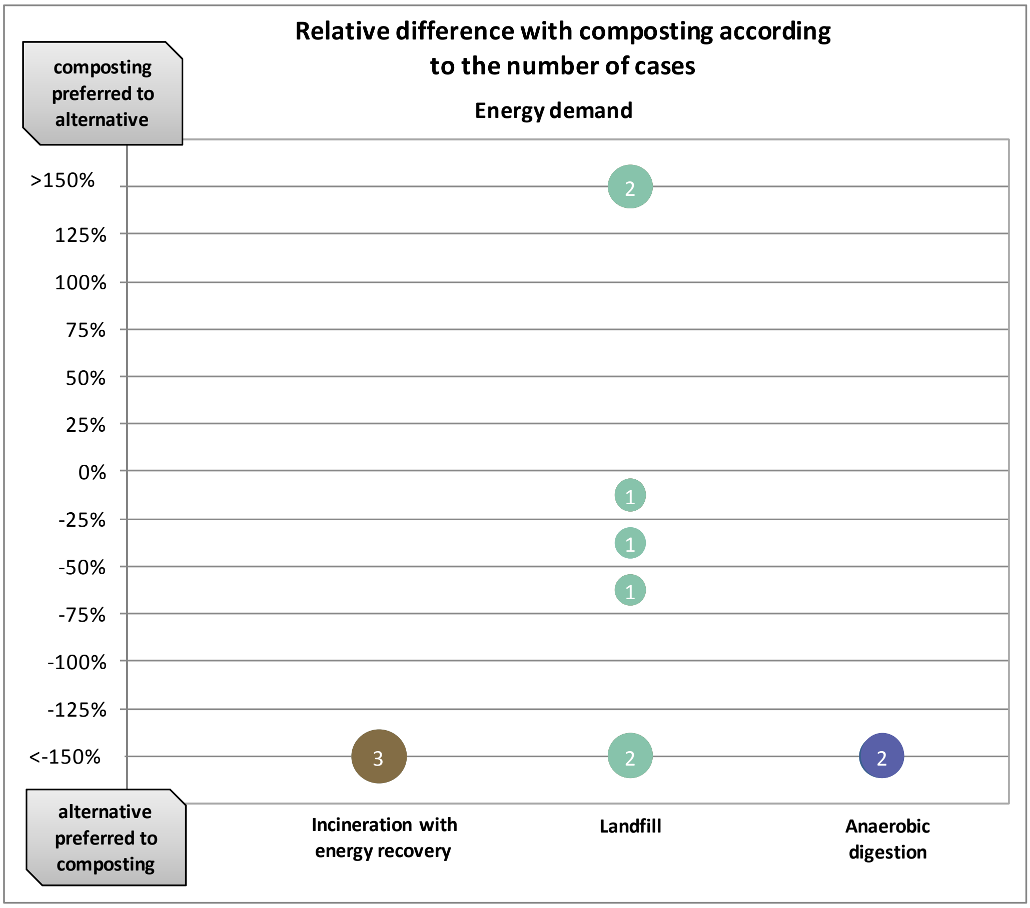

Figure 38 Relative difference between the impacts from the different end-of-life options vs. composting for energy demand for food and garden waste. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

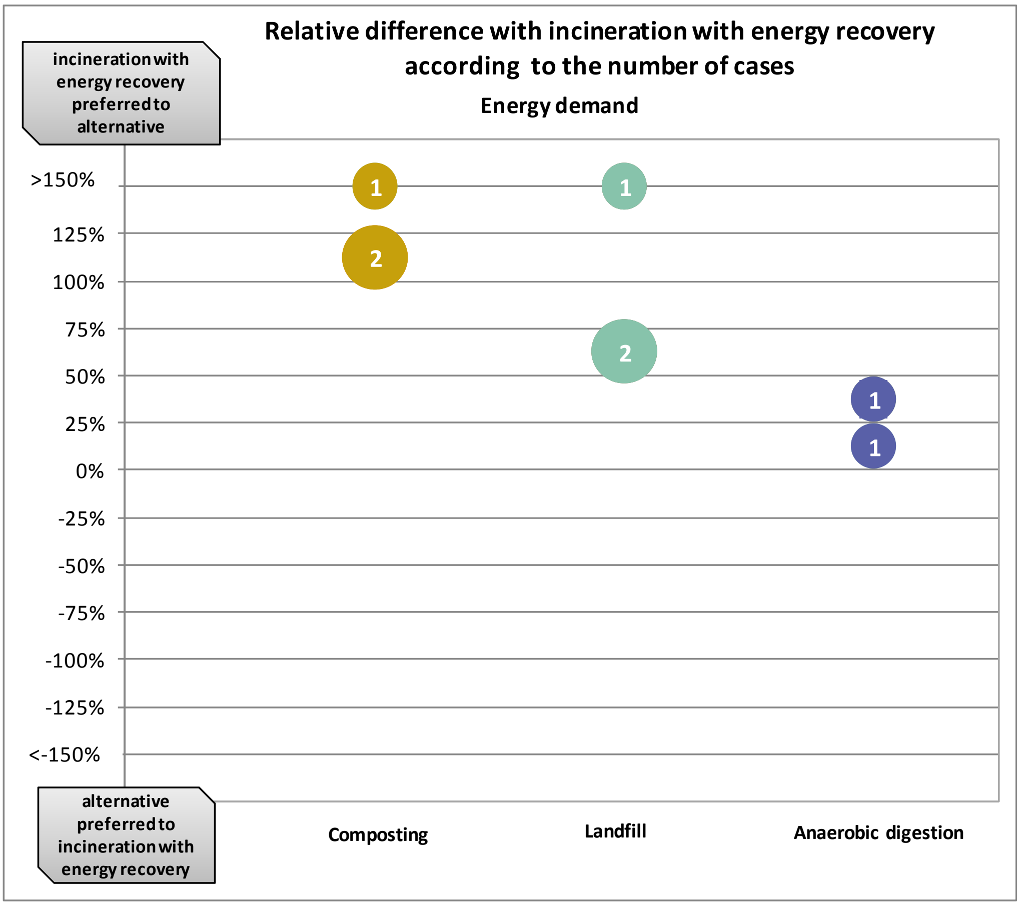

Figure 39 Relative difference between the impacts from the different end-of-life options vs. incineration for energy demand for food and garden waste. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Water consumption

This impact category was only examined by one study (no 3) and the results show a preference for composting over landfill. In fact, in all three cases included in that study composting was clearly superior, as Table 75 below indicates.

Home composting in study no 3 is examined through both artificial anaerobic (case FW2) and artificial fully aerobic (case FW3) conditions. Both systems perform similarly for all indicators but climate change. Therefore, cases FW2 and FW3 have the same value for water consumption. The centralised compost (case FW1) requires twice as much water as home composting, but it is still much better than landfill.

In this impact category, the production of secondary material enabled by composting is the decisive factor that separates the results of composting and landfill. The use of compost on land and the substitution of cow manure (in study no 3) leads to some irrigation savings that landfill cannot produce.

Table 75 Relative difference between the impacts from the different end-of-life options vs. composting for water consumption for organics. A positive value means that composting is preferable to the other end-of-life option. A negative value means that composting causes a larger environmental burden than the other end-of-life option.

	Composting versus other alternatives		
N° case	3[FW1]	3[FW2]	3[FW3] *
Landfill	150%	380%	380%
Only study n°3 includes a comparison with composting for this indicator			

* Composting scenario assuming total anaerobic degradation

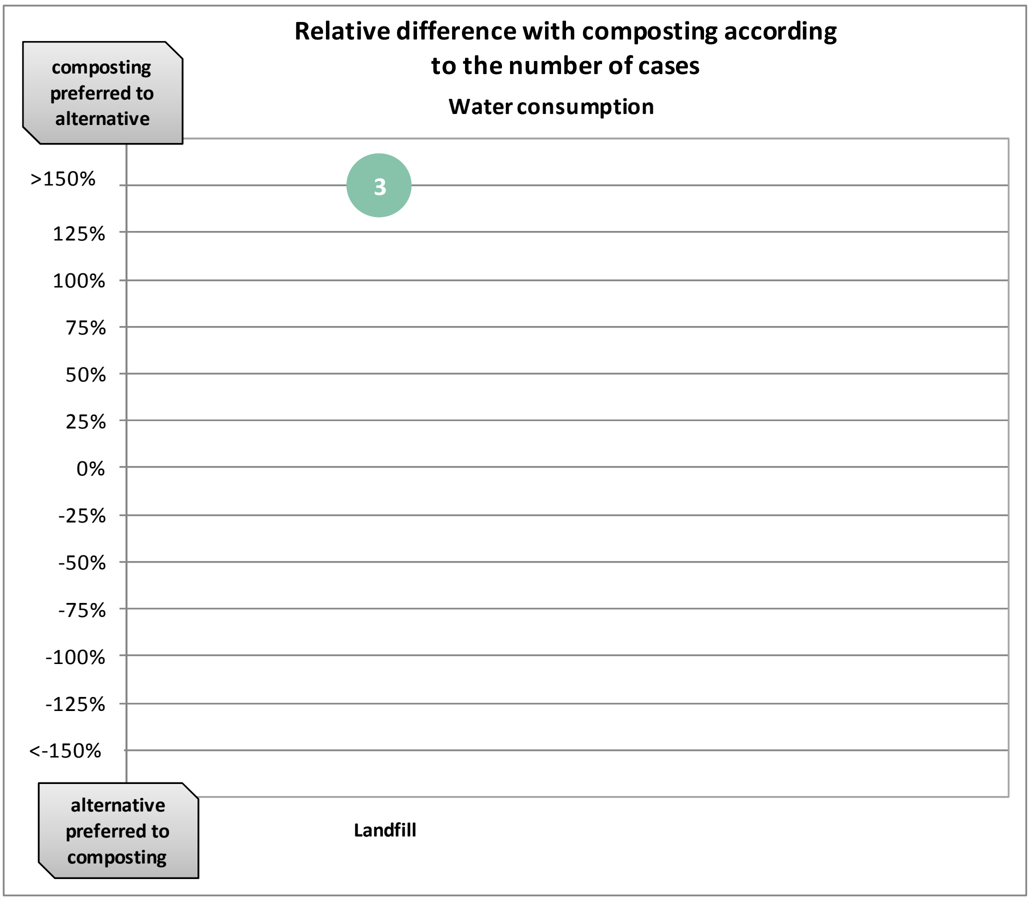

Figure 40 Relative difference between the impacts from the different end-of-life options vs. composting for water consumption for food and garden waste. The size of the "bubble" is proportional to the number of cases coming up with a value within the same range as another.

Other indicators

Acidification

In this impact category the situation is quite diverse, since there is no clear preference for either the best or the worst treatment route. Anaerobic digestion is superior in the case in which it has been included, but the sample is not sufficient. On the other hand, landfill seems to be the worst in most cases but one. Interestingly, when there is a comparison available between them, incineration performs better than composting.

Table 76 Ranking of end-of-life options within each scenario for acidification

	Case	Composting	Incineration with energy recovery	Landfill	Anaerobic digestion
Acidification (kg SO_2 eq)	1[OR]	+++		+	
	2[GW1]	+	+++		
	2[GW2]	+	+++		
	3[FW1]	+		+++	
	3[FW2]	+++		+	
	3[FW3]*	+++ *		+	
	7[OR]		+		+++
	Studies n°4, 5 and 6 do not include this indicator				

+++	best option
+	worst option
	option not assessed

* Composting scenario assuming total anaerobic degradation

Photochemical oxidation

The conclusion that emerges from the table below is that incineration with energy recovery is the most beneficial option. It is also interesting to note that composting performs better than landfill.

Table 77 Ranking of end-of-life options within each scenario for photochemical oxidation

	Case	Composting	Incineration with energy recovery	Landfill	Anaerobic digestion
Photochemical oxydation (kg ethylene eq)	1[OR]	+++		+	
	2[GW1]	+	+++		
	2[GW2]	+	+++		
	4[FW1]	++	+++	+	++
	4[FW2]	++	+++	+	++
	7[OR]		+++		+
	Studies n°3, 5 and 6 do not include this indicator				

+++	best option
++	intermediary option
+	worst option
	option not assessed

Eutrophication

In this impact category, composting appears to have an advantage. Artificial fertilisers are quite intensive for this impact category mainly because of their high content of phosphorus and nitrogen. The chemical fertiliser saved because of the use of compost gives important benefits to compost versus the other alternatives. Incineration mainly and landfilling, in that order, seem to be the worst. For eutrophication, as for acidification, anaerobic digestion is better than incineration but only in the one available comparison.

Table 78 Ranking of end-of-life options within each scenario for eutrophication

	Case	Composting	Incineration with energy recovery	Landfill	Anaerobic digestion
Eutrophication (kg O_2 eq)	1[OR]	+++		+	
	2[GW1]	+++	+		
	2[GW2]	+++	+		
	3[FW1]	+		+++	
	3[FW2]	+++		+	
	3[FW3]*	+++ *		+	
	7[OR]		+		+++
	Studies n°4, 5 and 6 do not include this indicator				

+++	best option
+	worst option
	option not assessed

* Composting scenario assuming anaerobic degradation

Human toxicity

Based on Table 79, it is hard to give an overall conclusion regarding the best option. It is interesting to notice that landfill and incineration give similar performances when compared. The picture is fairly balanced between composting and landfill.

Table 79 Ranking of end-of-life options within each scenario for human toxicity

	Case	Composting	Incineration with energy recovery	Landfill	Anaerobic digestion
Human Toxicity	3[FW1]	+		+++	
	3[FW2]	+++		+	
	3[FW3]*	+++ *		+	
	4[FW1]	+	+++	+++	++
	4[FW2]	+	+++	+++	++
	Only studies n°3 and 4 include this indicator				

+++	best option
++	intermediary option
+	worst option
	option not assessed

* Composting scenario assuming total anaerobic degradation

Key parameters

There are some parameters that have been proved more important than others in an organic waste LCA framework. The key parameters that have been identified in the selected LCA studies are:

- The electricity mix
- The inclusion of carbon storage and binding
- Material substitution
- Level of technology and relevant efficiencies

Electricity mix

The choice of electricity mix is a key parameter for many organic waste treatment routes and many impact categories. In the organic waste management system, there are not many processes that are energy intensive. As a result, whether the electricity mix is based on carbon-intensive fuels (e.g. coal) or not (e.g. renewable sources) has little influence on the results. However, especially during the past few years, the energy recovery operations have been embedded in many technologies, such as anaerobic digestion, besides the more traditional incineration and landfill. Therefore, a significant amount of energy is produced as a result of food and garden waste treatment. The selected LCA approach determines whether the substitution of energy will follow the marginal fuel or the average mix. If all recovered energy (which is converted to electricity or heat) substitutes for one fuel source only which is carbon intensive, the benefits for the system are great. If an average mix is assumed to produce the substituted energy, the benefits depend on the average contribution of the mix to climate change.

An example that depicts the influence of the substituted energy mix is the examination of the incineration results for climate change. The studies that assume an exclusive fossil-based mix replaced by energy recovery produce net negative results (studies 2 and 5). On the other hand, the studies that include some percentage of renewable energy sources (study no 4 substitutes partly forest residues for heat and study no 6 Scandinavian and Norwegian mixes) attribute worse results to incineration. This observation is illustrated in the Table 80.

Table 80 Analysis of the influence of the electricity mix on the performances of incineration regarding the climate change potential. A negative % means that incineration is more beneficial than composting. A positive value means that composting is more beneficial than incineration.

Study number	Substituted energy	Type of mix	Impacts of incineration compared to composting regarding climate change (% difference)
2	Coal	Fossil	From -1320% to -400%
5	Fossil	Fossil	0%
4	Hard coal/forest residues	Partly renewable	22%
6	Norwegian/Scandinavian mix	Partly CO2 neutral	150%

Issues around carbon sequestration and biogenic CO_2

As for other degradable materials, the issue of the inclusion or exclusion of biogenic CO_2 is of importance for food and garden waste. As explained above, the problem is in deciding how to deal with the emissions of the CO_2 that occur during degradation and that counterbalance the CO_2 absorption during the growth of the plants or trees. The question is thus whether the emissions of biogenic CO_2 should be counted as contributing to climate change. There is some controversy among experts about this issue. According to the Joint Research Center, biogenic and non biogenic CO_2 emissions should both be inventoried, but there is still debate about how to deal with this issue in the calculations. Indeed the method of accounting biogenic CO_2 has a major influence on the results since if biogenic CO_2 emissions are disregarded, it means that burning organic waste in the case of incineration does not contribute to climate change. In study no 4, it is argued that the exclusion of biogenic CO2 can lead to erroneous results by creating unfair advantages for one of the compared options. For example, when comparing landfill to incineration, biogenic CO_2 from incineration would be disregarded, while methane from landfill counts. Moreover, combustion leads to immediate release of CO_2 while there is some trapped CO_2 in the landfill, emitted later. This difference cannot be registered based on the biogenic exclusion assumption.

Other issues that arise around the fate of the carbon content during composting are carbon storage and carbon binding. Carbon storage refers to the carbon part of the material being composted that is not degraded and that remains stored in the compost after a certain amount of time (usually 100 years), thus avoiding some biogenic CO_2 and methane emissions. The issue of carbon binding arises during compost utilisation. Indeed, compost utilisation stimulates additional carbon storage in soils through a variety of processes, such as better soil humus formation and better retention of carbon in the soil from plant residues, leading to increased plant primary productivity. Carbon storage and binding are thus both linked with climate change mitigation. Table 81 below illustrates the studies' assumptions regarding carbon binding or storage. All studies have addressed these issues but only four have decided to take them into account. They all agree, however, that the dynamics of the carbon binding/storage are quite complex and, given the great amount of time necessary for these functions to unfold, the uncertainty is rather high. Moreover, the numbers used for each study's calculations are presented in such a way that a comparison of the level of carbon binding/storage across studies is impossible (the reference quantity changes from one study to another). In all studies that consider carbon binding/storage, the benefits of composting manage to overcome the burdens, except for study no 1. Studies 3 and 4 which do not take into account either of the two carbon phenomena, present higher burdens than benefits. Study no 1 has a high value of benefits due to carbon binding, but the results show higher burdens. The reason behind this observation could be that study no 1 is the only one that includes biogenic carbon dioxide emissions in the results.

Table 81 Carbon binding and storage function in the studies

Study number	Carbon Binding inclusion	Carbon Storage inclusion	Amount
1	Yes	No	Binding: 48 kg of CO2-equivalent per ton of biowaste composted or 173 kg of CO2-equivalent per ton of compost
2	No	Yes	15% of initial quantity
3	No	No	-
4	No	No	-
5	Yes	No	40-65 tons per acre
6	No	Yes	48 kg of C per ton of compost

The fate of the carbon is also related to the degradation conditions assumed in the case of composting and landfill. Different assumptions regarding this issue can lead to completely different results. For instance, in study no 3, the degradation occurs in either assumed aerobic or anaerobic conditions and the results revealed that home composting under assumed artificial total anaerobic conditions produces results 94 times higher for climate change than the corresponding assumed total aerobic home composting.

Material substitution

The only treatment options that produce a recovered material are composting and anaerobic digestion. The recovered material from both these activities can be used for substitution of many fertilising products, the most common of which are fertiliser, peat, mulch and soil conditioner.

Out of the six studies that contain either of these two treatment methods, only one assumes no substitution of virgin material at all (study no 5). However, the rest of the studies claim that there can be high benefits from the avoidance of virgin production in some impact categories. For example, peat substitution leads to high savings in climate change as peat is assumed to be of fossil origin and releases high concentrations of methane after being applied. The substituted products for composting and anaerobic digestion, as well as the carbon binding issue are presented in the Table 82.

Table 82 Substituted products for composting and anaerobic digestion and assumptions regarding carbon storage

Study number	Substituted material by compost	Substituted material by digestate	Carbon storage inclusion
1	Fertiliser	/	No
2	Peat and inorganic fertiliser	/	Yes
3	Cow manure	/	No
4	Fertiliser	Fertiliser	No
5	No substitution	/	Yes
6	30% peat, 60% fertiliser	30% peat, 60% fertiliser	Yes
7	/	Fertiliser	No

Nevertheless, the influence of the indirect avoided emissions on the overall results cannot be determined precisely since the results are not consistent for each substituted material and the inventory data is not published. An important observation from the table, however, refers to study no 5. Even if this study assumes no material substitution, the result for composting in climate change is net negative, which means that the benefits are greater than the burdens. This fact indicates that there are great benefits in carbon binding (the only other source for indirect emissions) which might supersede the benefits stemming from material substitution.

Level of technology and relevant efficiencies

The assumptions regarding the technological status involved in the waste management system are vital for the overall results but also for allowing a minimum common ground for comparison of results across studies. In addition, the credibility of an LCA report increases if the same technological advancement is assumed for the different treatment options.

This problem is encountered when anaerobic digestion is a part of an LCA comparison. In all studies that examined anaerobic digestion, the recovery efficiencies and the conversion to electricity efficiencies are quite high. Therefore, this mode of treatment acquires an *a priori* advantage over the other alternatives.

The recovery and energy conversion (to electricity or heat) efficiencies assumed, especially in energy recovery processes, are decisive for the amount of crediting for the system. The recovered energy is a major source for indirect emissions in a waste system because of the avoided production of primary energy. The efficiencies play an important part for the overall LCA since they determine the factor with which these indirect emissions are multiplied before being included in the emissions inventory. Unfortunately, the assumed efficiency is not always clearly stated in the studies, as illustrated in the Table 83.

Table 83 Overview of the incinerator efficiencies in the selected studies.

Study number	Energy produced with incinerator	Efficiency
2	electricity + heat	n.a.
4	electricity + heat	n.a.
5	electricity	n.a.
6	electricity + heat	n.a.
7	electricity + heat	80%

3.5.4 Conclusion

The overview of the selected reports can lead to important conclusions about the fate of organic municipal waste. Although the analysed treatment technologies include the traditional methods (landfill, incineration and composting) and anaerobic digestion, the impact assessment for each method is well documented and sufficient in order to draw conclusions regarding their relative classification.

A first observation from the life cycle impact assessment results is that there is no technology that is generally superior to the others. Some options prevail in some categories while they are considered as the worst for other indicators. Therefore, the compilation of a weighting classification of impacts depends on the scope of the study.

In this review, four indicators are considered to be most important: depletion of natural resources, global warming, energy demand and water consumption. Anaerobic digestion seems to be the best option even if it is not included in many studies (only three out of the seven selected studies include this option). Incineration with energy recovery also presents good results and it is never classified as the worst option for these four indicators, even though food waste has a relatively low heating value. Landfill, on the contrary, generally should be placed last in the list of preferable options.

The seven selected studies examine four different types of organic municipal waste. This general fraction includes garden waste and food waste, but some studies concentrate only on only one of the two sub-fractions, as has already been explained. The results for different materials should be interpreted with respect to different properties of these materials. However, no safe conclusions can be drawn as the results of the review of the life cycle assessments did not locate any consistency among results for the same type of material. The differences in key parameters influence the results so much that comparisons across studies are impossible.

Another important issue relates to specialised technologies targeting only part of the organic municipal waste. Besides obvious statements (incineration is more suitable for garden waste because of its higher heating value, as garden waste includes branches and some wood), the selected studies did not compare treatment options for different types of organic waste. Moreover, no study stated in its scope any specific interest in applying a specific technology to garden or food waste, namely to differentiate the treatment according to the type of food or garden waste.

The scarcity of credible studies and the fact that many studies examine site-specific issues, which is an intrinsic problem of LCAs, do not allow a proper and comprehensive review in an international context. However, the selected studies provide an overview of the more traditional treatment options for the organic fraction of the municipal waste and some general conclusions can be transferred to other environments given that the specific assumptions and parameters are taken into account.

3.5.5 Data gaps/further research

Key parameters

Most studies give very precise information about the energy mixes used for waste management processes or for avoided processes. When examining the issues of carbon storage and binding, the uncertainty of the processes involved is mentioned but the values and processes used for the impact assessment are mentioned in only one out of five studies that take carbon binding into account. In order to better understand and evaluate the mechanisms and functions simulated in each study, there is a need for further transparency of assumptions. On the other hand, the description of technologies used as well as their efficiencies is quite extensive and well documented.

Coverage of the various end-of-life alternatives

The selected studies for this report focus mainly on comparisons among the traditional municipal waste treatment options (landfill, incineration, composting). Some variants within these traditional options are explored, such as home composting, central composting and landfill, with or without energy recovery. Anaerobic digestion, which is being developed rapidly, was also examined and presents quite optimistic results in most impact categories when compared to other options. However, this alternative has not been properly tested in different local conditions and a sensitivity analysis for different operational conditions would be necessary in order to test the viability of this option. The data requirements to ensure the quality of the study make it difficult to conduct LCAs on upcoming options that are still at the experimental stage.

Environmental indicators

The current trend to prioritise global warming as an environmental indicator is illustrated in the selected LCA studies. All examined reports include climate change in their range of addressed impact categories. Primary energy demand, eutrophication, acidification and photochemical oxidation are the most popular indicators, while the rest of the indicators are included in a maximum of two studies.

Two of the priority indicators according to the scope of this report, depletion of resources and water consumption, were each investigated by one study each only. The individual scope of each LCA meant that the reports could not provide a more comprehensive picture for the environmental implications of organic waste life cycle. In particular, specific impacts such as the depletion of groundwater resources to landfill and compost were poorly addressed. On the other hand, all toxicity and ecotoxicity impact categories calculations possess an inherit uncertainty, which renders the impact assessment relatively unreliable. Therefore, until more solid assumptions and impact potential factors are assessed, many reports will appear hesitant in including a complete toxicity analysis.

3.6 Wood

3.6.1 Presentation

Wood is used in a very large range of applications: the paper industry, particleboard, the building sector, furniture, packaging and bioenergy. All along the wood processing chain, wood wastes arise, resulting from its cultivation in forests, sawing, processing to products and disposal, Significant amounts of the waste wood generated in the UK arises from the construction and demolition sector.

The sustainable use of wood resources is also closely linked to the issue of forests preservation which is essential for the protection of biodiversity and to tackle the climate change issue. Optimising the use of forest biomass by valorising wood waste is thus recognised as a way to enhance long-term environmental sustainability. Nevertheless, Daian & Ozarska reports (2009) that the wood recycling rate is low in comparison with other wastes such as metals.

The available options for the end-of-life of wood waste depend on the waste characteristics since:

- wood waste is a broad category that includes everything from wood dust from sawing or to complete boards resulting from the demolition of buildings
- wood waste can be raw or with additives such as glue or preservatives (CCA/CCB[3] or other metal-containing preservatives for example).

The main available options are recycling and incineration. The main uses of recovered wood are mulch, fuel, recycled timber, animal bedding and recycling into particleboard. However, animal bedding and much are also produced from forestry co-products. In Europe, the dominant routes are recycling into particleboard and energy recovery (Daian & Ozarska, 2009). However, the contaminant content of treated wood is an issue for instance for the production of composted products or animal bedding. There can also be a toxicity issue in the case of incineration because of the fumes released during the combustion processes. Wood landfill is still in use in some places but in European countries the recent EU waste directives have resulted in landfill disposal of wood waste being either banned or made very expensive for companies or householders.

The management of wood wastes seems to receive little attention from LCAs practitioners since very few LCAs on the subject have been published. The situation has therefore not evolved significantly since the previous edition of this report which featured three such studies. However, a comparative study conducted by Petersen & Solberg (2005) that analysed LCAs comparing the environmental impacts of substitution between wood and alternative materials (concrete and steel) in the construction sector pointed out that wood has less impact than competing materials on global warming, under the condition that the wood is not landfilled after use. This conclusion thus highlights the importance of the handling of wood wastes.

Because of the lack of studies a comparative analysis between the various end-of-life alternatives for wood waste could not be conducted but available literature has been analysed to enrich the debate.

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[3] CCA: Copper chrome arsenic, CCB: Copper chrome boric acid

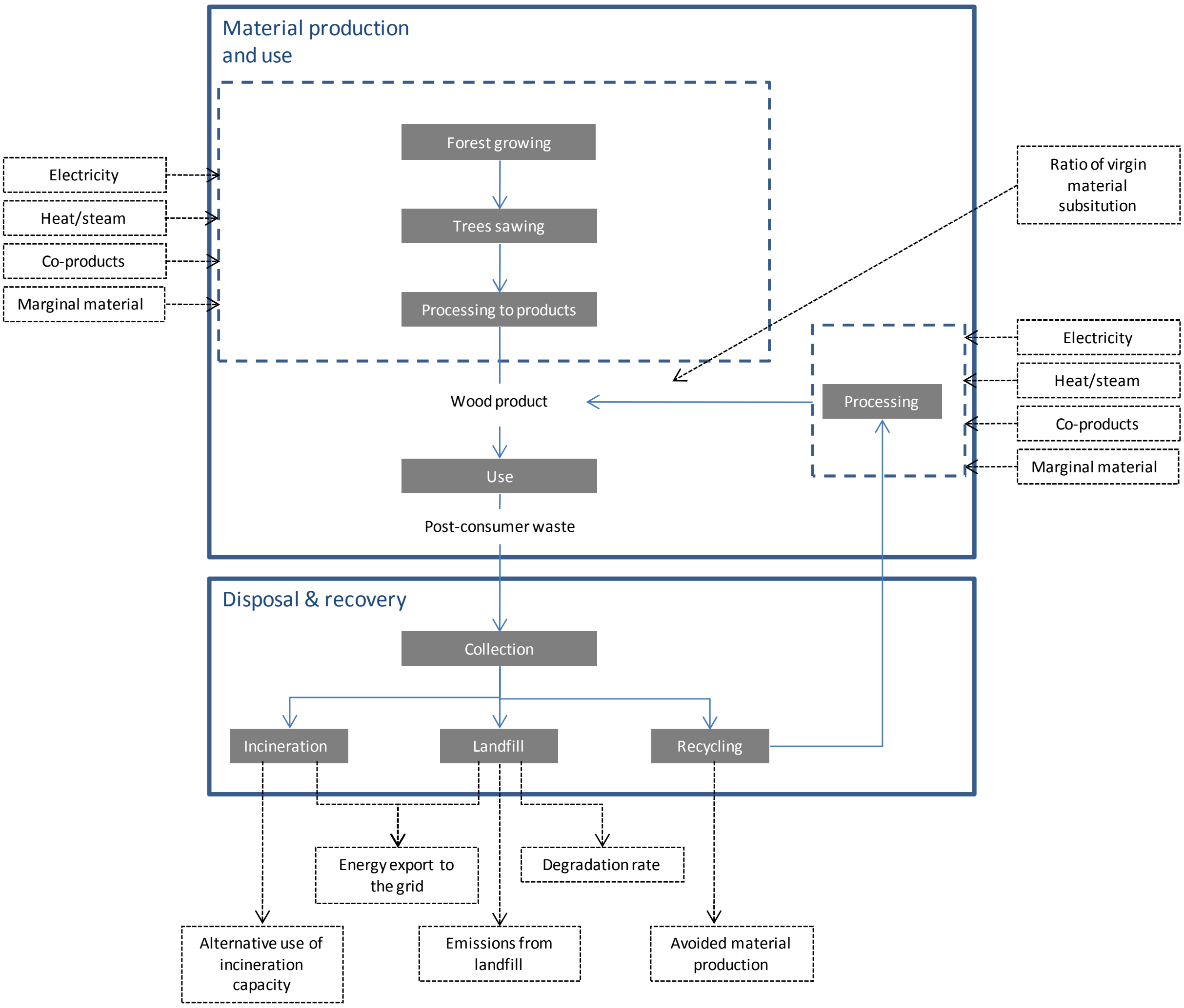

Figure 41 The wood system and key parameters

3.6.2 Comparison between the various end-of-life options

Recycling enables the material content to be fully exploited and thus appears as an attractive option. Recycling for particleboard production is one of the main recycling routes for low quality recovered wood. The wood is first shredded and reduced into chips and then agglomerated. A study entitled ‘Life Cycle Assessment for optimising the level of separated collection in integrated MSW management systems’ (2009) conducted by Rigamonti, Grosso and Giugliano estimated no less than 77% energy savings can be gained when producing particleboard from wood waste instead of producing plywood from virgin material.

In the study ‘Life Cycle Assessment of wood wastes: A case study of ephemeral architecture’ (Rivela, et al., 2006), the recycling of wood waste for particleboard manufacture is compared to the incineration of wood with energy recovery. The results suggest that the **recycling of wood waste is more favourable regarding human health and ecosystem quality** (including climate change). This can be explained by the reduction of the environmental impact caused by forest activities (e.g. sawing and transport) since some wood or timber is saved. However, **recycling represents a larger contribution of damage to resource due to the use of fossil fuels**.

In addition, the 2006 study conducted by the US EPA about solid waste management and greenhouse gases previously cited in the sections covering plastics, paper and food/garden waste also included a comparison of end-of-life alternatives for dimensional lumber and medium-density fibreboard. The alternatives under study are recycling, incineration with energy recovery and landfill. **Regarding climate change, recycling is preferable to incineration, with an improvement from incineration of 70%**. **Landfill appears as the worst alternative since recycling has been estimated to perform 80% better**. **For energy demand the results obtained are also in line with Rivela’s study, i.e. recycling is the most energy-consuming option** while incineration is associated with an energy credit. As a result, incineration presents an advantage of over 150% compared to both other alternatives.

A comparison between various disposal options for wood is also conducted in 'Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives' (Börjesson & Gustavsson, 2000). Although this study does not follow the LCA methodology, it includes three scenarios for disposal of wood waste, i.e. incineration with energy recovery, 50% of the wood reused as building materials and 50% incinerated, and landfill. The results show that **recycling is slightly preferable to incineration with energy recovery regarding GHG emissions**. **Landfill is reported to be the worst option**, incineration being 60% better. A comparison of the performances of landfill with and without biogas collection is also conducted. It reveals that the landfill benefits increase by 70% if there is biogas capture and recovery of energy. **However, the overall ranking between alternatives is not affected.**

A case study was also conducted in Vienna by Adolf Merl (2007) to compare energy recovery, recycling as sawn timber and particleboards and landfill regarding the impacts on climate change. This case study was conducted using a combination of regional mass flow analysis and LCA methodology. The results obtained are in line with the previous observations since landfill appears by far as the option with the most associated emissions while recycling seems slightly preferable to incineration.

The DEFRA project that led to the report 'Carbon Balances and Energy Impacts of the Management of UK Wastes' (ERM, 2006) also evaluates greenhouse gas benefits and impacts associated with alternative management routes for wood waste. Nevertheless, it should be noted that this study cannot be qualified as an LCA. **The results showed that incineration with energy recovery is more favourable than recycling for energy demand but also for climate change**. In addition, the study highlights that **the extent of the recycling benefits depend on the assumptions regarding the quality of the wood wastes that determines the recycling route**. The benefits from recycling high quality wood waste into timber products or firewood[4] were compared with the benefits from recycling low quality wood waste into particleboard. The benefits turned out to be much higher in the first case.

Lastly, WRAP recently published an LCA on a specific wood recycling technology, the Microrelease process, which recovers wood fibres from medium-density fibreboard (MDF) waste using microwave technology (WRAP, 2009 (a)). The study assumes that the fibres produced through this technique are put back into the MDF manufacturing process. This study includes a comparison between this type of recycling, incineration and landfill disposal. The results highlight that **disposal by landfill has the highest environmental impact** for the ten impact categories considered. Thanks to the avoided production of virgin fibre but also to the avoidance of disposal of the MDF through conventional routes, recycling of MDF waste brings some significant environmental benefits but nevertheless **it is a complicated trade-off between recycling and incineration with energy recovery**. Indeed, the scenario for heat and power cogeneration has a marginally lower environmental impact in most impact categories while in contrast, when considering only heat or only power generation, Microrelease appears as a better option.

The overall conclusion therefore seems to be that wood incineration with energy recovery brings more energy credit, especially if both heat and electricity are generated, while recycling appears more advantageous when it comes to climate change potential. On the other hand, wood landfill is to be avoided due to the associated methane emissions.

3.6.3 Comparison with the results from the previous report edition

In the previous edition of this review, the evaluation process resulted in the selection of only three studies. Among these three studies, seven scenarios comparing incineration and landfill were identified. In all scenarios, the incineration of wood waste was found to be preferable to landfill. No evaluation of recycling was included.

3.6.4 Data gaps/further research

First, there is a need for LCAs studies dedicated to the comparison of the alternative options for the management of wood wastes. In addition, it should also be noted that the few studies dealing with wood waste management that have been reviewed in this study focus on the climate change potential and energy consumption. The analysis of a larger set of indicators would be required in order to be able to come up with reliable evidence of the benefits of wood recycling.

[4] *We assume that it is the waste from the timber production that is converted into firewood but this is not clear in the study*

In addition, it would be necessary to have more insight regarding the key assumptions and parameters that can influence the outcome of the comparison between the different alternatives. For instance, one of the issues affecting the assessment of the benefits brought by wood recycling is for instance the **allocation of forestry processes** which determines the environmental impacts that are offset thanks to the saved wood resources. Another critical point is how **forest carbon sequestration** is included. In the case of recycling, some studies consider that the trees that would otherwise be harvested are left standing, and thus carbon is still being sequestered. However, in the case of sustainable forests, harvested trees are assumed to be replaced and young trees growing rapidly sequestrate more carbon. The issues relating the sustainability of forests are thus of major importance and enter the balance when carrying out the environmental assessment of wood waste management alternatives. In addition, forest sustainability also raises the debate around land use change. Currently only 30% of forests are considered sustainable.

Other end-of-life options could also be investigated. Any type of clean wood waste is for example suitable for composting. There is also increasing interest in bioenergy and bioenergy from wood residues is currently on trial at the pilot scale (Daian & Ozarska, 2009).

3.7 Textiles

3.7.1 Presentation

In the UK, approximately 8% by weight of all household waste was composed of clothes or textiles in 2005 (Oakdene Hollins Ltd et al., 2006) and each person discards on average 30 kg of clothing and textiles per year (Allwood et al., 2006). In addition, the current consumption trends encourage the public to buy more clothes and to keep them for a shorter time. As a result, textiles are the fastest-growing sector in terms of household waste (Oakdene Hollins Ltd et al., 2006). About 25% of the discarded clothes are currently collected separately. According to Woolridge et al. (2006):

- 47% of these collected clothes are reused as second-hand clothes;
- 45% are recycled into wipers, filling materials or reclaimed fibres; and
- 8% end up as waste.

The rest of the clothes are discarded together with household waste and end up landfilled or incinerated. In the case that there is some evidence of the environmental benefits of recycling, there could be real potential for developing textile recycling.

Literally, textile recycling should refer to the processing of fibres back to make new products. However a broader definition is usually used and textile recycling refers to:

- Conversion to industrial cleaning wipers
- Processing back to fibers for use as filling materials for mattresses, car insulation, roofing felts or furniture padding (mainly for natural fibres such as cotton or wool)
- Processing back to fibers which are then respun into yarns to make new fabric products, especially for textiles made out of man-made fibers that are transformed into carpets or blankets

Textile reuse as second-hand clothes is also sometimes considered as a form of textile recycling while there is no reprocessing. A fairly large amount of textiles is recycled into wipers or used as filling material but the actual processing of recovered textile into new products is still relatively minor (Korhonen & Dahlbo, 2007).

The literature review revealed a **large gap in terms of LCAs conducted over the end-of-life of textiles**. This finding was confirmed by the small amount of literature on the subject in which the lack of studies concerning the environmental impacts of textile recycling is highlighted. Several LCAs or LCA-like studies (e.g. Allwood et al., 2006; EDIPTEX, 2007) deal with the assessment of the environmental impacts of clothing but little emphasis was placed on potential benefits from recycling. There has been more discussion on the effects of changes in terms of manufacturing and consumers' choices before the garment is discarded. Indeed, the use phase is usually found to represent more than half of the impacts of the total life cycle of clothes (see Table 84) thus most benefit could be achieved by addressing this stage. Therefore, a comparative study regarding the end-of-life alternatives could not be conducted as for the other fractions. Nevertheless, the studies dealing with the environmental assessment of textile waste were reviewed in order to realise a qualitative comparison of the environmental impacts associated with the various possible end-of-life options.

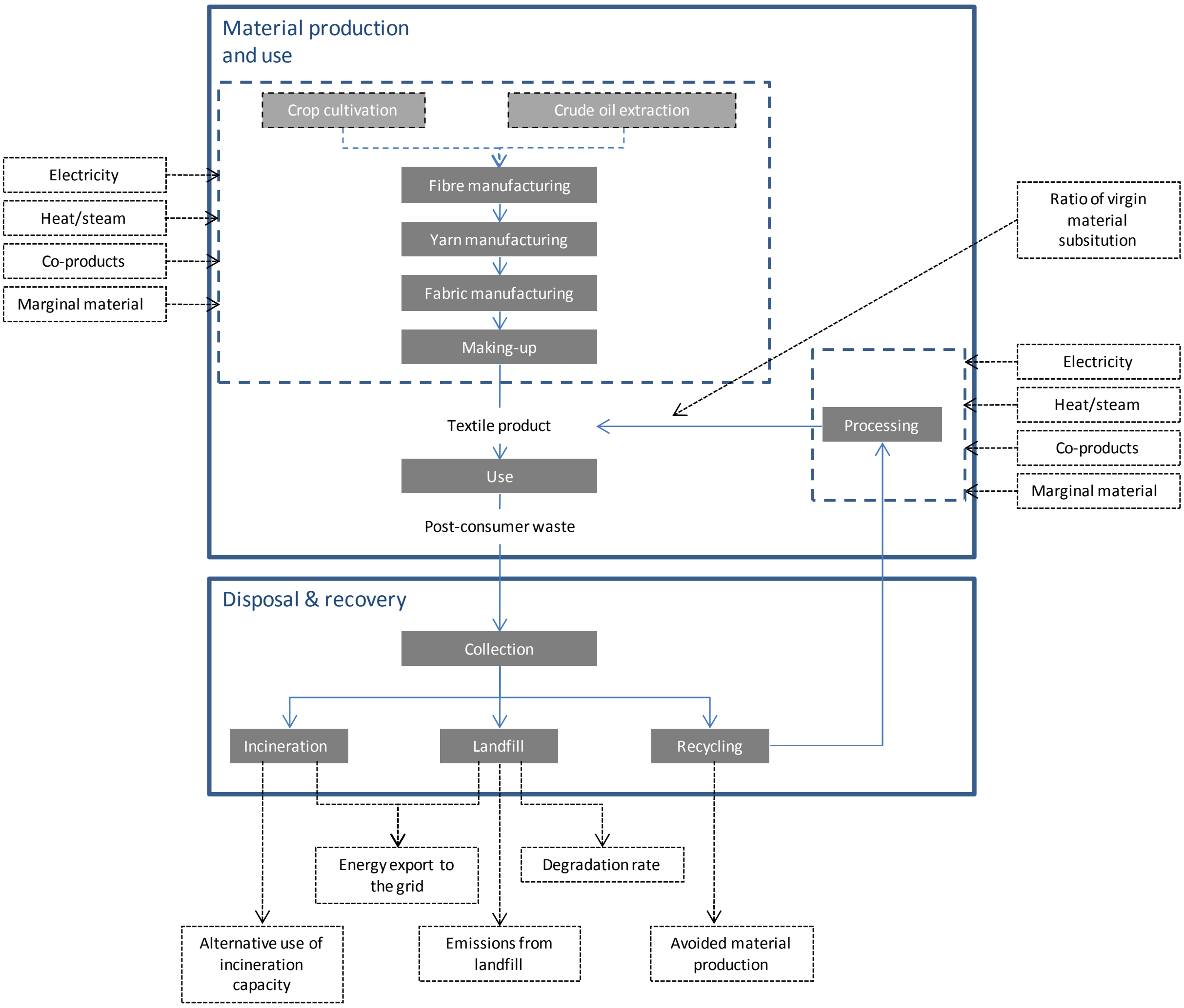

Figure 42 The textile system and key parameters

Table 84 Contribution to the climate change potential and energy demand of the different life cycle stages for a cotton T-shirt (EDIPTEX, 2007)

	T-shirt 100% cotton	
Life cycle stage	Climate change potential	Energy demand
Raw materials	8%	10%
Production	10%	12%
Transport	2%	2%
Use	**82%**	**78%**
Disposal	-2%	-2%

3.7.2 Comparison between the various end-of-life options

In the few studies investigating the environmental impacts associated with textiles disposal, the only indicators looked at are energy consumption and potential impacts on global warming.

Regarding **energy consumption**, the first requirement to ensure savings via recycling is that the energy consumption resulting from collecting and sorting the clothes offsets the energy used to manufacture them from virgin materials. A study of Salvation Army textile reuse and recycling operations established that 'the reuse (collection, sorting, baling and distribution) of 1 tonne of polyester garments only uses 1.8% of the energy required for the manufacture of these goods from virgin materials and that the reuse of 1 tonne of cotton clothing only uses 2.6% of the energy required to manufacture them from virgin materials'(ERM, 2002 (a)). Although this study more specifically addresses clothing reuse rather than recycling, it suggests that **some**

substantial savings can be obtaining by off-setting the production of products made from virgin materials.

The **potential greenhouse gas emission savings of textile recycling** have been considered in a study from the Finnish Environment Institute conducted by Marja-Riitta Korhonen and Helena Dahlbo (Korhonen & Dahlbo, 2007). In this study, the GHG emissions of oil sorbents manufactured from recovered textile fibres (wool, PP and cotton) are compared with the emissions of polypropylene fibres, serving the same purpose of use but manufactured from virgin raw materials. The results for this specific case revealed that **using textile waste to replace virgin plastic products can bring significant emissions reduction**. **The parameter that was found to be the most influential on the extent of the achieved reductions was the choice of the disposal option from which the textile waste is diverted in case of recycling.** The GHG savings potentials were found to be of 6 tons of CO_2 eq per ton of oil sorbent produced in the case of avoided combustion and of 9.2 tons of CO_2 eq in the case of avoiding landfill. Indeed the emissions savings are higher because of the avoided emissions from textile decomposition in the landfill. In addition, when recycling replaces incineration, the energy otherwise produced by incineration is assumed to be generated by the average fuel mixture of the electricity and heat supply in Finland (50% based on fossil fuels), generating some emissions. Another sensitivity analysis was conducted in this study to assess the influence of the type of energy substituted by the energy generated from waste (both in the recycled and reference product systems). The average fuel mixture was replaced first by coal and then by renewable fuels but it did not substantially affect the emission savings potential. **The assumed origin of the textile material being recycled, 100% natural fibres or 100% man-made was not found to have a significant influence either.**

The DEFRA project that led to the report 'Carbon Balances and Energy Impacts of the Management of UK Wastes' (ERM, 2006) also evaluates **greenhouse gas benefits and impacts associated with alternative management routes for textile waste.** Nevertheless, it should be noted that this study was not conducted as an LCA. **The results showed that recycling is more favourable than incineration**. However, the study highlights that **the extent of benefits depends on the assumptions regarding the recovery route (which determines the reprocessing requirements) and the alternative materials avoided**. The benefits from avoiding primary cloth production were compared with the benefits from reprocessing the textile waste into rag/packing material offsetting the production of low grade paper material. The benefits turned out to be much higher in the first case, as illustrated in Table 85 due to high resources requirements for primary material production (cotton and polyester).

Table 85 Avoided burdens per kg of textile recycled according to the alternative materials avoided (ERM, 2006)

	Avoided burdens per kg of textile recycled	
	Climate change potential (kg CO_2 eq avoided/kg)	Fossil energy demand (MJ eq avoided/kg)
Conversion to wipers - Avoided production of cotton cloth (50%) and PET (50%)	1,75	39,95
Conversion to rags or filling materials - Avoided production of kraft paper	0,93	12,30

The GHG savings enabled by textile recycling have also been quantified in another study conducted on behalf of DEFRA entitled 'Recycling of Low Grade Clothing Waste' (Oakdene Hollins Ltd et al., 2006). The conclusion was that **recycling of clothing as fibres saves about 4 kg CO_2 eq. per kg of clothing compared to disposal thanks to the displacement of fibre production**.

Although very different assumptions are made in these studies, the overall conclusion is that textile recycling brings substantial environmental benefits. Textile recycling can thus be an interesting incentive lever, which presents the advantage of not requiring a change of behaviour of consumers during the use stage. In addition, the scale of the benefits mainly depends on the recovery routes assumed as they determine the material production that is avoided.

3.7.3 Data gaps/further research

To build up stronger evidence of the benefits of textile recycling, there is a need for LCA studies that focus on a larger set of indicators rather than only on carbon impacts or energy consumption.

In addition, no study assessing 'closed-loop' recycling whereby recycled fibres are used in the manufacture of new clothing has been found. This would be an interesting issue to investigate as it could bring more benefits than using textile waste to replace low quality products such as wipers. Indeed, from an economic point of view, wipers have a very limited economic value; therefore it could be more attractive to recover energy from them by incineration. It would also be interesting to check how the performances of recycling can vary from one geographical area to another since the available recycling technologies may differ.

Moreover, textile fibres are very diverse and can have different characteristics. A comparison of the environmental performances of different end-of-life options for the various types of fibres would thus also be advisable since it might reveal that the environmentally preferred alternative depends on the fibre type.

4.0 Relevance of the findings in the UK context

4.1 The UK context

4.1.1 Waste management

34.4 million tonnes of municipal waste were generated through the UK in 2007/2008:

- 28.5 million tonnes in England (DEFRA, 2008 (a))
- 3 million tonnes in Scotland (Scottish Environment Agency, 2009)
- 1.8 million tonnes in Wales (Welsh Assembly Government, 2009)
- 1.1 million tonnes in Northern Ireland (Northern Ireland Environment Agency, 2009)

This corresponds to the generation of 20-25 kg of waste per household per week in UK countries. Figure 43 presents the evolution of municipal waste arisings for England and reveals that municipal waste arisings have stayed relatively stable since 2001/02. The main route for municipal waste disposal in the UK has traditionally been landfill. Although less municipal waste is sent to landfills, still 54% of England's municipal waste (DEFRA, 2008 (a)), 66% of Scotland's (Scottish Environment Agency, 2009), 65% of Wales' (Welsh Assembly Government, 2009) and 71% of Northern Ireland's (Northern Ireland Environment Agency, 2009) still ends up in landfills. The percentage of municipal waste that is recycled is increasing rapidly . For instance, in England it has increased from 17.6% in 2003-2004 to 34.5% in 2007-2008 (Environment Agency, 2009). The recycling and composting rate is rather similar in the other UK countries, i.e. 32% in Scotland (Scottish Environment Agency, 2009), 33% in Wales (Welsh Assembly Government, 2009) and 29% in Northern Ireland (Northern Ireland Environment Agency, 2009) for 2007-2008. The remaining waste is being incinerated. Most UK incinerators only recover electricity (13 out of 19) while cogeneration of electricity and heat is carried out at four incineration plants (DEFRA, 2007 (a)).

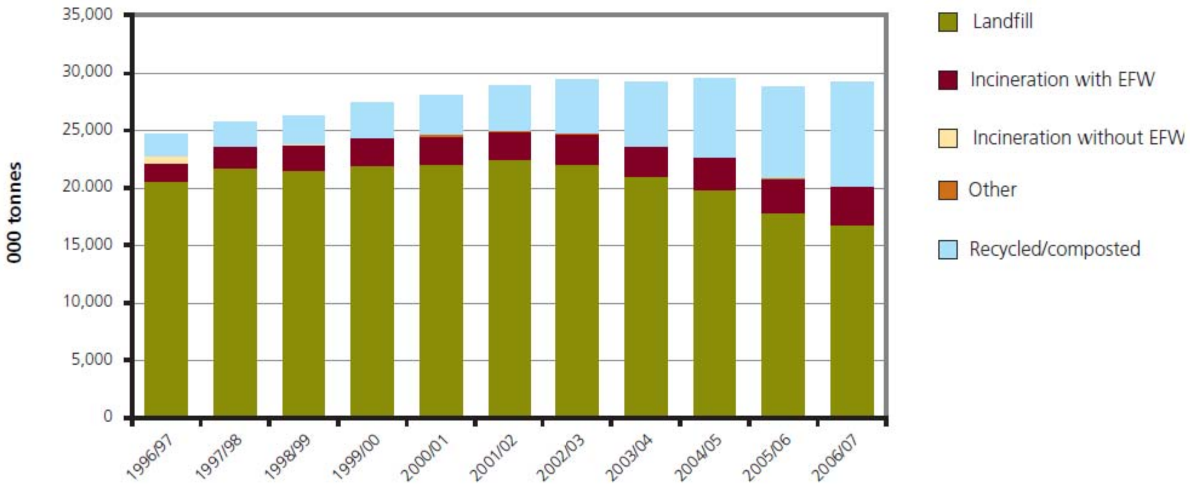

Figure 43 Evolution of municipal waste arisings and proportion of waste following the different disposal routes in **England** (DEFRA, 2008 (c))

4.1.2 Environmental challenges in relation to waste management

Among the 20 UK Sustainable Development Strategy Framework indicators that highlight priority areas, the ones linked with waste management are:

- Waste
- Greenhouse gas emissions
- Resource use
- Ecological impacts of air pollution

Progress assessment regarding these indicators highlights that significant improvement has been achieved in the areas of waste and greenhouse gas emissions. Indeed, the total amount of waste being landfilled fell by 19.5% between 2002 and 2007 while emissions of the main six greenhouse gas emissions are about 20% below the 1990 level (DEFRA, 2009 (a)).)). In 2009, the Department for Energy and Climate Change (DECC) launched a Low Carbon Transition Plan in order to be able to reach a 34% cut in emissions on 1990 levels by 2020 (DECC, 2009). Although this target does not relate to reductions in the waste sector, it highlights that the UK is currently making efforts to reduce its GHG emissions and energy recovery from waste can help the UK to address the climate change issue.

On the other hand, there is a lot of concern about resource use and the ecological impacts of air pollution. Thes impacts relate mainly to acidification and eutrophication which result from burning fossil fuels and waste from farm animals. Around one-third of UK land area is sensitive to acid deposition, and one-third to eutrophication (DEFRA, 2009 (b)). Resource use is affected by the consumption of fossil fuels resources for electricity generation. Figure 44 illustrates that between 1990 and 2007 electricity consumption rose by 24%, and fossil fuel used in electricity generation rose by 12%.

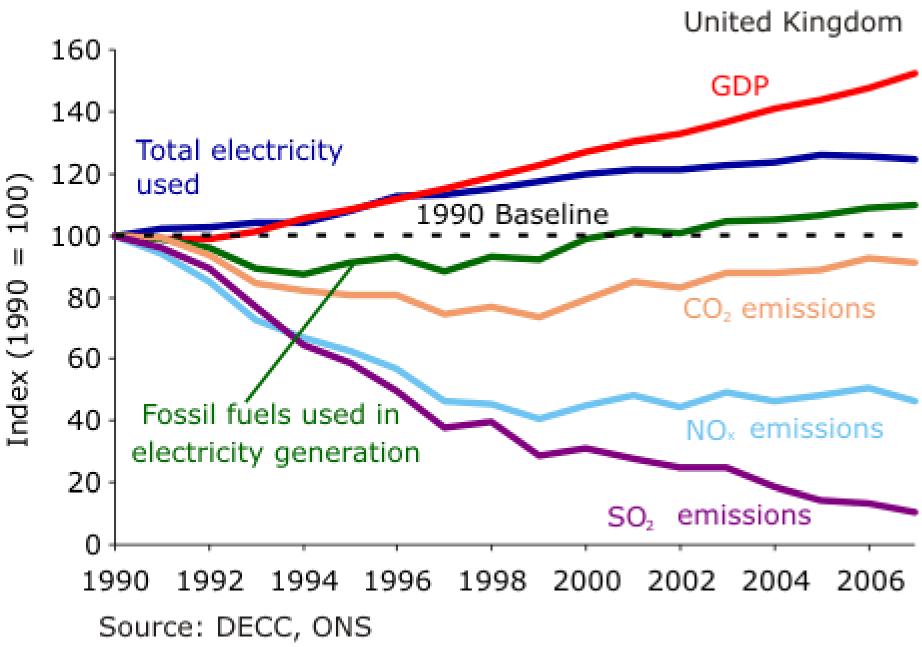

Figure 44 Electricity generated, CO2, NOx and SO2 emissions by electricity generators and GDP, 1990 to 2007 (DEFRA, 2009 (c))

Indeed, the main energy sources for electricity production in the UK are coal (37%) and gas (36%) while nuclear power is in third position (18%) as displayed in figure 45.

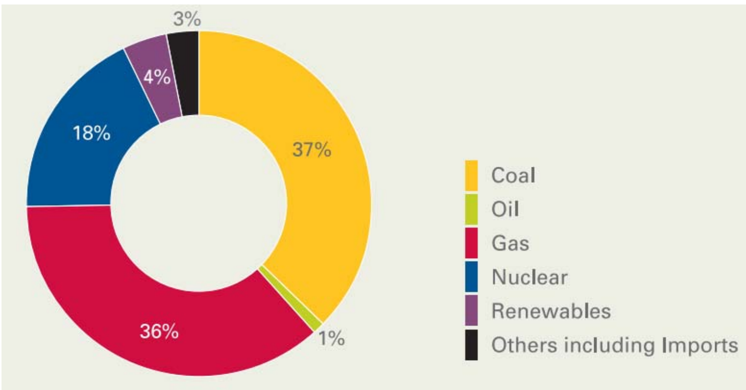

Figure 45 The UK electricity mix in 2006 (Department of Trade and Industry, 2007)

In the Climate Change Act 2008, the UK government has set out the objective of an 80% reduction of carbon dioxide emissions by about 2050 against a 1990 baseline, with real progress by 2020 (Department of Energy and Climate Change, 2008). Meeting this target will imply significant improvements in energy efficiency and the emergence of a more renewable energy. As an example, the Low Carbon Transition Plan sets the objective of producing 30% of UK electricity from renewables by 2020 (Department of Energy and Climate Change, 2009). Indeed, electricity suppliers are already obliged to source a growing proportion of the electricity they supply from renewable sources including waste, confirmed by Renewables Obligation Certificates (ROCs) (DEFRA, 2007).

4.1.3 Waste strategy

The ambitions of UK countries in terms of waste management are outlined in the respective national Waste Strategy documents. The overall objective is to reduce the reliance on landfill. The focus is especially on biodegradable waste which contributes to climate change via the methane emitted during degradation. The targets for reducing biodegradable municipal waste have been set by the European Landfill Directive and will be delivered through the **Landfill Allowance Trading Scheme**. These are as follows (DEFRA, 2007 (c)):

- 2010 - reduce to 75% of 1995 level
- 2013 – reduce to 50% of 1995 level
- 2020 – reduce to 35% of 1995 level

In line with these ambitious targets, other objectives have been set **to promote recycling and composting** of household waste as displayed in the Table 86.

Table 86 Targets for Recycling and Composting across the UK (Source: Department of the Environment, Northern Ireland, 2006)

Region	Recycling and Composting target
Northern Ireland	35% by 2010 40% by 2015 45% by 2020
England	40% by 2010 45% by 2015 50% by 2020
Wales	15% by 2005 25% by 2007 40% by 2010
Scotland	25% by 2006 30% by 2008 55% by 2020

Reaching these targets would also mean an increase in energy recovery to about 25% of municipal waste in 2020 compared to around 10% today (DEFRA, 2007 (b)). Energy recovery including incineration is indeed recognised as a much better option than landfill for residual waste. For food waste, anaerobic digestion is encouraged while for wood waste incineration is promoted.

Specific recycling targets have also been set up for packaging waste as required in the 1994 EC Directive on Packaging and Packaging Waste revised in 2004. It required all Member States to ensure that a minimum of 60% of all packaging waste was recovered (of which 55% must be recycled) by 31 December 2008. The UK has been able to achieve this target as in 2008 61% of packaging waste was recycled. Significant progress has thus been made, as in 1997 only 28% of packaging waste was recovered (DEFRA, 2009 (d)). However packaging waste is predicted to continue to rise slightly so efforts need to be sustained. The UK ambition is to move further towards the recycling rates of the best EU performers. The Packaging Regulations set annual business targets as displayed in Table 87.

Table 87 UK business recycling targets up to 2010 (DEFRA, 2009 (d))

	2008	2009	2010
Paper recycling	67.5%	68.5%	69.5%
Glass recycling	78%	80%	81%
Aluminium recycling	35%	38%	40%
Steel recycling	68%	68.5%	69%
Plastic recycling	26%	27%	29%
Wood recycling	20.5%	21%	22%
Overall recovery *	72%	73%	74%

* of which 92% minimum must be achieved through recycling

4.1.4 *Summing up: influence of the UK policy on end-of-life options*

The previous paragraphs have outlined current UK policy in the waste and energy sectors. The expected influence of the identified policy instruments on the development of the various end-of-life options that have been reviewed in this study is presented in the Table 88. An arrow up means that the implementation of the given policy instrument could favour the development of the relevant end-of-life option. On the contrary, an arrow down means that the implementation of the policy instrument could hinder the development of the relevant end-of-life option. Explanations are given below the table.

Table 88 Influence of the UK policy on the various end-of-life options reviewed in the study

	Trend regarding the end-of-life options					
UK policy instruments	Recycling	Composting	Anaerobic digestion	Pyrolysis	Incineration	Landfill
1 Landfill Allowance Trading Scheme	↗	↗				↘
2 Low Carbon Transition Plan			↗	↗	↗	↘
3 Renewables Obligation			↗	↗	↗	↗
4 Recycling and composting targets	↗	↗				

↗	Encouraging the development of the concerned end-of-life option
↘	Hindering the development of the concerned end-of-life option

1 The Landfill Allowance Trading Scheme aims at reducing the biodegradable municipal waste going to landfills.
2 The Low Carbon Transition Plan promotes the use of energy recovery from waste.
3 The Renewables Obligation scheme forces electricity suppliers to source a growing proportion of the electricity they supply from renewable sources including waste. This scheme therefore promotes the development of energy from waste.
4 The recycling and composting targets set up by the Government directly encourage the development of the recycling and composting channels.

4.2 Relevance of findings in the UK context for paper and cardboard

In 2006 58% of the paper and board consumed in the UK was collected for recycling. The collection rate is estimated to have grown by about 10% between 2003 and 2006 as illustrated in Figure 46. While around one-third of the paper recovered consists of newspapers, periodicals and magazines, the majority of recovered paper and board is collected from commercial and industrial companies. However, more and more paper is recovered from households since municipal paper collections have nearly doubled since 2005 (WRAP, 2007 (a)).

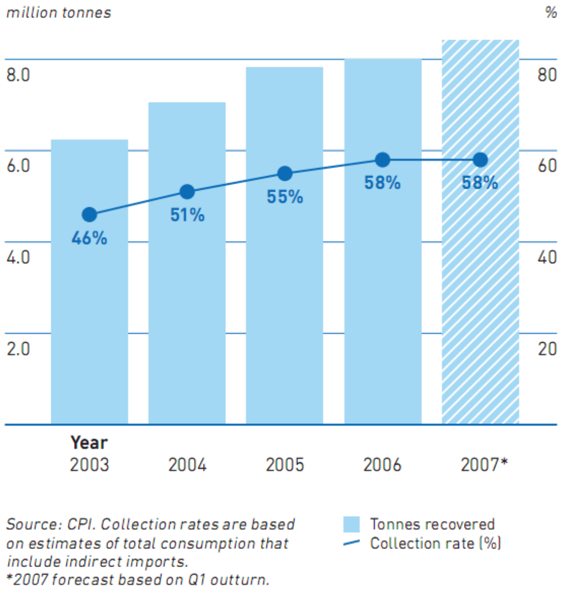

Figure 46 The UK paper recovery (WRAP, 2007 (a))

About half of the paper and board recovered in the UK is used in the UK while the rest of it is exported overseas, as shown in Figure 47. However the picture changes according to the paper grade; whilst over 80% of mixed paper is exported, only 20% of high grade papers are sent abroad (WRAP, 2007 (a)). Among the paper and cardboard recycled in the UK, news and magazines are used for the production of newsprint while cardboard and mixed grade are used in packaging manufacture. High grade papers are mainly used in tissue manufacture (WRAP, 2007 (a)).

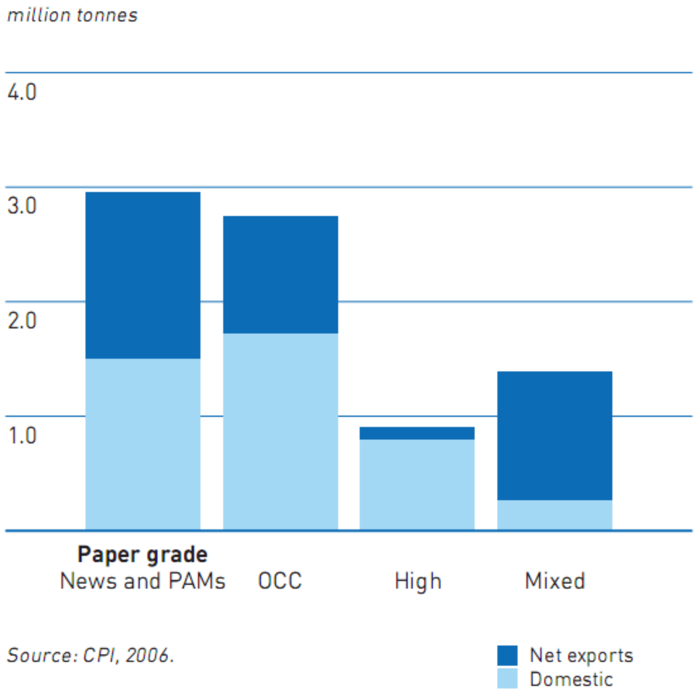

Figure 47 Utilisation of different paper grades in the UK (WRAP, 2007 (a))

Prior to the analysis of the findings in the UK context, it should first be noted that the study has highlighted that there is a need for new studies that would give a better insight into the influence of key parameters and evaluate the potential of other technologies such as composting or pyrolysis.

The outputs of the comparison between the various possible end-of-life alternatives for paper and card are summed up in Table 89. The indicators that have been chosen to be displayed in this table are those corresponding to the main environmental issues the UK is facing. Eutrophication has not been included because only one of the selected studies assessed this indicator which does not allow for any conclusions to be drawn. The results of the study have highlighted that paper should not end up in landfills since landfill appeared as the worst option for all indicators except eutrophication. This is in line with the EU Landfill Directive which aims to ban the landfill of biodegradable waste. The most promising options among those assessed for paper and card are incineration and recycling, both of which are preferable to landfill.

Table 89 Overview of the best and worst end-of-life options for managing paper waste based on the results of the study

	Paper waste management		Number of studies
Indicator	Best option	Worst option	
Climate change	Recycling/Incineration	Landfill	5
Depletion of natural resources	*No clear preferred option*		2
Energy demand	Recycling	Landfill	4
Acidification	Recycling	Landfill	2

Recycling and material quality

The UK has set up objectives for recycling paper packaging (see section 4.1.3) and is thus encouraging this end-of-life management. Virgin paper production is energy intensive because of the pulping stage thus significant savings can be reached with recycling that only requires energy for repulping, mixing and drying.

The main inconvenience of paper recycling lies in the fact that it does not allow a 1:1 substitution ratio since recycled waste paper and virgin paper do not have the same quality and functionality. The recycling process shortens the fibres, so that the maximum number of recycling cycles is usually around 6 or 7. As a result, to ensure a sufficient fibre length, a certain amount of virgin paper needs to be added to paper recycled products, often about 20% (Villanueva & Wenzel, 2007). Future progress in recycling technologies may increase the number of times fibres can be recovered.

In order to optimise the environmental benefits of paper recycling, a possible future option could be to develop a recycling process that includes material recovery. For instance, the paper could be recycled and then the sludge resulting from the recycling process and the fibres not suitable for reuse could be used for energy generation.

The performance of recycling is also influenced by the quality of the collected material, which depends on the way the paper waste is collected, i.e. either mixed with other materials or separately.

The paper and card market

In Europe, in 2007 119 million tonnes of wood were used to generate 45 million tonnes of paper and board. 58.6 million tonnes of recovered paper and board were also used to generate approximately 49 million tonnes of paper and board (CEPI, 2008). Therefore it could be said that without paper recycling, the demand for wood would be much higher which could contribute to deforestation in the case of wood that comes from unsustainable forests. This is quite likely to be the case, as of the 3 952 million hectares of forests in the world (FAO, 2005) only 342 million hectares, i.e. about 9%, are certified sustainably managed through the PEFC (Programme for the Endorsement of Forest Certification schemes) and FSC (Forest Stewardship Council) schemes (FAO, 2005; PEFC, 2009; FSC, 2009). However, it is important to notice that usually wood is not usually harvested for the sole purpose of producing paper and cardboard, especially in Europe. For example, in CEPI countries, the wood used for paper and cardboard production is mainly a mix of round wood (75%) and chips (25%). Furthermore, according to the Ullmann's encyclopaedia (Patt et al., 2002), the European paper mills use mainly wood residues: '*In Europe sawmill residues and wood from thinning of forests are used in the production of wood pulp. In countries with good growth conditions, wood for pulp production is predominantly cultivated on plantation'.* Deforestation is instead linked with the need for extra agricultural land. Therefore the link between paper recycling and forest use is not straightforward.

Another issue linked to the paper and card market is that both virgin and recycled paper and card are internationally traded commodities. As in several European countries, many UK paper mills manufacturing virgin paper have closed down with the supply replaced by imports from Scandinavia. Half of the paper and card recovered for recycling is processed in the UK. As mentioned previously, half of the recovered paper is exported (see Figure 47) mostly to China and other East Asian countries where the demand is growing as in other East Asian countries (WRAP, 2007 (a)).

One can thus raise some concern around the environmental impacts of transportation but these are not expected to be significant as long as the paper and card waste is shipped to the recycling destination. It is more the energy mix used for the recycling operations, and the nature of the virgin production being avoided, that is likely to cause adverse environmental effects if the energy is obtained from fossil fuels. This is also true of the paper and card waste that is recycled in the UK. Here, the issue is that UK electricity is derived from mainly fossil sources, whereas virgin paper imported from Scandinavia is manufactured using renewable energy.

Under this assumption, incineration can appear to be preferable over recycling. However, such results are based on the assumption that the paper being used is sustainably sourced and that biogenic carbon is in equilibrium.

Another aspect that hinders the development of recycling facilities in the UK is that the potential for domestic use of recycled products is not expected to rise in future years (WRAP, 2007 (a)). It seems that the future trend will therefore be an increase in exports of collected paper and card to developing countries. The challenge in the UK may thus be more on the collection side than on the recycling process side than on the collection side. The key is to adjust the collection schemes to meet the needs of domestic and export markets in terms of paper quality.

Another possible area for development could be in open loop recycling, e.g. the manufacture of moulded paper pulp products and insulation material which are currently believed to consume only around 1% of the paper recovered in the UK (WRAP, 2007 (a)). Paper pulp products could be used on a larger scale as packaging material for instance.

The promotion of energy from waste

The results of the study suggest that incineration is also a satisfactory option for managing paper and card waste which would otherwise be sent to landfill. Paper and card are characterised by a relatively high heating value, similar to wood. Incineration is especially advantageous if both electricity and heat are generated (better efficiency) and substitute for electricity and gas from the public grid. The benefits are all the more important for the UK where the electricity mix relies mostly on coal and gas (see section 4.1.2). However, currently most UK incinerators only generate electricity (DEFRA, 2007 (a)). The benefits of energy recovery would be higher if future energy from waste plant generated electricity and heat, provided that infrastructure and markets were in place to utilise this heat. District heating is not widespread in the UK so there is a lack of infrastructures to ensure heat distribution. Alternatively, the benefits of energy recovery could diminish if the efficiency of the fossil energy generation technologies increases in the few next years, and they are also used to generate heat and power.

The conducted study highlights that landfill disposal is the worst alternative for paper and card due to the formation and release of methane during degradation. The percentage of paper and card being landfilled is destined to be reduced in the near future because of the Landfill Directive. However, in the UK landfill disposal is likely to remain the marginal end-of-life route and priority should thus be given to landfills with high biogas recovery efficiency. Indeed the results of the study highlight that the environmental burden of paper landfill disposal can be significantly reduced by selling the generated electricity to the grid, thus reducing the use of fossil fuels. Due to the biogas valorisation, the results of the comparison for depletion of natural resources show that the difference between landfill, energy recovery and recycling is not as significant as intuition would suggest.

Summing up

The following table sums up how the UK waste sector contribute to make the relevant end-of-life option more or less beneficial from an environmental point of view and how future trends could change the picture. An arrow up means that the given context element could contribute to increasing the environmental benefits of the concerned end-of-life option. On the contrary, an arrow down means that this element could contribute to make the concerned end-of-life option less beneficial from an environmental point of view. Tables built on this principle are used to sum up the findings for each fraction.

Table 90 Influence of the UK context on the various end-of-life options for paper waste management

		Influence on the end-of-life options		
	Elements of the UK context	Recycling	Incineration	Landfill
Sector-based elements	1 Energy mix based on fossil fuels	↘	↗	↗
	2 Paper production based on low carbon energy	↘		
	3 Co-mingled paper collection	↘		
	4 Lack of domestic demand for recycled products	↘		
Future trends	5 Low carbon energy mix	↗	↘	↘
	6 Increased use of cogeneration		↗	
	7 Improved recycling technology	↗		

↗	Could contribute to make the concerned end-of-life option more beneficial from an environmental point of view
↘	Could contribute to make the concerned end-of-life option less beneficial from an environmental point of view

1 Currently, the UK energy mix is mainly based on fossil fuels. Therefore the energy savings brought by incineration or landfills make this option advantageous while on the contrary recycling is associated with energy consumption.

2 Since the UK virgin paper is essentially produced in Scandinavia, based on low carbon energy, avoiding the production of virgin paper via recycling does not bring so many environmental benefits.

3 Co-mingled paper collection results in a relatively low quality of the collected paper and thus limits the environmental benefits of recycling.

4 The lack of domestic demand for recycled paper products does not encourage the development of the paper recycling channels.

5 If in the future the energy produced no longer replaces fossil energy, the advantages would not be as high as today. On the contrary, the energy used for recycling would generate fewer environmental impacts.

6 The Increased use of cogeneration would optimize the energy efficiency of incinerators.

7 Improved recycling technology could reduce the energy needs for the recycling process or minimize the part of the collected waste that ends up as residual waste.

4.3 Relevance of findings in the UK context for plastics

The plastic waste category is dominated by plastic packaging, estimated to comprise around 8% of the household waste stream in the UK. Of this, around 22% is collected for recycling. At the time of writing, the target for plastic packaging is a recycling rate of 29%. The study has clearly highlighted that mechanical recycling is the preferable option for managing plastic waste, shown in the table below. The indicators that have been chosen to be displayed in Table 91 are those corresponding to the main environmental issues the UK is facing. It is interesting to note that the ranking presented below also corresponds to the findings from study no 2 (Shonfield, 2008) which was conducted in a UK context. Nevertheless, in that specific study, pyrolysis appeared preferable to recycling for both energy demand and eutrophication while incineration performed worse than landfill regarding climate change.

Table 91 Overview of the best and worst end-of-life options for managing plastic waste based on the results of the study

	Plastic waste management		Number of studies
Indicator	Best option	Worst option	
Climate change	Recycling	Incineration/Landfill	8
Depletion of natural resources	Recycling	Landfill	4
Energy demand	Recycling/Pyrolysis	Landfill	7
Acidification	Recycling	Landfill	4
Eutrophication	Recycling/Pyrolysis	Landfill	4

Recycling and material quality

The analysis conducted highlighted that mechanical recycling is indeed the best option regarding climate change, depletion of abiotic resources and acidification. As CO_2 emissions and air pollution are issues of specific interest in the UK it would be beneficial to further develop plastic recycling.

There is some concern about the need to wash the material prior to recycling, especially for packaging which represents around one-third of the plastic consumed in the UK as illustrated in Figure 48. Washing needs have not been taken into account in the selected studies but could affect the energy balance in the event that hot water is used for washing.

Additionally, in the case of plastic waste arising from electronic and electrical equipment or end-of-life vehicles, the preliminary recovery operations prior to the recycling process (sorting, crushing, etc.) may require some energy. Incineration could then become a preferable option on this aspect, since the balance between the two was already tight. The plastic waste recovered from these types of wastes can also be of low quality (mix of different plastic types and colours), thus leading to low quality recycled products for which an end-market might not be available. However, certain WEEE recycling channels seem promising. For instance a recent LCA found that significant environmental benefits can be gained from producing recycled high-impact polystyrene resin from discarded televisions compared with producing virgin high-impact polystyrene resin (Frey & Dowling, 2009), despite the transport and recycling impacts. Nevertheless, the data for recycled resin was confined to one manufacturer in that study therefore the LCA results cannot be generalised and further research is needed to come up with reliable conclusions regarding the recycling potential of WEEE.

Another problem has also arisen due to the European Commission REACh[5] regulation which came into force in 2007 and that regulates the production and use of chemical substances. The regulation does not apply to wastes themselves but some questions remain to be answered regarding the recycling of products containing substances covered by REACh. Indeed the content of those substances will have an influence on the recycled products quality and thus on their value.

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[5] *European Commission Regulation on the Registration, Evaluation, Autorisation and Restriction of Chemical Substances (REACh)*

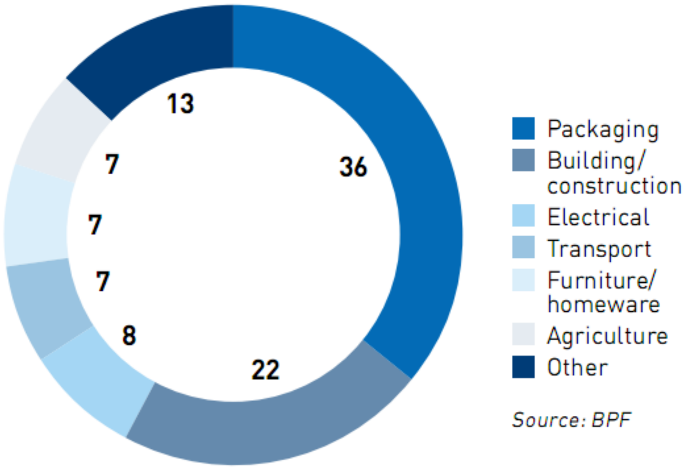

Figure 48 End markets of plastic products manufactured in the UK (by weight), 2005 (WRAP, 2007 (b))

Another burden on recycling performances is the low quality of the recovered plastic which is likely to result in a high loss rate during sorting. Compared to recovered plastics from other countries, UK material is reported to be of lower quality (WRAP, 2007 (b)). This can be explained by the fact that most plastics are recovered from post-consumer as co-mingled waste.

The lack of domestic recycling infrastructures

A further problem is the lack of recycling infrastructures in UK. For instance the UK does not have any polyester fibre manufacturing capacity thus the recycling of PET bottles into fibres needs to be performed abroad (WRAP, 2007 (b)). The majority of mixed plastics are also exported because of a lack of domestic capacity. Around two-thirds of the packaging plastics recovered from the UK waste stream are exported for recycling overseas, mainly in China as illustrated below. Export of collected packaging plastics have almost tripled between 2005 and 2007 (see Figure 49) while the quantity of plastic reprocessed in the UK fell by about 20% (WRAP, 2007 (b)). The impacts associated with long-distance transportation thus need to be added to the analysis of recycling. Transport especially affects climate change and energy demand in particular. In addition, as the waste is mainly exported to China, it means that energy derived from fossil fuels will be used for the recycling processes, which also increases the environmental impacts. In order to maximise the environmental benefits of recycling it is thus essential to develop the domestic recycling capacity. This does seem to be happening, as there has recently been progress in ‘closed-loop’ packaging recycling capacity in the UK, whereby for instance recycled food and beverage bottles can be substituted for virgin PE (and PET) in bottle manufacture (AMA Research Ltd, 2009).

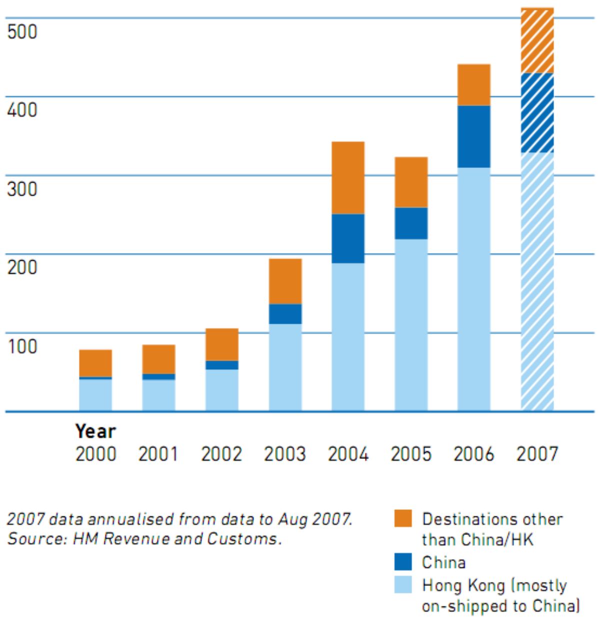

Figure 49 Exports of recovered plastics, in thousand tonnes (WRAP, 2007 (b))

Dealing with the climate change issue

Incineration can appear as a viable option for plastic waste management thanks to the high heating value of plastics. Incineration is thus an interesting option regarding depletion of abiotic resources and energy demand, especially for plastics with a heating value above 40 MJ/ton such as HDPE or PP for example (while not for PET and PVC). However, incineration raises some concerns regarding CO_2 emissions. These emissions are partly compensated by the energy recovered that substitutes coal and natural gas but incineration is still not recommended if the focus is put on climate change.

As argued in current European and National policies, disposal in landfills is globally an unfavourable option. Nevertheless, when looking at GHG emissions on a 100-year perspective landfill can perform better than incineration as no degradation is assumed to take place. As plastics are not covered by the Landfill Directive which deals with imposing requirements on biodegradable waste only, disposal in landfills might remain the preferred option for the residual waste than cannot be recycled since incineration is to be avoided if the main priority is the reduction of CO_2 emissions. As plastics are not degradable it has been suggested that they could be stored in landfills in order to be recycled in the future when the recycling infrastructure is more developed. The criticism that may be raised over this option is that it does not appear sustainable since it implies leaving the next generation to deal with our waste.

The promotion of energy from waste

The analysis has also pointed out the good performance of pyrolysis. Pyrolysis appeared preferable over incineration regarding the impacts on climate change and depletion of abiotic resources. The analysis also suggested that pyrolysis is less energy-demanding than either recycling or incineration. The performances regarding eutrophication and acidification also confirm that this is a promising option. This technology is still in early development and so the results may not be representative of commercial operations. Nevertheless, the results highlight that pyrolysis should be promoted, in line with the UK policy that aims at promoting energy from waste. Indeed, via the 'Renewables Obligation', the UK government is supporting electricity produced from the biomass content of waste treated in gasification, pyrolysis, anaerobic digestion and good quality combined heat and power plants (DEFRA, 2007).

Summing up

Table 92 sums up how the UK waste sector contribute to make the relevant end-of-life option more or less beneficial from an environmental point of view and how future trends could change the picture.

Table 92 Influence of the UK context on the various end-of-life options for plastic waste management

		Influence on the end-of-life options			
	Elements of the UK context	Recycling	Pyrolysis	Incineration	Landfill
Sector-based elements	1 Energy mix based on fossil fuels	↘	↗	↗	↗
	2 Co-mingled plastic collection	↘			
	3 Lack of domestic recycling facilities	↘			
Future trends	4 Low carbon energy mix	↗	↘	↘	↘
	5 Increased use of cogeneration			↗	
	6 Separate collection	↗			
	7 Development of domestic recycling facilities	↗			

↗	Could contribute to make the concerned end-of-life option more beneficial from an environmental point of view
↘	Could contribute to make the concerned end-of-life option less beneficial from an environmental point of view

1 Currently, the UK energy mix is mainly based on fossil fuels. Therefore the energy savings brought by incineration, pyrolysis and landfills make these options advantageous while on the contrary recycling is associated with energy consumption.

2 Co-mingled plastic collection results in a relatively low quality of the collected plastics and thus limits the environmental benefits of recycling.

3 The lack of domestic recycling facilities implies that the collected plastics need to be exported to be recycled and transportation is increasing the environmental impacts of the recycling process.

4 If in the future the energy produced no longer replaces fossil energy, the advantages would not be as high as today. On the contrary, the energy used for recycling would generate fewer environmental impacts.
5 The increased use of cogeneration would optimise the energy efficiency of incinerators.
6 Separate collection ensures the recovery of materials of higher quality and thus a lower loss rate for recycling.
7 The development of domestic recycling facilities would reduce the environmental impacts of the recycling process by avoiding transportation

4.4 Relevance of findings in the UK context for biopolymers

As they are based on renewable resources, biopolymers contribute to the conservation of fossil resources and reduction in CO_2 emissions and thus appear to be a promising innovation for sustainable development (European Bioplastics, 2009). The UK is currently seeing a significant growth in the development and use of biopolymer and compostable packaging especially in the retail grocery sector while there is currently no appropriate infrastructure for the biopolymer materials to be collected and treated in the UK (WRAP, 2009 (c)). The end of life issue is believed to be a major barrier for mass production of bioplastics and biopolymers (InCrops, 2009). Their market share in the EU is currently insignificant compared to conventional plastics, i.e. 50,000 tonnes compared to 40 million tonnes according to the European Bioplastics Association. Nevertheless, the market is growing strongly, especially for certain application areas such as packaging and agricultural films (European Bioplastics, 2009).

There is also considerable confusion among consumers regarding the appropriate end-of-life for biopolymers. Consumers need to be informed about how to distinguish biopolymers from other polymers and how to dispose of them appropriately at end of life. This study examined the available options in order to come up with some recommendations regarding the options to be favoured. The main findings are summed up in the Table 93.

Table 93 Overview of the best and worst end-of-life options for managing biopolymer waste based on the results of the study

	Biopolymer waste management		Number of studies
Indicator	Best option	Worst option	
Climate change	*No clear preferred option*		7
Depletion of natural resources	Recycling/Incineration	Composting	2
Energy demand	Recycling/Incineration	Composting	4
Acidification	Recycling/Incineration	Composting/Landfill	5
Eutrophication	*No clear preferred option*		4

Issues around biopolymer differentiation

The principal problem that arises in the end of life stage comes from the fact that biopolymers are hard to distinguish from fossil-based plastics.

While one advantage of biopolymers is that some are compostable, there is a risk of contamination with conventional plastics. Because of this, currently no UK local authority will accept biopolymer packaging in the organic waste collection, except kitchen caddy liners (WRAP, 2009 (c)).).

Compostable biopolymers may also end up in the recyclables stream and contaminate it. Biopolymers could probably be separated from conventional plastics using near infra red and laser fluorescence technologies but this would require a significant investment by waste management companies and would increase the cost of recycling (WRAP, 2009 (c)).

Alternatively biopolymers could be added to the residual waste stream and increase the biodegradable waste sent to landfill, making it harder for the UK to meet its obligations under the EU Landfill Directive and increasing the amount of methane gases generated (WRAP, 2009 (c)).

The word biopolymers covers a very broad category of materials with differing properties. It is therefore difficult to come up with a single recommendation for the end-of-life stage. And if the recommendations differ according to the biopolymer type, then there is a risk that the consumer will get confused. Considering these issues, incineration can appear as a good compromise, combining good environmental performances and simplifying the routing after disposal. As conventional plastics, biopolymers have high calorimetric values and incineration thus generates energy credits. However, as mentioned earlier, to maximise benefits both electricity and heat should be generated and valorised.

Future potential for recycling

The study highlighted that recycling, together with incineration, are the most beneficial alternatives regarding depletion of abiotic resources, energy demand and acidification.

However, some detail needs to be provided regarding the type of recycling that was included in the reviewed study. Two of the selected studies evaluated mechanical recycling for PLA and Mater-Bi. However, these were prospective scenarios since this technology is not yet in place. These scenarios have thus been evaluated extrapolating data from fossil-based plastics recycling processes. In both cases, the results indicated that mechanical recycling was the best option.

Another recycling option for biopolymers is chemical recycling. Chemical recycling has been assessed in study no 3 for PLA, based on the process used to recover PLA production waste. The biopolymer is first hydrolysed and then repolymerised into similar or other products. Chemical recycling appeared to perform better that composting and anaerobic digestion regarding all the indicators assessed. As for mechanical recycling, sufficient amounts of source-separated collected wastes are needed in order to be able to develop this recycling option.

The last type of recycling investigated in the studies was feedstock recycling, in which biopolymer waste is used as a reducing agent in blast furnaces or converted to methanol. The advantage of this option is that there is no need for specific infrastructures and the biopolymer waste can be treated together with mixed plastics. This option was assessed in two scenarios and the results showed that this option does not bring additional benefits compared to incineration or anaerobic digestion. This option thus brings fewer environmental benefits than the other forms of recycling.

Based on these findings, mechanical and chemical recycling of biopolymers seem promising but further research is needed to assess the real potential of these options depending on the biopolymer type. Councils and recycling authorities will then need to develop the logistics associated with mass disposal of biopolymers (WRAP, 2009 (c)).

Following biowastes routes

In the case they are degradable, biopolymers can also follow the waste routes designed for biowastes such as food waste. The main options are thus composting and anaerobic digestion. The study has highlighted that anaerobic digestion, when assessed, performs better than composting. Anaerobic digestion has the advantage of generating energy that can replace electricity and heat from the grid. This finding goes along with the UK waste strategy which promotes anaerobic digestion. For instance, anaerobic digestion benefits from the Renewables Obligations scheme. Nevertheless, it should be noted that anaerobic digestion has only been assessed in two studies for PLA and maize starch and that there is to date little knowledge about the behaviour of biopolymers during anaerobic digestion. Further research would thus be needed to confirm the benefits of anaerobic digestion.

Regarding composting, it should first be noted that degradable biopolymers are not necessarily compostable. Compostable packaging should comply with the standard EN 13432 which defines the characteristics of compostable materials. Composting was found to perform quite poorly, due to the fact that composting does not bring any energy credit, compared to anaerobic digestion or incineration, and the composition of biopolymers is such that they offer no nutrient replacement value in compost. However, the degradation rate of the materials has been found to be of key importance when assessing composting performances, especially for the climate change issue. This degradation rate depends on the type of biopolymer. For biopolymers with a low degradation rate, composting can be more advantageous than incineration with energy recovery. More knowledge about degradation behaviour is thus needed to further discuss the potential for composting. Composting also presents some advantages regarding eutrophication since LCA studies generally assume that the compost is used as a replacement for fertilisers. In order to optimise the environmental performances of composting it would thus be interesting to develop technologies for gas emission recovery. Composting could then allow combining material (via compost production) and energy recovery.

Summing up

Table 94 sums up how the UK waste sector contributes to make the relevant end-of-life option more or less beneficial from an environmental point of view and how future trends could change the picture.

Table 94 Influence of the UK context on the various end-of-life options for biopolymer waste management

		Influence on the end-of-life options				
	Elements of the UK context	Recycling	Incineration	Anaerobic digestion	Composting	Landfill
Sector-based elements	1 Energy mix based on fossil fuels	↘	↗	↗		↗
	2 Few products on the market	↘				
	3 No existing recycling infrastructures	↘				
	4 No clear instruction for collection	↘			↘	↘
Future trends	5 Low carbon energy mix	↗	↘	↘		↘
	6 Increased use of cogeneration		↗	↗		
	7 Improved recycling technology	↗				
	8 Development of the biopolymer market	↗				

↗	Could contribute to make the concerned end-of-life option more beneficial from an environmental point of view
↘	Could contribute to make the concerned end-of-life option less beneficial from an environmental point of view

1 Currently, the UK energy mix is mainly based on fossil fuels. Therefore the energy savings brought by incineration, anaerobic digestion or landfills make these options advantageous while on the contrary recycling is associated with energy consumption.
2 As few biopolymers are currently on the market, there is no real interest in developing specific biopolymer recycling channels.
3 The lack of recycling infrastructures for biopolymers does not allow to exploit the recycling potential of biopolymers to be exploited.
4 As there is currently no clear instruction for collection of biopolymers, there is a risk that biopolymers are mixed with fossil-based plastics
5 If in the future the energy produced no longer replaces fossil energy, the advantages would not be as high as today. On the contrary, the energy used for recycling would generate fewer environmental impacts.
6 The increased use of cogeneration would optimise the energy efficiency of incinerators. and anaerobic digesters
7 Improved recycling technology could reduce the energy needs for the recycling process or minimise the part of the collected waste that ends up as residual waste.
8 The development of the biopolymer market would be an incentive for the development of specific recycling channels for biopolymers

4.5 Relevance of findings in the UK context for food and garden waste

In the UK, around 25 million tonnes of food and garden wastes are generated annually, around half of which comes from the municipal waste stream. Food waste is a huge issue in the UK since approximately 8.3 million tonnes of food and drink are thrown away, of which 60% could be avoided if better stored and managed (WRAP, 2009(d)).

An interesting point is also that there is a strong tradition for home composting in the UK since about one-third of UK households with gardens compost at home. In addition, the number of local authorities operating kerbside organic waste collection schemes is increasing rapidly (WRAP, 2009 (c)). The large majority of organic material recovered is garden waste as illustrated in Figure 50. Over 50% of garden waste is now collected and this is not expected to increase significantly. By contrast, food waste collections are likely to continue to increase in the next few years. Today the preferred option for collected source-separated food and garden waste is composting and there was a 20% average annual growth in the amount of organic waste composted between 2002 and 2007, as shown in Figure 51. Investment in anaerobic digestion for treating food waste in particular has only a short history in the UK and is also growing. This trend can be related to the Landfill Directive which requires organic waste to be diverted from landfills (WRAP, 2009 (c)).

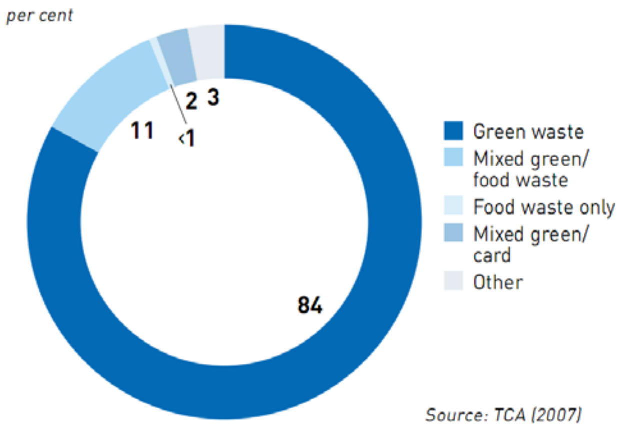

Figure 50 Composition of municipal organic waste collected separately for composting, data 2005/06 (WRAP, 2009 (c))

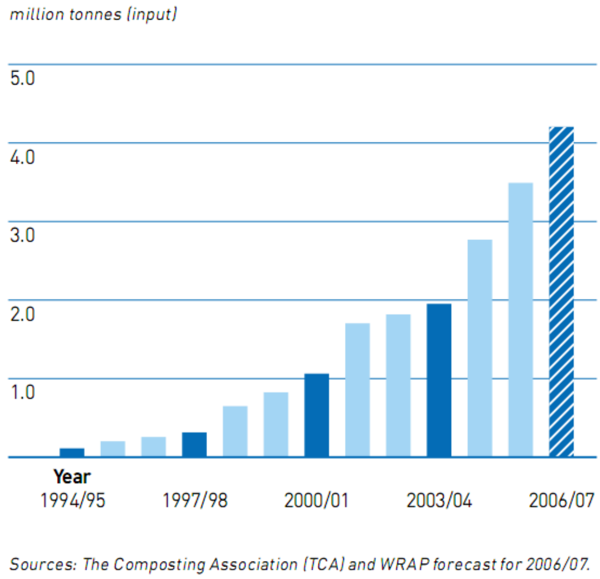

Figure 51 Composting of source segregated waste (WRAP, 2009 (c))

Besides composting (either centralised or home composting), anaerobic digestion and incineration with energy recovery are other possible alternatives that can be used for diverting food and garden waste from landfills. The outputs from the comparison between these various end-of-life options are summed up in the Table 95. Depletion of natural resources has not been included because only one of the selected studies assessed this indicator which does not allow any reliable conclusions to be drawn. The results highlight that landfill should be avoided, especially for climate change because of the methane emissions. Composting appears to be advantageous regarding eutrophication thanks to the production of compost that avoids the use of chemical fertilisers which contribute to this indicator. However, concerning the other indicators, composting was not found to perform well compared to the other options assessed, although for acidification, no option clearly stands out as the best one. Composting appears to be the worst option regarding energy demand since it is not associated with energy recovery, unlike the other alternatives.

Table 95 Overview of the best and worst end-of-life options for managing food and garden waste based on the results of the study

	Food and garden waste management		Number of studies
Indicator	Best option	Worst option	
Climate change	Anaerobic digestion	Landfill	7
Energy demand	Incineration	Composting	4
Acidification	*No clear preferred option*		4
Eutrophication	Composting	Incineration/Landfill	4

The issues around composting

As illustrated in Figure 51, composting is currently being developed very rapidly. Another study conducted by WRAP suggests that to meet the targets of the EU Landfill Directive, 5 million tonnes of municipal organic waste will need to be composted by 2012/13. However, the results of the study have highlighted that composting may not be an ideal solution from an environmental point of view, especially regarding climate change and energy consumption, since it does not allow any energy recovery, unlike anaerobic digestion for example.

In the UK, home composting is very common and is being promoted by the authorities and by many other organisations. As an example, over 75% of local authorities responsible for household waste collection and disposal in England and Wales have promoted home composting via subsidies (Smith & Jasim, 2009). Home composting does indeed present some significant advantages. First, home composting is a low-cost solution that diverts organic waste from landfill and does not require specific infrastructures such as separate collection schemes or composting centres. The compost obtained is also used as fertiliser in gardens and prevents consumers from using chemicals instead.

However, there is some concern that if there is not enough air in the composter (if it is not mixed regularly or if there is only food waste that does not allow the formation of air pockets), the process can become anaerobic and produce methane, contributing significantly to climate change. Methane releases from home composting are very hard to measure. Three studies were identified which sought to measure greenhouse gas emissions from home composting. Of these, Wheeler and Parfitt (2002) and Colón et al. (2010) found there were negligible or no emissions of methane from home composting, whilst Amlinger et al. (2008) identified clear emissions. There has been no evaluation of the greenhouse potential of the 500,000 tonnes of garden and food waste that are home composted annually in the UK. Some scientists argue that any methane formed in the composter is oxidised by the bacteria present at the interface between aerobic and anaerobic zones and that consequently home composting is unlikely to be a significant source of methane emissions (Smith & Jasim, 2009). However, there seems to be little research data available on the subject; thus there is a need for more investigation in this area.

The future potential for anaerobic digestion

As anaerobic digestion is still a relatively new technology, it is not assessed as frequently as composting, landfill and incineration in LCAs. However, the review highlighted that anaerobic digestion seems to be a very promising option for treating food waste, in particular to tackle the climate change issue. Indeed, the biogas produced can be burnt to generate heat and/or hand electricity or can be used as a vehicle fuel. Besides biogas, anaerobic digestion also produces a solid and liquid residue called digestate which can be used as a soil conditioner to fertilise land. However, end markets still need to be found for the digestate (WRAP, 2009 (c)).

In theory, anaerobic digestion is suitable for both food and garden waste but in practice, too much garden waste in the organic mix reduces the yield of biogas, as a substance called lignin which is found in woody materials cannot break down without oxygen (Friends of the Earth, 2007).

It therefore appears that anaerobic digestion should be promoted for food waste. The development of anaerobic digestion for treating food waste requires the collection of source-separated food waste. One additional constraint is that the collection frequency of food waste needs to be rather high (weekly or fortnightly) to avoid smell and vermin problems. Kerbside collection of food waste is currently growing rapidly in the UK, which is an encouraging sign for the development of anaerobic digestion. To encourage this channel, the construction of more anaerobic digestion plants will be necessary because until recently anaerobic digestion has until recently been limited to small on-farm digesters (Friends of the Earth, 2007).

Anaerobic digestion is now recognised by the UK Government for its potential in treating food waste by the UK Government. The Waste Strategy for England 2007 sets out the important contribution that anaerobic digestion can make to achieving the UK's waste management goals (DEFRA, 2007 (d)). Anaerobic digestion also enters in the framework of the Government's Renewable Energy Strategy and will contribute to the switch to a low-carbon energy mix. DEFRA estimates that by 2020 anaerobic digestion will be an established technology in the UK and that the country will be recognised as 'a world leader in the cost effective, innovative and beneficial use of anaerobic digestion and in anaerobic digestion technology and expertise' (DEFRA, 2009 (e)).

Incineration

The study pointed out that incineration is the best option when looking at energy demand thanks to the energy credits, despite the low heating value of wet organic waste. The analysis has also highlighted that performances of incineration depend on the energy mix that is substituted thanks to the energy produced. Incineration was found to perform better than composting regarding climate change when the energy produced replaces fossil fuel combustion as is the case in the UK where coal and natural gas are the main energy sources.

Summing up

Table 96 sums up how the UK waste sector contribute to make to the relevant end-of-life option more or less beneficial from an environmental point of view and how future trends could change the picture.

Table 96 Influence of the UK context on the various end-of-life options for food and garden waste management

		Influence on the end-of-life options			
	Elements of the UK context	Anaerobic digestion	Incineration	Composting	Landfill
Sector-based elements	1 Energy mix based on fossil fuels	↗	↗		↗
	2 Strong tradition for home composting			?	
	3 Current development of kerbside organic waste collection	↗	↗		
	4 Lack of anaerobic digestion infrastructures	↘			
Future trends	5 Low carbon energy mix	↘	↘		↘
	6 Increased use of cogeneration	↗	↗		
	7 Development of end markets for compost and digestate	↗		↗	
	8 Development of anaerobic digestion infrastructures	↗			

↗	Could contribute to make the concerned end-of-life option more beneficial from an environmental point of view
↘	Could contribute to make the concerned end-of-life option less beneficial from an environmental point of view

1 Currently, the UK energy mix is mainly based on fossil fuels. Therefore the energy savings brought by incineration, anaerobic digestion and landfills make these options advantageous.
2 Home composting is well developed through the UK but there is some concern whether this form of composting is beneficial or not regarding GHG emissions due to the possible formation of local anaerobic conditions. More research is needed in this area.
3. The current development of kerbside organic waste collection could reduce the amount of organic waste, which has a low heating value, going to incinerators. It would also enable the development of technology for anaerobic digestion of food waste which seems promising.
4 The lack of anaerobic digestion infrastructures does not allow for the potential of this alternative to be exploited.
5 If in the future the energy produced no longer replaces fossil energy, the advantages would not be as high.
6 The increased use of cogeneration would optimise the energy efficiency of incinerators and anaerobic digesters.
7 The development of end markets for compost and digestate would optimise the environmental benefits of these options since it would avoid the use of inorganic products instead.
8 The development of anaerobic digestion infrastructures would contribute to developing this alternative on a larger scale and improving the technology efficiency.

4.6 Relevance of findings in the UK context for wood

Wood is used for a whole range of applications in the UK as illustrated in Figure 52, and wood waste therefore arises from municipal waste, construction, demolition and from manufacturing of packaging, furniture, joinery and fencing. Estimates of the amounts of wood waste generated in the UK are hard to obtain and available surveys present different results. However, the construction and demolition sector appears to be the greatest contributor to wood waste arisings (WRAP, 2009 (c)).

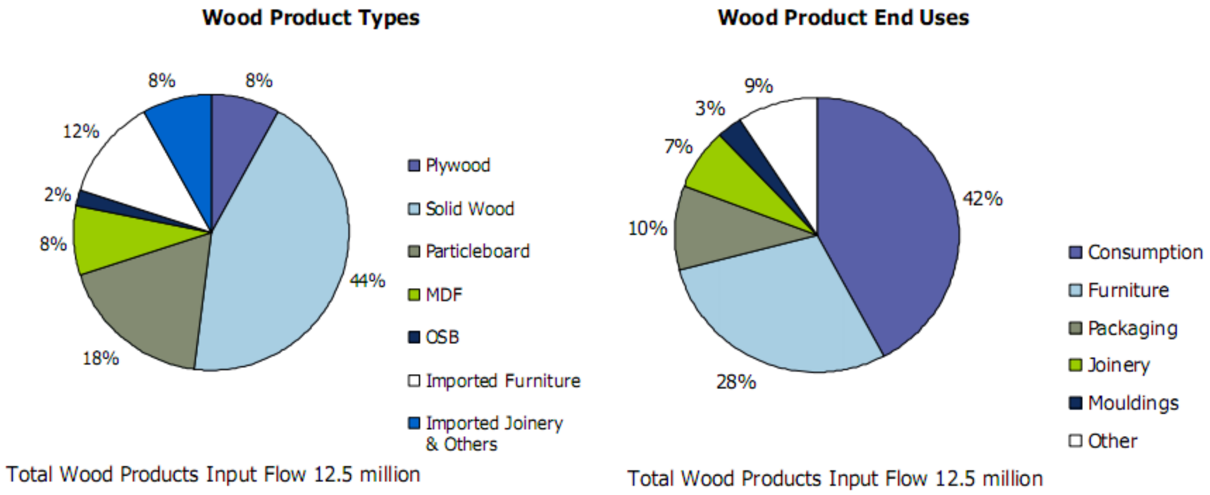

Figure 52 Wood products types and end uses in the UK (WRAP, 2009 (c))

Concern around forest preservation contributes to the promotion of wood waste recovery and reuse. Wood waste is currently used mostly for wood panel board manufacture: in 2007, about half of the UK recovered wood waste was used by panel manufacture (See Figure 53). Other widespread options are dedicated biomass energy generators and agricultural or horticulture product manufacturers (WRAP, 2009 (c)). Among these three main options, recovery in dedicated biomass energy plants is the route that has expanded the most rapidly recently.

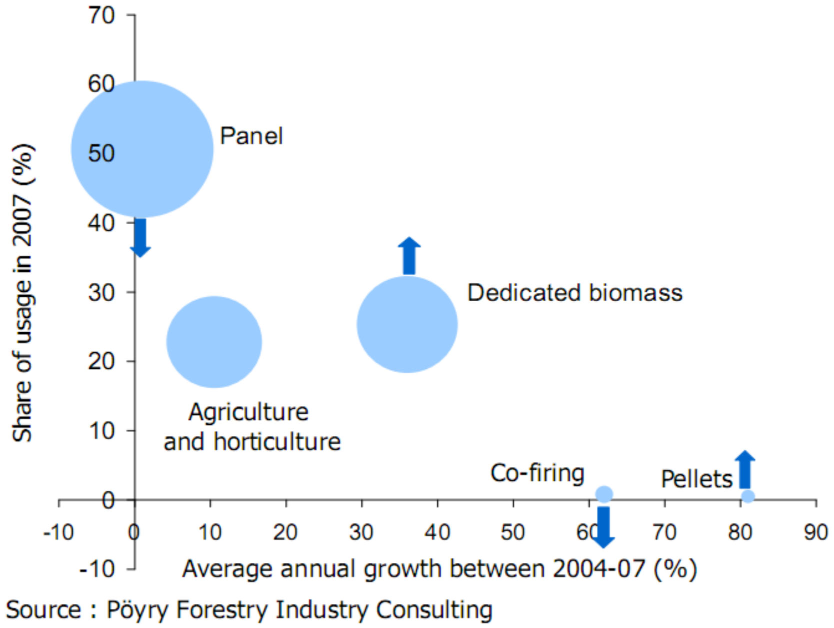

Figure 53 Use of recovered wood by various industries in the UK (WRAP, 2009 (c))[6]

The study revealed that very few LCAs have been published on wood waste management. However the few studies available still provide interesting information and led to conclusions that seem rather consistent from one study to another.

The study has highlighted that unsurprisingly landfill disposal clearly appears as the worst option, because the carbon is then converted to methane during wood decomposition and thus contributes to climate change. This is in line with the EC Landfill Directive, which and the UK Landfill Tax which aim to prevent biodegradable (active) waste from ending up in landfills.

[6] Arrows indicate expected direction of movement in share of usage and bubble size reflects usage in million tonnes.

The comparison between incineration and recycling is more complex. When looking at energy consumption, incineration with energy recovery tends to be more favourable than recycling. The picture is more balanced regarding the contribution to climate change since the environmental impacts of recycling and incineration are of a similar scale. The final conclusion depends on the type of recycling which determines the avoided material production and the type of energy recovery (electricity, heat or both). This result is again influenced by assumptions regarding the sustainable nature of forestry activities (see following section).

Carbon storage

Being a renewable resource, the organic carbon contained in the wood is of biogenic origin. This carbon is stored all along the product lifecycle. Then during the end-of-life stage the available options differ regarding what happens to this biogenic carbon. In the case of sustainable forestry practices, the input and output of biogenic CO2 may be in equilibrium. Per tonne of wood, this equates to a flow of 1.4 tonnes CO2 equivalent.

In the case of incineration or landfill disposal, the biogenic carbon is released. If the wood is burned, this carbon will be released as CO_2. However, as this carbon is of biogenic origin, these CO_2 emissions are not accounted for global warming since the quantity of CO_2 emitted corresponds to the quantity absorbed during the growth of trees. When wood waste is landfilled, the carbon is released as methane and thus there is a significant contribution to global warming if the landfill gas is not collected.

In the case of recycling and reuse, the biogenic carbon is not released but remains stored in the wood. This property provides benefits in the event that wood wastes are recycled into products with a long lifetime such as particleboard or medium density fibreboard which can be incorporated in buildings or furniture. This allows the carbon storage period to be extended for several decades.

Supply and demand

Recycling and reuse also bring environmental benefits via the associated avoided manufacture of products from virgin wood. Reducing the use of virgin wood is especially interesting for a country like the UK which imports most of its wood products. For example in 2008, UK production accounted for around one-third of the UK sawnwood market and around half of the UK woodbased panel and paper markets (Forestry Commission, 2009). While sawn softwood, particle particleboard and fibreboard are mainly imported from EU countries, UK imports of plywood commonly come from countries outside of the EU, such as China, Brazil and Malaysia (Forestry Commission, 2009). Importing wood from these countries raises the issue of forest sustainability, as wood exploitation in these areas contributes to deforestation. However, as mentioned in section 4.2 about paper and cardboard, deforestation is rather driven more by the need for extra land for agricultural purposes than by the need for wood. Therefore the link between wood recycling and forest use is not straightforward even though wood recycling and reuse can to some extent contribute to the reduction of wood importation from unsustainable forests.

In addition, in order to expand recycling and reuse, adequacy is needed between supply and demand for recycled products. The main constraint is that wood recycling can require certain quality criteria for the wood waste, depending on the recycling channel. For instance panel manufacturers require clean woodchips uncontaminated by preservatives, glues or metals (Magin, 2001). Items such as railway sleepers or telegraph poles are therefore unsuitable for panel manufacture. Such constraints limit the proportion of wood waste arisings suitable for the given recycling option and make the wood recycling market more complex by creating different submarkets depending on the wood waste quality. It makes it harder to ensure the adequacy between supply and demand for each submarket and to guarantee the sustainability of the wood recycling industry.

The potential of energy from waste

The studies have highlighted that the comparison of incineration and recycling is very close. Energy recovery is particularly promising with regard to the energy and resource depletion aspects, when wood waste is used in combined heat and power plants.

Another option that has not been assessed in this review but that is currently developing in the UK as mentioned earlier is the use of wood waste in dedicated biomass energy plants. Compared to incineration, this option presents the advantage of a better efficiency but also requires certain quality criteria and is not suitable for all wood types (contamination issues). For instance, some restrictions apply to preservative-treated wood that may produce toxic emissions when burnt (Magin, 2001).

These two waste-to-energy options are promoted by the Government via the Renewables Obligations scheme, so demand for wood waste as a fuel can be expected to grow in the UK. However, in contrast with recycling, these alternatives do not reduce the demand for new timber and the pressure on forests.

4.7 Relevance of findings in the UK context for textiles

The UK generates approximately 1.5-2 million tonnes per year (2006) of clothing waste (DEFRA, 2008 (c)). Textiles represent about 3% by weight of a household bin. Textiles waste is currently the fastest-growing stream in household waste and is forecast to continue increasing as sales of new clothing continue to rise (Waste on line, 2006; DEFRA, 2008 (c)). Around 25% of the textile waste is reused or recycled in the UK (Waste on line, 2006) while the rest is mostly disposed of via landfills. This places the UK above the EU average since across Europe, an estimated 15 to 20% of the potential existing tonnage is collected (Textile Recycling Association, 2005). Textile reuse was not within the scope of the study but is in practice closely linked to textile recycling for post-consumer clothing waste. One major characteristic of the textile waste sector is that it is dominated by charitable organisations that collect the textile waste via drop-off containers (textile banks) or charity shops which are very common through the UK. The main players in the UK are the Salvation Army and Oxfam. These charities collect used clothing and sell it in charity shops or in developing countries in order to raise funds for development projects. Clothes unsuitable for reuse are recycled in the UK or overseas into lower value products (e.g. mattresses, wipes, carpet underlay, automotive components or niche clothing) (DEFRA, 2008 (c)). Table 97 shows the fates of the textiles collected by the Salvation Army and members of the Textile Recycling Association.

Table 97 Summary of fates of collected textiles, based on sruveys conducted by the Salvation Army (SATCoL) and members of the Textile Recycling Association (TRA) in 2005 (Oakeden Hollins, 2006)

Disposal Route	SATCoL (2003)	TRA (2005)	SATCoL (2005)	Average 2005 SATCoL/TRA
UK Re-use	71%	3%	3%	3%
Export Re-use		63%	55%	60%
Wiper Grade	8%	10%	14%	12%
Recycling Grade	15%	18%	21%	19%
Waste	6%	6%	7%	6%

Concerning the environmental benefits of the various options, the study revealed that there is a large lack of LCAs focusing on the end-of-life of textiles. However, the review of the few studies investigating the environmental impacts associated with textiles disposal highlighted that textile recycling brings substantial benefits regarding energy consumption and climate change. The benefits are obtained by off-setting the production of products from virgin fibres. The studies also pointed out that the second best option is incineration with energy recovery while landfill disposal has the worst environmental profile.

Dealing with the climate change issue

In the UK, textile recovery, encompassing both recycling and reuse, also presents the advantage of diverting waste from landfills. This is of major importance for natural fibres that decompose in landfills and generates methane which is a heavy contributor to global warming. For natural fibres, avoiding landfill disposal via incineration with energy recovery for instance should therefore be of a high priority if reuse or recycling is not possible.

Lack of recycling technologies

Nevertheless, the potential for textile recycling is currently limited (excluding reuse) due to the lack of technologies. For instance, the recycling of used clothing into new clothes is very marginal. In addition, no option for textiles made from blended fibres is currently available. The equipment used to shred and convert clothes back into fibres is not suitable for blended fibres and it is difficult to make new yarns out of mixed fibres. For garments made from a mix between natural and synthetic fibres, it might be possible in the future to dissolve natural fibres (e.g. cotton) to recover the synthetic ones (e.g. polyester) but this technology is not economically feasible at present. Fibre separation technologies therefore need to be developed. There is also a need for develop a demand for recycled products.

Limited demand for wipers

One of the biggest end market for recycled textile products is wipers which are used for instance in the car industry as polishing cloths. The environmental benefits of this recycling channel arise from the avoided production of virgin materials such as cotton cloths which are replaced by the used textile. This type of recycling is more valuable from an environmental point of view than conversion to filling materials since in the latter case used textile replaces, for instance, kraft paper which generates fewer environmental impacts than cotton cloths during production.

However, if recycling was to be developed on a larger scale there is a risk that the demand for wipers made from used clothing would not be high enough. It would therefore be interesting to develop other applications for recycling; e.g. insulation materials. Furthermore, such wipers are low quality products with a very limited economic value therefore it could be more attractive to recover energy from them by incineration. The extent of the environmental benefits of recycling is also highly dependent on the type of alternative materials avoided.

The quality issue

A key aspect in the textile reuse and recycling business is the quality of the collected clothes since it determines the route followed, i.e. reuse, recycling or disposal. The 'fast fashion' trend that encourages consumers to buy more clothes but of lower quality is leading to a fall in the quality of clothes collected. The second-hand clothing business is also suffering from the competition with cheap Asian clothing since second-hand cloths no longer represent a real economic advantage. It is thus of key importance to act on the donors' side to ensure the collection of good quality items valuable on the reuse and recycling market.

Governmental support

An encouraging sign for the development of textile reuse and recycling in the UK is that the Government has already launched various initiatives. Promoting textile recovery has been identified by the UK Government as an area of intervention for waste reduction as well as GHG emissions reduction. As part of Sustainable Consumption and Production (SCP), ten product roadmaps are being developed to reduce the environmental and social impacts across the life cycle of a range of priority products and clothing is one of these products (DEFRA, 2009 (e)). A revised Action Plan for the Sustainable Clothing Roadmap was thus launched in September 2009 in order to improve the sustainability performance of clothing and maximising reuse and recycling is one action area that has been identified.

Several projects are supported by the Government. These projects aim at:

- Encouraging the development of closed loop remanufacturing of clothing
- Promoting the donation of unwanted clothing and textiles for reuse to charity shops via media releases and other promotional activity to influence consumer behaviour
- Encouraging take back processes from textile retailers

  (DEFRA, 2009 (e))

Summing up

Table 98 sums up how the UK waste sector contributes to each relevant end-of-life option more or less beneficial from an environmental point of view and how future trends could change the picture. In addition, the potential for the development of other end-of-life options such as composting and pyrolysis should be assessed from a technical, environmental and economic point of view.

Table 98 Influence of the UK context on the various end-of-life options for textile waste management

		Influence on the end-of-life options		
	Elements of the UK context	Recycling	Incineration	Landfill
Sector-based elements	1 Energy mix based on fossil fuels	↘	↗	↗
	2 No kerbside waste collection	↘		
	3 Widespread use of blended fibres and diversity of possible blends	↘		
	4 Lack of demand and market for recycled products	↘		
	5 Lack of recycling infrastructures	↘		
Future trends	6 Low carbon energy mix	↗	↘	↘
	7 Increased use of cogeneration		↗	
	8 Improved recycling technology	↗		

↗	Could contribute to make the concerned end-of-life option more beneficial from an environmental point of view
↘	Could contribute to make the concerned end-of-life option less beneficial from an environmental point of view

1 Currently, the UK energy mix is mainly based on fossil fuels. Therefore the energy savings brought by incineration and landfill make this option advantageous while on the contrary recycling is associated with energy consumption.

2 As there is no kerbside collection of textiles, a small fraction of the textile waste is currently recovered for recycling.

3 The widespread use of blended fibres and diversity of possible blends makes the recycling process difficult.

4 The lack of demand and market for recycled products does not encourage the development of textile recycling on a large scale

5 The lack of recycling infrastructures does not allow exploiting the potential of this alternative to be exploited.

6 If in the future the energy produced no longer replaces fossil energy, the advantages would not be as great as today. On the contrary, the energy used for recycling would generate fewer environmental impacts.

7 The increased use of cogeneration would optimise the energy efficiency of incinerators.

8 Improved recycling technology could reduce the energy needs for the recycling process and increase the types of textiles suitable for recycling.

References

AMA Research Ltd. (2009). Plastics Recycling Market.

Amlinger, F., Peyr, S., and Cuhls, C., (2008) Green house gas emissions from composting and mechanical biological treatment *Waste Management & Research* 26: 47–60

Allwood, J., Laursen, S.E., Malvido de Rodriguez, C. & Bocken, N. (2006). *Well Dressed? The present and future sustainability of clothing and textiles in the United Kingdom*. University of Cambridge Institute for Manufacturing. Available at:
http://www.ifm.eng.cam.ac.uk/sustainability/

APME. (2001). *Plastics packaging processors: Insight into consumption and recovery in Western Europe*.

Börjesson, P., Gustavsson, L. (2000). Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. *Energy Policy, 28, 575-588.*

Colón, J., Martínez-Blanco, J., Gabarrell, X., Artola, A., Sánchez, A., Rieradevall, J., and Font, X. (2010) Environmental assessment of home composting, *Resources, Conservation and Recycling:* in press

CEPI. (2008). *Key Statistics 2007. European Pulp and Paper Industry*.
Available at:
http://www.cepi.org/Content/Default.asp?PageID=4

Daian, G., Ozarska, B. (2009). Wood waste management practices and strategies to increase sustainability standards in the Australian wooden furniture manufacturing sector. *Journal of Cleaner Production*, in press.

DEFRA. (2007) (a). *Incineration of Municipal Solid Waste*.
Available at:
http://www.defra.gov.uk/environment/waste/residual/newtech/documents/incineration.pdf

DEFRA. (2007) (b). *Waste strategy factsheets: Energy from waste and anaerobic digestion*.
Available at:
http://www.defra.gov.uk/environment/waste/strategy/factsheets/energy.htm

DEFRA. (2007) (c). *Waste strategy factsheets: National waste target for England*.
Available at:
http://www.defra.gov.uk/environment/waste/strategy/factsheets/targets.htm

DEFRA. (2007) (d). *Waste strategy for England. Executive summary*.
Available at:
http://www.defra.gov.uk/environment/waste/strategy/index.htm

DEFRA. (2008) (a). *Municipal Waste Management Statistics*.
Available at:
http://www.defra.gov.uk/evidence/statistics/environment/wastats/bulletin08.htm

DEFRA. (2008) (b). *Waste strategy annual progress report 2007/08*.
Available at:
http://www.defra.gov.uk/environment/waste/strategy/index.htm

DEFRA. (2008) (c). *Sustainable clothing roadmap briefing note December 2007: Sustainability impacts of clothing and current interventions*.
Available at:
http://www.defra.gov.uk/environment/business/pdf/clothing-briefing-Dec07.pdf

DEFRA. (2009) (a). *UK Government Sustainable Development Framework indicators*.
Available at:
http://www.defra.gov.uk/sustainable/government/progress/national/framework.htm

DEFRA. (2009) (b). *UK Government Sustainable Development Framework indicators. Natural resource protection and enhancing the environment*
Available at:
http://www.defra.gov.uk/sustainable/government/progress/national/28.htm

DEFRA. (2009) (c). *UK Government Sustainable Development Framework indicators. Climate change and energy*.
http://www.defra.gov.uk/sustainable/government/progress/national/5.htm

DEFRA. (2009) (d). *Making the most of packaging. A strategy for a low carbon economy*.
Available at:
http://www.defra.gov.uk/environment/waste/producer/packaging/documents/full-packaging-strategy.pdf

DEFRA. (2009) (e). *Sustainable Clothing Action Plan* (update Sept 2009).
Available at:
http://www.defra.gov.uk/environment/business/products/roadmaps/pdf/sustainable-clothing-action-plan.pdf

Department for Business Enterprise & Regulatory Reform. (2008). Updated energy and carbon missions projections*. The Energy White Paper*.
Available at:
http://www.decc.gov.uk/media/viewfile.ashx?filepath=publications/white_paper_07/file39387.pdf&filetype=4

Department of Energy and Climate Change. (2008). *Climate Change Act 2008*.
Available at:
http://www.decc.gov.uk/en/content/cms/legislation/cc_act_08/cc_act_08.aspx

Department of Energy and Climate Change. (2009). *The UK Low Carbon Transition Plan*.
Available at:
http://www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx

Department of the Environment, Northern Ireland. (2006). *Towards Resource Management-The Northern Ireland Waste Management Strategy 2006 – 2020*.
Available at:
http://www.doeni.gov.uk/towards_resource_management.pdf

Department of Trade and Industry. (2007). *Meeting the energy challenge. A white paper on energy*.
Available at:
http://www.berr.gov.uk/files/file39387.pdf

EDIPTEX. (2007). *Environmental assessment of textiles*. Danish Ministry of the Environment, Environmental Protection Agency.

Ekvall T., Weidema B.P. (2004). System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. *International Journal of Life Cycle Assessment*, 9 (3), 161 – 171

Environment Agency. (2009). *Waste – an overview.*

ERM. (2002) (a). *Streamlined Life Cycle Assessment of Textile Recycling*. Report completed for the Salvation Army Trading Company Ltd by Environmental Resources Management (ERM) Ltd.

ERM. (2002) (b). *Streamlined Life Cycle Assessment of Two Marks & Spencer plc Apparel Products*. Report completed for Marks & Spencer by Environmental Resources Management (ERM) Ltd.

ERM (2006). *Carbon Balances and Energy Impacts of the Management of UK Wastes*. Report completed for DEFRA by Environmental Resources Management (ERM) Ltd.

European Bioplastics. (2009) *Bioplastics at a Glance*
Available at:
http://www.european-bioplastics.org/index.php?id=182

FAO. (2005). *Extent of forest and other wooded land 2005*
Available at:
http://www.fao.org/forestry/32032/en/

Forestry Commission. (2009). *Foresty Statistics 2009*.
Available at:
http://www.forestresearch.gov.uk/website/forstats2009.nsf/0/75ED8D37A57AB21C802573560029A282?open&RestrictToCategory=1

FSC. (2009). *FSC facts & figures*
Available at:
http://www.fsc.org/facts-figures.html?&L=

Frey, S, Dowling, M. (2009). *LCA for demonstration of recycled content in electrical and electronic equipment*. Giraffe.

InCrops. (2009). *Bioplastics and Biopolymers. Summary of the discussion "What is needed to accelerate innovation in renewable biopolymers and bioplastics?"*
Available at:
http://www.incropsproject.co.uk/documents/Events/Bioplastics2009/Summary%20of%20the%20discussion%20for%20the%20web.pdf

International Energy Agency. (2006). *Electricity/heat in United Kingdom in 2006*.
Available at:
http://www.iea.org/Textbase/stats/electricitydata.asp?COUNTRY_CODE=GB

Korhonen, M.R., Dahlbo, H. (2007). *Reducing Greenhouse Gas Emissions by Recycling Plastics and Textiles into Products*. Finnish Environment Institute.

Magin, G. (2001). *An introduction to wood waste in the UK*. Fauna & Flora international.
Available at:
http://www.globaltrees.org/downloads/WoodWasteIntro.pdf

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

Merl, A. (2007). Reuse, recycling, and energy generation of recovered wood from building constructions. *Proceeding from E31 Final Conference*, Klagenfurt, May 2nd to 4th, 2007.

Northern Ireland Environment Agency. (2009). *Northern Ireland Environmental Statistics Report*.
Available at:
http://www.doeni.gov.uk/northern_ireland_environmental_statistics_report_-_january_2009.pdf

Oakdene Hollins Ltd, Salvation Army Trading Company Ltd & Nonwovens Innovation & Research Institute Ltd. (2006). *Recycling of Low Grade Clothing Waste*.
Available at:
http://www.oakdenehollins.co.uk/pdf/Recycle-Low-Grade-Clothing.pdf

Patt, R., Kordsachia, O., Süttinger, R., Ohtani, Y., Hoesch, J.F., Ehrler, P., Eichinger, R., Holik, H., Hamm, U., Rohmann, M.E., Mummenhoff, P., Petermann, E., Miller, R.F., Frank, D., Wilken, R., Baumgarten, H.L., Rentrop, G-H. (2002). *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley.

PEFC. (2009). *Statistical figures on PEFC certification*.
Available at:
http://register.pefc.cz/statistics.asp

Petersen, A.K., Solberg, B. (2005). Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. *Forest Policy and Economics*, 7, 249-259.

Rigamonti, L., Grosso, M., Giugliano, M. (2009). Life cycle assessment for optimising the level of separated collection in integrated MSW management systems. *Waste Management*, 29, 934-944.

Rivela, B., Moreira, M.T., Munoz, I., Rieradevall, J., Feijoo, G. (2006). Life cycle assessment of wood wastes: A case study of ephemeral architecture. *Science of the Total Environment*, 357, 1-11.

Recycled Organics Unit, (2007). *Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems-2nd edition*

Scottish Environment Agency. (2009). *Waste Data Digest 9: Key facts and trends*.
Available at:
http://www.sepa.org.uk/waste/waste_data/waste_data_digest.aspx

Textile Recycling Association. (2005). *OUVERTES Project - Report by Textile Reuse and Recycling Players on the Status of the Industry in Europe*.
Available at:
http://www.textile-recycling.org.uk/Report_Ouvertes_Project_June2005%5B1%5D.pdf

Thomas, B., McDougall, F. (2005). Note from the field International expert group on life cycle assessment for integrated waste management. *Journal of Cleaner Production*, 13, 321-326.

US EPA. (2006). *Solid waste management and greenhouse gases, A Life-Cycle Assessment of Emissions and Sinks*.

Villanueva, A., Wenzel, H. (2007). Paper waste-Recycling, incineration or landfill ? A review of existing life cycle assessments. *Waste Management*. 27 S29-S46.

Waste on line. (2006). *Textile recycling information sheet*.
Available at:
http://www.wasteonline.org.uk/resources/InformationSheets/Textiles.htm

Welsh Assembly Government. (2009). *Municipal Waste Management Annual Bulletin, 2007-08*.
Available at:
http://wales.gov.uk/docs/statistics/2009/090624sb352009en.pdf?lang=en

Wheeler, P.A. & Parfitt, J.P. (2002) Life cycle assessment of home composting. In: *Proceedings of the Waste 2002 Conference*. Stratford, UK. The Waste Conference Ltd, Coventry, UK

Woolridge, A., Ward, B., Phillips, P., Collins, M. & Gandy, S. (2005). Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: An UK energy saving perspective. *Resources, Conservation and Recycling*, 46, 94-103.

WRAP. (2006). *Environmental benefits of recycling*. Banbury: WRAP

WRAP. (2007) (a). *Market Situation Report-Realising the value of recovered paper*.
Available at:
http://www.wrap.org.uk/downloads/Paper_report.41701db9.4072.pdf

WRAP. (2007) (b). *Market Situation Report-Realising the value of recovered plastics*.
Available at:
http://www.wrap.org.uk/downloads/PlasticsMktRep.1558857b.4755.pdf
WRAP. (2009) (a). *Life Cycle Asssessment of Closed Loop MDF recycling: Microrelease Trial*.

WRAP. (2009) (b). *Information sheet. Biopolymer packaging in UK grocery market*.
Available at:
http://www.wrap.org.uk/retail/materials/biopolymers.html

WRAP. (2009) (c). *Wood Waste Market in the UK*.
Available at:
http://www.wrap.org.uk/downloads/Wood_waste_market_in_the_UK.a6841cff.7547.pdf

WRAP (2009) (d) *Household Food and Drink Waste in the UK*
Available at:
http://www.wrap.org.uk/document.rm?id=8048

Appendix 1 Description of the selected environmental indicators

Indicator	Description
Climate change	Climate change is also referred to as global warming. Global warming refers to the increase in the average temperature of the Earth's surface, due to a potential increase in the greenhouse effect, caused by anthropogenic emissions of greenhouse gases (carbon dioxide, methane, nitrous oxide, fluorocarbons (e.g. CFCs and HCFCs), and others).
Depletion of natural resources	Resource depletion can be defined as the decreasing availability of natural resources. The resources considered in this impact are fossil and mineral resources, excluding biotic resources, and associated impacts such as species extinction and loss of biodiversity.
Energy demand	Primary energy is raw energy available in nature and is divided into renewable and non-renewable primary energies. The main non-renewable primary energies are: oil, coal, natural gas, and nuclear energy. Renewable primary energies are: hydraulic, biomass, solar and wind energy.
Water consumption	Water consumption refers to the withdrawal of water from the different sources (rivers, seas, groundwater) for some use by humans. This water is not returned to the source.
Acidification	Air acidification consists of the accumulation of acidifying substances (e.g. sulphuric acid, hydrochloric acid) in the water particles in suspension in the atmosphere. Deposited onto the ground by rains, acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings).
Photochemical oxidation	This pollution results mainly from chemical reactions induced by solar light between nitrogen oxides and volatile organic compounds (VOC), commonly emitted in the combustion of fossil fuels. It provokes high levels of ozone and other chemicals toxic for humans and flora.
Eutrophication	Eutrophication is a process whereby water bodies, such as lakes or rivers, receive excess chemical nutrients – typically compounds containing nitrogen or phosphorus – that stimulate excessive plant growth (e.g. algae). Nutrients can come from many sources, such as fertilisers applied to agricultural fields and golf courses, deposition of nitrogen from the atmosphere, erosion of soil containing nutrients, and sewage treatment plant discharges
Human toxicity	Human Toxicity Potential characterises health risks to humans by quantitatively assessing the risks posed by chemicals to human health and the environment. This indicator is based on "risk characterisation ratios" that indicate when chemical releases are likely to result in toxic doses that exceed acceptable levels.

Appendix 2 Summary of key elements from the studies on paper & cardboard

Paper & card - n°1

Title	Environmental Assessment of Paper Waste Management Options by Means of LCA Methodology
Year	2004
Author	Arena et al

		Case	1[PB]		
		Material composition	Paper and board		
		Sub-scenario	Landfill	Recycling	Incineration
Material production	Virgin material				
		Material marginal: which?	/	swedish paper	/
		Electricity marginal: which?	/	average Swedish mix	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	Yes	Yes	Yes
	Recovered material				
		Material marginal: which?	/	paper for packaging	/
		Electricity marginal: which?	average Italian mix	average Italian mix	average Italian mix
		Steam marginal: which?	/	/	/
		Co-products dealt with?	Yes	Yes	Yes
Material recovery		Material recovery included?	/	Yes	/
		Type of recycling	/	Downcycling	/
		Alternative use of land/wood included?	No	No	No
		In which ratio does recycled material substitute virgin material?	/	/	/
Material disposal	General				
		Technology	High integrity bottom and top membranes, reverse osmosis, flaring of uncollected	mechanical cleaning and deinking or without deinking	/
		Infrastructures taken into account?	/	/	/
		Transport included?	Yes	Yes	Yes
		Energy production	Yes	No	Yes
		Produced energy substitutes electricity?	Yes	/	Yes
		Produced energy substitutes heat?	No	No	No
		Avoided processes - credits	electricity	virgin material	electricity
		Material substitutes	/	paper and board	/
		Carbon sequestration issue taken into account?	No	No	No
	Waste characteristics				
		Heating value	/	/	13 MJ/t
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	/	/	No
		Efficiency	/	/	27.7% electricity
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
	Landfill				
		Methane emissions included?	Yes	/	/
		Efficiency	55% biogas collection, 60% in gas engine, electrical conversion 35%.	/	/

Paper & card - n°1

Title	Environmental Assessment of Paper Waste Management Options by Means of LCA Methodology
Year	2004
Author	Arena et al

Impact assessment

Methodology Specific methodology

disposal stage only

the management of sufficient postconsumer waste, 1.17 t of paper and board packaging waste collected as a single material stream (with a moisture content of 15%), to produce 1 t of paper and board for packaging (with a moisture content of 7%).

	1[PB]		
	Landfill	Recycling	Incineration
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq)	-208	620	-1160
Cumulative enerhy demand (MJ/t)	16318	9232	5415
Water consumption (kg/t)	51534	8197	51586
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)	18,51	6,92	7,878
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)	~1380	~115	~250

Indicator not included

Paper & card - n°2

Title	Life cycle assessment of energy from solid waste
Year	2000
Author	Finnvenden et al

		Case	2[NS]		
		Material composition	Newspaper		
		Sub-scenario	Incineration	Landfilling	Recycling
Material production	Virgin material				
		Material marginal: which?	/	/	pulp
		Electricity marginal: which?	/	/	pulp
		Heat marginal: which?	/	/	pulp
		Co-products dealt with?	/	/	pulp
	Recovered material				
		Material marginal: which?	/	/	pulp
		Electricity marginal: which?	Hard coal	Hard coal	Hard coal
		Heat marginal: which?	Forest residues	Forest residues	Forest residues
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	Yes	Yes
		Type of recycling	/	/	/
		In which ratio does recycled material substitute virgin material?	1:1	1:1	1:1
Material disposal	General				
		Technology			
		Infrastructures taken into account?	No	No	No
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	Yes	Yes	Yes
		Produced energy substitutes heat?	Yes	Yes	Yes
		Avoided processes - credits	energy	energy	pulp
		Material substitutes	/	/	pulp
		Carbon sequestration issue taken into account?	No	No	No
	Waste characteristics				
		Heating value	/	/	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon binding of compost included?	/	/	/
		% of carbon remaining in compost after 100 uears	/	Modeled	/
	Landfill				
		Methane emissions included?	/	Yes	/

Paper & card - n°2

Title	Life cycle assessment of energy from solid waste
Year	2000
Author	Finnvenden et al

Impact assessment

Methodology EDIP, USES-LCA, Ecoindicator 99

disposal stage only

Treatment of the amount of the included waste fractions collected in Sweden during one year

	2[NS]		
	Incineration	Landfilling	Recycling
Depletion of abiotic resources (MJ/ton)	482,60	-1987,17	-14194,05
Climate change (kg CO2-eq/ton)	53,71	1342,68	-11,82
Cumulative enerhy demand (MJ/ton)	-15698,62	-3576,90	-43717,67
Water consumption (m^3)			
Eutrophication (kg PO4 eq)*	-0,20	2,05	1,06
Acidification (kg SO2 eq)**	-0,07	-0,02	-0,08
Photochemical oxydation (kg ethylene eq)	-0,31	0,96	-0,14
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Ecotoxicity (SEK/ton) EDIP	-16,29	0,09	-0,38
Human Toxicity (SEK/ton) EDIP	-218,59	-67,56	-476,92

* without effect from Nox

** without effect from Sox and Nox

Indicator not included

Paper & card - n°2

Title	Life cycle assessment of energy from solid waste
Year	2000
Author	Finnvenden et al

		Case	2[CC]		
		Material composition	Corrugated Board		
		Sub-scenario	Incineration	Landfilling	Recycling
Material production	Virgin material				
		Material marginal: which?	/	/	pulp
		Electricity marginal: which?	/	/	pulp
		Heat marginal: which?	/	/	pulp
		Co-products dealt with?	/	/	pulp
	Recovered material				
		Material marginal: which?	/	/	pulp
		Electricity marginal: which?	Hard coal	Hard coal	Hard coal
		Heat marginal: which?	Forest residues	Forest residues	Forest residues
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	Yes	Yes
		Type of recycling	/	/	/
		In which ratio does recycled material substitute virgin material?	1:1.1	1:1.1	1:1.1
Material disposal	General				
		Technology			
		Infrastructures taken into account?	No	No	No
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	Yes	Yes	Yes
		Produced energy substitutes heat?	Yes	Yes	Yes
		Avoided processes - credits	energy	energy	pulp
		Material substitutes	/	/	pulp
		Carbon sequestration issue taken into account?	No	No	No
	Waste characteristics				
		Heating value	/	/	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon binding of compost included?	/	/	/
		% of carbon remaining in compost after 100 uears	/	Modeled	/
	Landfill				
		Methane emissions included?	/	Yes	/

Paper & card - n°2

Title	Life cycle assessment of energy from solid waste
Year	2000
Author	Finnvenden et al

Impact assessment

Methodology EDIP, USES-LCA, Ecoindicator 99

disposal stage only

Treatment of the amount of the included waste fractions collected in Sweden during one year

	2[CC]		
	Incineration	Landfilling	Recycling
Depletion of abiotic resources (MJ/ton)	478,28	-2809,89	1733,76
Climate change (kg CO2-eq/ton)	18,10	1809,70	-135,73
Cumulative enerhy demand (MJ/ton)	-15484,28	-234,36	-16739,76
Water consumption (m^3)			
Eutrophication (kg PO4 eq)*	-0,14	2,79	-8,37
Acidification (kg SO2 eq)**	-0,07	-0,03	-0,22
Photochemical oxydation (kg ethylene eq)	-0,30	1,28	0,35
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Ecotoxicity (SEK/ton) EDIP	-17,58	-0,33	2,39
Human Toxicity (SEK/ton) EDIP	-205,06	-50,22	-17,16

* without effect from Nox

** without effect from Sox and Nox

Indicator not included

Paper & card - n°2

Title	Life cycle assessment of energy from solid waste
Year	2000
Author	Finnvenden et al

		Case	2[MC]		
		Material composition	Mixed Cardboard		
		Sub-scenario	Incineration	Landfilling	Recycling
Material production	Virgin material				
		Material marginal: which?	/	/	pulp
		Electricity marginal: which?	/	/	pulp
		Heat marginal: which?	/	/	pulp
		Co-products dealt with?	/	/	pulp
	Recovered material				
		Material marginal: which?	/	/	pulp
		Electricity marginal: which?	Hard coal	Hard coal	Hard coal
		Heat marginal: which?	Forest residues	Forest residues	Forest residues
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	Yes	Yes
		Type of recycling	/	/	/
		In which ratio does recycled material substitute virgin material?	1:1.15	1:1.15	1:1.15
Material disposal	General				
		Technology			
		Infrastructures taken into account?	No	No	No
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	Yes	Yes	Yes
		Produced energy substitutes heat?	Yes	Yes	Yes
		Avoided processes - credits	energy	energy	pulp
		Material substitutes	/	/	pulp
		Carbon sequestration issue taken into account?	No	No	No
	Waste characteristics				
		Heating value	/	/	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon binding of compost included?	/	/	/
		% of carbon remaining in compost after 100 uears	/	Modeled	/
	Landfill				
		Methane emissions included?	/	Yes	/

Paper & card - n°2

Title	Life cycle assessment of energy from solid waste
Year	2000
Author	Finnvenden et al

Impact assessment

Methodology EDIP, USES-LCA, Ecoindicator 99

disposal stage only

Treatment of the amount of the included waste fractions collected in Sweden during one year

	2[MC]		
	Incineration	Landfilling	Recycling
Depletion of abiotic resources (MJ/ton)	499,34	-2316,52	-3397,56
Climate change (kg CO2-eq/ton)	642,78	2337,39	183,10
Cumulative enerhy demand (MJ/ton)	-15855,28	-4252,10	-18017,37
Water consumption (m^3)			
Eutrophication (kg PO4 eq)*	67,26	103,30	-19,22
Acidification (kg SO2 eq)**	-0,05	0,00	-0,02
Photochemical oxydation (kg ethylene eq)	-0,29	1,07	-0,46
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Ecotoxicity (SEK/ton) EDIP	-16,58	-3,53	-6,41
Human Toxicity (SEK/ton) EDIP	-209,00	-165,76	-245,04

* without effect from Nox

** without effect from Sox and Nox

Indicator not included

Paper & card - n°3

Title	Analyse du Cycle de Vie comparative de différents modes d'adressage pour magazines et imprimés
Year	2007
Author	BIOIS

	Case	3[PS]		
	Material composition	paper stripe		
	Sub-scenario	Incineration with energy recovery	Recycling	Landfill
Material production	Virgin material			
	Material marginal: which?	/	/	/
	Electricity marginal: which?	/	/	/
	Steam marginal: which?	/	/	/
	Co-products dealt with?	/	/	/
	Recovered material			
	Material marginal: which?	/	/	/
	Electricity marginal: which?	/	/	/
	Steam marginal: which?	/	/	/
	Co-products dealt with?	/	/	/
Material recovery	Material recovery included?	/	Yes	/
	Type of recycling	/	Closed-loop	/
	In which ratio does recycled material substitute virgin material?	/	0,7	/
Material disposal	General			
	Technology	semi-humid cogeneration 32% efficiency	recycling of paper/card in corrugated board	50% biogas captation
	Infrastructures taken into account?	No	No	No
	Transport included?	Yes	Yes	Yes
	Energy production	Yes	No	Yes
	Produced energy substitutes electricity?	average France 2000	/	average France 2000
	Produced energy substitutes steam?	substitution: 37,5% gas, 30,2% coal, 32,3% oil	/	No
	Avoided processes - credits	/	paper production from virgin wood fibres	/
	Material substitutes	/	/	/
	Carbon sequestration issue taken into account?	/	/	/
	Waste characteristics			
	Heating value	No inf.	/	/
	Degradation rate (over 100 years)	/	/	No inf.
	Incineration			
	Alternative use of incineration capacity included?	No inf.	/	/
	Composting			
	Compost spreading for composting taken into account?	/	/	/
	Compost leaching after spreading taken into account?	/	/	/
	Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill			
	Methane emissions included?	/	/	Yes

Paper & card - n°3

Title	Analyse du Cycle de Vie comparative de différents modes d'adressage pour magazines et imprimés
Year	2007
Author	BIOIS

Impact assessment

Methodology CML

full life cycle of the magazines and printed matters packaging

1000 magazines and printed matters sent

	3[PS]		
	Incineration with energy recovery	Recycling	Landfill (including 3% incineration without energy recovery)
Depletion of abiotic resources (kg Sb eq)	0,02	0,03	0,03
Climate change (kg CO_2 eq)	3,51	4,91	9,24
Cumulative enerhy demand (MJ)*	57,02	61,38	68,48
Water consumption (m^3)	0,23	0,18	0,23
Eutrophication (kg PO4 eq)	0,01	0,012	0,01
Acidification (kg SO2 eq)	0,03	0,02	0,03
Photochemical oxydation (kg ethylene eq)	0,03	0,02	0,03
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)	2,54	2,46	2,67
Ecotoxicity in water (kg 1,4-DB eq)	0,61	0,61	0,63
Exoctoxicity in sediments (kg 1,4-DB eq)	1,15	1,17	1,20
Ecotoxicity in soil (kg 1,4-DB eq)	0,04	0,03	0,04

* the energy demand in this study corresponds to the consumption of non-renewable resources

[grey box] Indicator not included

Paper & card - n°3

Title	Analyse du Cycle de Vie comparative de différents modes d'adressage pour magazines et imprimés
Year	2007
Author	BIOIS

		Case	3[EN]		
		Material composition	envelope in vellum paper		
		Sub-scenario	Incineration with energy recovery	Recycling	Landfill
Material production	Virgin material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	/	Yes	/
		Type of recycling	/	Closed-loop	/
		In which ratio does recycled material substitute virgin material?	/	0,7	/
Material disposal	General				
		Technology	semi-humid cogeneration 32% efficiency	recycling of paper/card in corrugated board	50% biogas captation
		Infrastructures taken into account?	No	No	No
		Transport included?	Yes	Yes	Yes
		Energy production	Yes	No	Yes
		Produced energy substitutes electricity?	average France 2000	/	average France 2000
		Produced energy substitutes steam?	substitution: 37,5% gas, 30,2% coal, 32,3% oil	/	No
		Avoided processes - credits	/	paper production from virgin wood fibres	/
		Material substitutes	/	/	/
		Carbon sequestration issue taken into account?	/	/	/
	Waste characteristics				
		Heating value	No inf.	/	/
		Degradation rate (over 100 years)	/	/	No inf.
	Incineration				
		Alternative use of incineration capacity included?	No inf.	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill				
		Methane emissions included?	/	/	/

Paper & card - n°3

Title	Analyse du Cycle de Vie comparative de différents modes d'adressage pour magazines et imprimés
Year	2007
Author	BIOIS

Impact assessment

Methodology CML

full life cycle of the magazines and printed matters packaging

1000 magazines and printed matters sent

	3[EN]		
	Incineration with energy recovery	Recycling	Landfill (including 3% incineration without energy recovery)
Depletion of abiotic resources (kg Sb eq)	0,12	0,20	-0,12
Climate change (kg CO_2 eq)	19,33	28,66	-19,00
Cumulative enerhy demand (MJ)*	282,41	311,61	-247,75
Water consumption (m^3)	1,48	1,16	-1,17
Eutrophication (kg PO4 eq)	0,05	0,04	-0,04
Acidification (kg SO2 eq)	0,12	0,08	-0,09
Photochemical oxydation (kg ethylene eq)	0,16	0,13	-0,13
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)	16,7	16,2	-14,03
Ecotoxicity in water (kg 1,4-DB eq)	4,06	4,09	-3,45
Exoctoxicity in sediments (kg 1,4-DB eq)	7,65	7,73	-6,51
Ecotoxicity in soil (kg 1,4-DB eq)	0,29	0,18	-0,22

* the energy demand in this study corresponds to the consumption of non-renewable resources

Indicator not included

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

		Case	4[CC]		
		Material composition	Corrugated cardboard		
		Sub-scenario	Recycling	Incineration	Landfilling
Material production	Virgin material				
		Material marginal: which?	Corrugated cardboard	/	/
		Electricity marginal: which?	US average	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	Corrugated cardboard	/	/
		Electricity marginal: which?	/	fossil	fossil
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	closed loop	/	/
		Alternative use of land/wood included?	No	/	/
		In which ratio does recycled material substitute virgin material?	0,93	/	/
Material disposal	General				
		Technology	USA	USA	USA
		Infrastructures taken into account?	/	/	/
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	/	Yes	Yes
		Produced energy substitutes heat?	/	No	No
		Avoided processes - credits	Paper production	Electricity production	Electricity production
		Material substitutes	Corrugated cardboard	/	/
		Carbon sequestration issue taken into account?	Yes	No	No
	Waste characteristics				
		Heating value	/	14.1 million Btu per ton	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
		Efficiency	/	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon storage taken into account?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes
		Efficiency	/	/	/
		Carbon storage taken into account?	/	/	Yes

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

disposal stage only

1 short ton of material

	4[CC]		
	Recycling	Incineration	Landfilling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	-850	-180	110
Cumulative enerhy demand (MBtu/t)	-15,42	-2,21	0,23
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

Indicator not included

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

		Case	4[MA]		
		Material composition	Magazine		
		Sub-scenario	Recycling	Incineration	Landfilling
Material production	Virgin material				
		Material marginal: which?	Magazine	/	/
		Electricity marginal: which?	US average	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	Magazine	/	/
		Electricity marginal: which?	/	fossil	fossil
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	closed loop	/	/
		Alternative use of land/wood included?	No	/	/
		In which ratio does recycled material substitute virgin material?	0,71	/	/
Material disposal	General				
		Technology	USA	USA	USA
		Infrastructures taken into account?	/	/	/
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	/	Yes	Yes
		Produced energy substitutes heat?	/	No	No
		Avoided processes - credits	Paper production	Electricity production	Electricity production
		Material substitutes	Magazine	/	/
		Carbon sequestration issue taken into account?	Yes	No	No
	Waste characteristics				
		Heating value	/	10.5 million Btu per ton	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
		Efficiency	/	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon storage taken into account?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes
		Efficiency	/	/	/
		Carbon storage taken into account?	/	/	Yes

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

disposal stage only

1 short ton of material

	4[MA]		
	Recycling	Incineration	Landfilling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	-840	-130	-80
Cumulative enerhy demand (MBtu/t)	-0,69	-1,58	0,41
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

[grey box] Indicator not included

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

		Case	4[NS]		
		Material composition	Newspaper		
		Sub-scenario	Recycling	Incineration	Landfilling
Material production	Virgin material				
		Material marginal: which?	Newspaper	/	/
		Electricity marginal: which?	US average	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	Newspaper	/	/
		Electricity marginal: which?	/	fossil	fossil
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	closed loop	/	/
		Alternative use of land/wood included?	No	/	/
		In which ratio does recycled material substitute virgin material?	0,94	/	/
Material disposal	General				
		Technology	USA	USA	USA
		Infrastructures taken into account?	/	/	/
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	/	Yes	Yes
		Produced energy substitutes heat?	/	No	No
		Avoided processes - credits	Paper production	Paper production	Electricity production
		Material substitutes	Newspaper	/	/
		Carbon sequestration issue taken into account?	Yes	No	No
	Waste characteristics				
		Heating value	/	15.9 million Btu per ton	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
		Efficiency	/	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon storage taken into account?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes
		Efficiency	/	/	/
		Carbon storage taken into account?	/	/	Yes

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

disposal stage only

1 short ton of material

	4[NS]		
	Recycling	Incineration	Landfilling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	-760	-200	-240
Cumulative enerhy demand (MBtu/t)	-16,49	-2,54	0,42
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

(grey box) Indicator not included

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

		Case	4[OP]		
		Material composition	Office paper		
		Sub-scenario	Recycling	Incineration	Landfilling
Material production	Virgin material				
		Material marginal: which?	Office paper	/	/
		Electricity marginal: which?	US average	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	Office paper	/	/
		Electricity marginal: which?	/	fossil	fossil
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	closed loop	/	/
		Alternative use of land/wood included?	No	/	/
		In which ratio does recycled material substitute virgin material?	0,66	/	/
Material disposal	General				
		Technology	USA	USA	USA
		Infrastructures taken into account?	/	/	/
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	/	Yes	Yes
		Produced energy substitutes heat?	/	No	No
		Avoided processes - credits	Electricity production	Paper production	Electricity production
		Material substitutes	Office paper	/	/
		Carbon sequestration issue taken into account?	Yes	No	No
	Waste characteristics				
		Heating value	/	13.6 million Btu per ton	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
		Efficiency	/	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon storage taken into account?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes
		Efficiency	/	/	/
		Carbon storage taken into account?	/	/	Yes

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

disposal stage only

1 short ton of material

	4[OP]		
	Recycling	Incineration	Landfilling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	-780	-170	530
Cumulative enerhy demand (MBtu/t)	-10,08	-2,13	0,01
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

Indicator not included (grey cells)

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

		Case	4[PB]		
		Material composition	Phonebooks		
		Sub-scenario	Recycling	Incineration	Landfilling
Material production	Virgin material				
		Material marginal: which?	Phonebooks	/	/
		Electricity marginal: which?	US average	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	Phonebooks	/	/
		Electricity marginal: which?	/	fossil	fossil
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	closed loop	/	/
		Alternative use of land/wood included?	No	/	/
		In which ratio does recycled material substitute virgin material?	0,71	/	/
Material disposal	General				
		Technology	USA	USA	USA
		Infrastructures taken into account?	/	/	/
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	/	Yes	Yes
		Produced energy substitutes heat?	/	No	No
		Avoided processes - credits	Electricity production	Paper production	Paper production
		Material substitutes	Phonebooks	/	/
		Carbon sequestration issue taken into account?	Yes	No	No
	Waste characteristics				
		Heating value	/	15.9 million Btu per ton	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
		Efficiency	/	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon storage taken into account?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes
		Efficiency	/	/	/
		Carbon storage taken into account?	/	/	Yes

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

disposal stage only

1 short ton of material

	4[PB]		
	Recycling	Incineration	Landfilling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	-720	-200	-240
Cumulative enerhy demand (MBtu/t)	-11,42	-2,54	0,42
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

[grey box] Indicator not included

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

		Case	4[TE]		
		Material composition	Textbooks		
		Sub-scenario	Recycling	Incineration	Landfilling
Material production	Virgin material				
		Material marginal: which?	Textbooks	/	/
		Electricity marginal: which?	US average	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	Textbooks	/	/
		Electricity marginal: which?	/	fossil	fossil
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	closed loop	/	/
		Alternative use of land/wood included?	No	/	/
		In which ratio does recycled material substitute virgin material?	0,69	/	/
Material disposal	General				
		Technology	USA	USA	USA
		Infrastructures taken into account?	/	/	/
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	/	Yes	Yes
		Produced energy substitutes heat?	/	No	No
		Avoided processes - credits	Electricity production	Electricity production	Paper production
		Material substitutes	Textbooks	/	/
		Carbon sequestration issue taken into account?	Yes	No	No
	Waste characteristics				
		Heating value	/	13.6 million Btu per ton	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
		Efficiency	/	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon storage taken into account?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes
		Efficiency	/	/	/
		Carbon storage taken into account?	/	/	Yes

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

disposal stage only

1 short ton of material

	4[TE]		
	Recycling	Incineration	Landfilling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	-850	-170	530
Cumulative enerhy demand (MBtu/t)	-0,53	-2,13	0,01
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

Indicator not included

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

		Case	4[MP]		
		Material composition	Mixed Paper		
		Sub-scenario	Recycling	Incineration	Landfilling
Material production	Virgin material				
		Material marginal: which?	Boxboard	/	/
		Electricity marginal: which?	US average	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	Boxboard	/	/
		Electricity marginal: which?	/	fossil	fossil
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	open loop	/	/
		Alternative use of land/wood included?	No	/	/
		In which ratio does recycled material substitute virgin material?	1	/	/
Material disposal	General				
		Technology	USA	USA	USA
		Infrastructures taken into account?	/	/	/
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	/	Yes	Yes
		Produced energy substitutes heat?	/	No	No
		Avoided processes - credits	Electricity production	Electricity production	Paper production
		Material substitutes	Boxboard	/	/
		Carbon sequestration issue taken into account?	Yes	No	No
	Waste characteristics				
		Heating value	/	14.1 million Btu per ton	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	No	No	No
		Efficiency	/	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon storage taken into account?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes
		Efficiency	/	/	/
		Carbon storage taken into account?	/	/	Yes

Paper & card - n°4

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

disposal stage only

1 short ton of material

	4[MP]		
	Recycling	Incineration	Landfilling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	-960	-180	90
Cumulative enerhy demand (MBtu/t)	-22,94	-2,22	0,24
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

Indicator not included

Paper & card - n°5

Title	Klimaregnskap for avfallshåndtering
Year	2009
Author	Raandal

		Landfill	Incineration	Recycling
	Case	5[PA]		
	Material composition	Paper		
	Sub-scenario	Landfill	Incineration	Recycling
Material production	Virgin material			
	Material marginal: which?	/	/	/
	Electricity marginal: which?	/	/	/
	Steam marginal: which?	/	/	/
	Co-products dealt with?	/	/	/
	Recovered material			
	Material marginal: which?	/	/	Paper
	Electricity marginal: which?	Scandinavian mix	Scandinavian mix	/
	Steam marginal: which?	Norwegian mix	Norwegian mix	/
	Co-products dealt with?	/	/	/
Material recovery	Material recovery included?	/	/	Yes
	Type of recycling	/	/	closed loop
	Alternative use of land/wood included?	/	/	/
	In which ratio does recycled material substitute virgin mate	/	/	0.81 or 0.85
Material disposal	General			
	Technology			
	Infrastructures taken into account?	/	/	/
	Transport included?	Yes	Yes	Yes
	Energy production			
	Produced energy substitutes electricity?	Yes	Yes	/
	Produced energy substitutes heat?	Yes	Yes	/
	Avoided processes - credits	energy production	energy production	paper production
	Material substitutes	/	/	paper
	Carbon sequestration issue taken into account?	No	No	No
	Waste characteristics			
	Heating value	/	15 MJ/kg	/
	Degradation rate (over 100 years)	/	/	/
	Incineration			
	Alternative use of incineration capacity included?	/	No	/
	Efficiency	/	/	/
	Composting			
	Compost spreading for composting taken into account?	/	/	/
	Compost leaching after spreading taken into account?	/	/	/
	Carbon storage taken into account?	/	/	/
	Landfill / AD			
	Methane emissions included?	Yes	/	/
	Efficiency	25% methane recovery, 38% used for electricity (35% conversion), 20% heat (64% conversion) and 42% flared	/	/
	Carbon storage taken into account?	/	/	/

Paper & card - n°5

Title	Klimaregnskap for avfallshåndtering
Year	2009
Author	Raandal

Impact assessment

Methodology IPCC

disposal stage only

Management of 1 kg of waste and associated transport and substitution of energy and/or material which is generated from waste management

	5[PA]		
	Landfill	Incineration	Recycling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	2,32	-0,37	-0,20
Cumulative enerhy demand (MBtu/t)			
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

Indicator not included

Paper & card - n°5

Title	Klimaregnskap for avfallshåndtering
Year	2009
Author	Raandal

		Case	5[MC]		
		Material composition	Cardboard		
		Sub-scenario	Landfill	Incineration	Recycling
Material production	Virgin material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	/	/	Paper and cardboard products
		Electricity marginal: which?	Scandinavian mix	Scandinavian mix	/
		Steam marginal: which?	Norwegian mix	Norwegian mix	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	/	/	Yes
		Type of recycling	/	/	open loop
		Alternative use of land/wood included?	/	/	/
		In which ratio does recycled material substitute virgin mate	/	/	1
Material disposal	General				
		Technology			
		Infrastructures taken into account?	/	/	/
		Transport included?	Yes	Yes	Yes
		Energy production			
		Produced energy substitutes electricity?	Yes	Yes	/
		Produced energy substitutes heat?	Yes	Yes	/
		Avoided processes - credits	energy production	energy production	cardboard production
		Material substitutes	/	/	cardboard products
		Carbon sequestration issue taken into account?	No	No	No
	Waste characteristics				
		Heating value	/	15 MJ/kg	/
		Degradation rate (over 100 years)	/	/	/
	Incineration				
		Alternative use of incineration capacity included?	/	No	/
		Efficiency	/	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Carbon storage taken into account?	/	/	/
	Landfill / AD				
		Methane emissions included?	Yes	/	/
		Efficiency	25% methane recovery, 38% used for electricity (35% conversion), 20% heat (64% conversion) and 42% flared	/	/
		Carbon storage taken into account?	/	/	/

Paper & card - n°5

Title	Klimaregnskap for avfallshåndtering
Year	2009
Author	Raandal

Impact assessment

Methodology IPCC

disposal stage only

Management of 1 kg of waste and associated transport and substitution of energy and/or material which is generated from waste management

	5[MC]		
	Landfill	Incineration	Recycling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	2,30	-0,36	-0,15
Cumulative enerhy demand (MBtu/t)			
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

Indicator not included

Appendix 3 Summary of key elements from the studies on plastics

Plastics- n°1

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

		Case	1[PE]		
		Material composition	100% HDPE		
		Sub-scenario	Incineration with energy recovery	Landfill	Recycling
Material production	Virgin material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	/	/	Yes
		Type of recycling	/	/	Mechanical recycling, closed-loop
		In which ratio does recycled material substitute virgin material?	/	/	1
Material disposal	General				
		Technology	cogeneration 1/2 humid 32% efficiency	captation of 50% of the biogas	grinding and granulation
		Infrastructures taken into account?	Yes	Yes	Yes
		Transport included?	not the transport for waste collection	not the transport for waste collection	not the transport for waste collection
		Energy production	Yes	Yes	No
		Produced energy substitutes electricity?	average France 2000	average France 2000	/
		Produced energy substitutes steam?	37,5% gas, 30,2% coal, 32,3% oil	No	/
		Avoided processes - credits	production of steel, aluminium and embankment	/	production of virgin HDPE
		Material substitutes	No	No	No
		Carbon sequestration issue taken into account?	/	/	/
	Waste characteristics				
		Heating value	18 MJ/kg	/	/
		Time period and degradation rate	/	100 years - 0% degradation	/
	Incineration				
		Alternative use of incineration capacity included?	No inf.	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill				
		Methane emissions included?	/	Yes	/

Plastics- n°1

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

Impact assessment

Methodology CML 2002

Included stages disposal stage only

Functional unit 1000 kg of material

	1[PE]		
	Incineration with energy recovery	Landfill	Recycling
Depletion of abiotic resources (kg Sb eq)	-6,83	3,94E-02	-19,87
Climate change (kg CO_2 eq)	1942	6,44	-920,84
Cumulative energy demand (MJ)*	-20646	106	-47981
Water consumption (m^3)			
Eutrophication (kg PO4 eq)	1,1	0,0126	-0,181
Acidification (kg SO2 eq)	-1,43	0,0433	-3,5
Photochemical oxidation (kg ethylene eq)	7,21	0,06	-1,61
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)	-35,8	0,51	-358,2
Ecotoxicity in water (kg 1,4-DB eq)	-23,22	0,0902	-2,91
Exoctoxicity in sediments (kg 1,4-DB eq)	-52,98	0,201	-6,83
Ecotoxicity in soil (kg 1,4-DB eq)	25,9	0,00391	-10,3

* the energy demand in this study corresponds to the consumption of non-renewable resources

(grey box) Indicator not included

Plastics- n°1

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

	Case	1[PET]			
	Material composition				
	Sub-scenario	Incineration with energy recovery	Landfill	Recycling
Material production	Virgin material			
	Material marginal: which?	/	/	/
	Electricity marginal: which?	/	/	/
	Steam marginal: which?	/	/	/
	Co-products dealt with?	/	/	/
	Recovered material			
	Material marginal: which?	/	/	/
	Electricity marginal: which?	/	/	/
	Steam marginal: which?	/	/	/
	Co-products dealt with?	/	/	/
Material recovery	Material recovery included?	/	/	/
	Type of recycling	/	/	Mechanical and chemical recycling, open and closed-loop
	In which ratio does recycled material substitute virgin material?	/	/	1
Material disposal	General			
	Technology	cogeneration 1/2 humid 32% efficiency	captation of 50% of the biogas	-regeneration - recycling in resin - recycling in filling material
	Infrastructures taken into account?	Yes	Yes	Yes
	Transport included?	not the transport for waste collection	not the transport for waste collection	not the transport for waste collection
	Energy production	Yes	Yes	No
	Produced energy substitutes electricity?	average France 2000	average France 2000	/
	Produced energy substitutes steam?	37,5% gas, 30,2% coal, 32,3% oil	No	/
	Avoided processes - credits	production of steel, aluminium and embankment	/	PET fibres, PET resin, PET
	Material substitutes	No	No	No
	Carbon sequestration issue taken into account?	/	/	/
	Waste characteristics			
	Heating value	22 MJ/kg	/	/
	Time period and degradation rate	/	100 years - 0% degardation	/
	Incineration			
	Alternative use of incineration capacity included?	No inf.	/	/
	Composting			
	Compost spreading for composting taken into account?	/	/	/
	Compost leaching after spreading taken into account?	/	/	/
	Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	No	/
	Landfill			
	Methane emissions included?	/	Yes	/

Plastics- n°1

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

Impact assessment

Methodology CML 2002

Included stages disposal stage only

Functional unit 1000 kg of material

	1[PET]		
	Incineration with energy recovery	Landfill	Recycling
Depletion of abiotic resources (kg Sb eq)	-3,95	3,94E-02	-20,78
Climate change (kg CO_2 eq)	1715	6,44	-1742,3
Cumulative energy demand (MJ)*	-11696	106	-54082
Water consumption (m^3)			
Eutrophication (kg PO4 eq)	0,65	0,0126	-1,34
Acidification (kg SO2 eq)	-0,78	0,0433	-24,28
Photochemical oxidation (kg ethylene eq)	4,27	0,06	-10,62
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)	-19,3	0,51	-408,27
Ecotoxicity in water (kg 1,4-DB eq)	-13,46	0,0902	-3,29
Exoctoxicity in sediments (kg 1,4-DB eq)	-30,7	0,201	-5,7
Ecotoxicity in soil (kg 1,4-DB eq)	15,24	0,00391	-10,8

* the energy demand in this study corresponds to the consumption of non-renewable resources

[grey box] Indicator not included

Plastics- n°2

Title	LCA of management options for mixed waste plastics
Year	2008
Author	Shonfield

		Case	2 [MIX]			
		Material composition	plastics mix (40% PP, 17% PET, 15% PE, 11% PVC, 6% PS, others)			
		Sub-scenario	Landfill	Incineration with energy recovery	Pyrolysis of PP and PE (+ recycling for PET and PVC)	Pyrolysis of PP, PE and PS (+ recycling for PET and PVC)
Material production	Virgin material					
		Material marginal: which?	/	/	No inf.	No inf.
		Electricity marginal: which?	/	/	average UK electricity mix	average UK electricity mix
		Steam marginal: which?	/	/	No inf.	No inf.
		Co-products dealt with?	/	/	No inf.	No inf.
	Recovered material					
		Material marginal: which?	/	/	No inf.	No inf.
		Electricity marginal: which?	/	/	average UK electricity mix	average UK electricity mix
		Steam marginal: which?	/	/	No inf.	No inf.
		Co-products dealt with?	/	/	No inf.	No inf.
Material recovery		Material recovery included?	/	/	Yes	Yes
		Type of recycling	/	/	Mechanical recycling, closed loop	Mechanical recycling, closed loop
		In which ratio does recycled material substitute virgin material?	/	/	1	1
Material disposal	General					
		Technology	landfill gas and leachate collection, leachate treatment	23% efficiency	Near-infrared sorting, BP polymer cracking process suitable for polyolefins	Near-infrared sorting, Ozmotech process
		Infrastructures taken into account?	No	No	No	No
		Transport included?	Yes	Yes	Yes	Yes
		Energy production	No	Yes	Yes	Yes
		Produced energy substitutes electricity?	/	gas-fired power plant	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues
		Produced energy substitutes steam?	/	No	No	No
		Avoided processes - credits	/	/	naphta, paraffin, refinery gas production for pyrolysis; virgin plastic production for recycling	diesel oil production for pyrolysis; virgin plastic production for recycling
		Material substitutes	/	/	/	/
		Carbon sequestration issue taken into account?	No sequestration	/	/	/
	Waste characteristics					
		Heating value	/	PE: 42,47 MJ/kg PP: 30,78 MJ/kg PET: 22,95 MJ/kg PS: 38,67 MJ/kg PVC: 21,51 MJ/kg	/	/
		Degradation rate (over 100 years)	No inf.	/	/	/
	Incineration					
		Alternative use of incineration capacity included?	/	No inf.	/	/
	Composting					
		Compost spreading for composting taken into account?	/	/	/	/
		Compost leaching after spreading taken into account?	/	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/	/
	Landfill					
		Methane emissions included?	Yes	/	/	/

Plastics- n°2

Title	LCA of management options for mixed waste plastics
Year	2008
Author	Shonfield

Impact assessment

Methodology CML 2001

Included stages disposal stage only
Functional unit 1000 kg of mixed plastic wastes arising from a materials recycling facility

	2 [MIX]			
	Landfill	Incineration with energy recovery	Pyrolysis of PP and PE (+ recycling for PET and PVC)	Pyrolysis of PP, PE and PS (+ recycling for PET and PVC)
Depletion of abiotic resources (kg Sb eq)	0,187	-5,49	-9,802	-10,16
Climate change (kg CO_2 eq)	159	1829	30	-61
Cumulative energy demand (MJ)	458	-12083	-18374	-18999
Water consumption (m^3)				
Eutrophication (kg PO4 eq)	1,053	0,045	-0,067	-0,359
Acidification (kg SO2 eq)	0,24	0,055	-1,68	-2,577
Photochemical oxidation (kg ethylene eq)	0,0148	-0,06	-0,3	-0,391
Ozone depletion (kg CFC-11 eq)	4,10E-06	-8,70E-05	-6,30E-05	-1,40E-04
Human toxicity (kg 1,4-DB eq)	1665,73	1350,05	573,09	577,54

Indicator not included

Plastics- n°2

Title	LCA of management options for mixed waste plastics
Year	2008
Author	Shonfield

	Case	2 [MIX]			
	Material composition	plastics mix (40% PP, 17% PET, 15% PE, 11% PVC, 6% PS, others)			
	Sub-scenario	Recycling of PE, PP, PET, PVC (residue: 84% to landfill, 16% to incineration)	Recycling of PE, PP, PET, PVC (residue: 84% to landfill, 16% to incineration)	Recycling of PE, PP, PET, PVC (residue: 84% to landfill, 16% to incineration)	Recycling of PE, PP, PET, PVC (residue: 84% to landfill, 16% to incineration)
Material production	Virgin material				
	Material marginal: which?	No inf.	No inf.	No inf.	No inf.
	Electricity marginal: which?	average UK electricity mix	average UK electricity mix	average UK electricity mix	average UK electricity mix
	Steam marginal: which?	No inf.	No inf.	No inf.	No inf.
	Co-products dealt with?	No inf.	No inf.	No inf.	No inf.
	Recovered material				
	Material marginal: which?	No inf.	No inf.	No inf.	No inf.
	Electricity marginal: which?	average UK electricity mix	average UK electricity mix	average UK electricity mix	average UK electricity mix
	Steam marginal: which?	No inf.	No inf.	No inf.	No inf.
	Co-products dealt with?	No inf.	No inf.	No inf.	No inf.
Material recovery	Material recovery included?	Yes	Yes	Yes	Yes
	Type of recycling	Mechanical recycling, closed loop	Mechanical recycling, closed loop	Mechanical recycling, closed loop	Mechanical recycling, closed loop
	In which ratio does recycled material substitute virgin material?	1	1	1	1
Material disposal	General				
	Technology	Near-infrared sorting, shredding, cleaning and extruding	Near-infrared sorting, shredding, cleaning and extruding	Near-infrared sorting, shredding, cleaning and extruding	Near-infrared sorting, shredding, cleaning and extruding
	Infrastructures taken into account?	No	No	No	No
	Transport included?	Yes	Yes	Yes	Yes
	Energy production	Yes	Yes	Yes	Yes
	Produced energy substitutes electricity?	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues
	Produced energy substitutes steam?	No	No	No	No
	Avoided processes - credits	virgin plastic production	virgin plastic production	virgin plastic production	virgin plastic production
	Material substitutes	/	/	/	/
	Carbon sequestration issue taken into account?	/	/	/	/
	Waste characteristics				
	Heating value	/	/	/	/
	Degradation rate (over 100 years)	/	/	/	/
	Incineration				
	Alternative use of incineration capacity included?	/	/	/	/
	Composting				
	Compost spreading for composting taken into account?	/	/	/	/
	Compost leaching after spreading taken into account?	/	/	/	/
	Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/	/
	Landfill				
	Methane emissions included?	/	/	/	/

Plastics- n°2

Title	LCA of management options for mixed waste plastics
Year	2008
Author	Shonfield

Impact assessment

Methodology CML 2001

Included stages disposal stage only

Functional unit 1000 kg of mixed plastic wastes arising from a materials recycling facility

	2 [MIX]			
	Recycling of PE, PP, PET, PVC (residue: 84% to landfill, 16% to incineration)	Recycling of PE, PP, PET, PVC (residue: 84% to landfill, 16% to incineration)	Recycling of PE, PP, PET, PVC (residue: 84% to landfill, 16% to incineration)	Recycling of PE, PP, PET, PVC (residue: 84% to landfill, 16% to incineration)
Depletion of abiotic resources (kg Sb eq)	-14,667	-13,698	-12,41	-13,01
Climate change (kg CO_2 eq)	-620	-556	-458	-492
Cumulative energy demand (MJ)	-12897	-12441	-11403	-11472
Water consumption (m^3)				
Eutrophication (kg PO4 eq)	-0,281	-0,221	-0,111	-0,142
Acidification (kg SO2 eq)	-7,875	-7,243	-6,499	-6,914
Photochemical oxidation (kg ethylene eq)	-0,855	-0,784	-0,712	-0,751
Ozone depletion (kg CFC-11 eq)	-1,00E-05	-1,20E-05	-1,10E-05	-1,00E-05
Human toxicity (kg 1,4-DB eq)	608,17	685,12	777,13	725,51

Indicator not included

Plastics- n°2

Title	LCA of management options for mixed waste plastics
Year	2008
Author	Shonfield

		Case	2 [MIX]			
		Material composition	plastics mix (40% PP, 17% PET, 15% PE, 11% PVC, 6% PS, others)			
		Sub-scenario	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)
Material production	Virgin material					
		Material marginal: which?	No inf.	No inf.	No inf.	No inf.
		Electricity marginal: which?	average UK electricity mix	average UK electricity mix	average UK electricity mix	average UK electricity mix
		Steam marginal: which?	No inf.	No inf.	No inf.	No inf.
		Co-products dealt with?	No inf.	No inf.	No inf.	No inf.
	Recovered material					
		Material marginal: which?	No inf.	No inf.	No inf.	No inf.
		Electricity marginal: which?	average UK electricity mix	average UK electricity mix	average UK electricity mix	average UK electricity mix
		Steam marginal: which?	No inf.	No inf.	No inf.	No inf.
		Co-products dealt with?	No inf.	No inf.	No inf.	No inf.
Material recovery		Material recovery included?	Yes	Yes	Yes	Yes
		Type of recycling	Mechanical recycling, closed loop	Mechanical recycling, closed loop	Mechanical recycling, closed loop	Mechanical recycling, closed loop
		In which ratio does recycled material substitute virgin material?	1	1	1	1
Material disposal	General					
		Technology	Density separation, shredding, cleaning and extruding	Pre-treatment, cleaning, extruding	Pre-treatment, cleaning, extruding	Density separation, shredding, cleaning and extruding
		Infrastructures taken into account?	No	No	No	No
		Transport included?	Yes	Yes	Yes	Yes
		Energy production	Yes	Yes	Yes	Yes
		Produced energy substitutes electricity?	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues
		Produced energy substitutes steam?	No	No	No	No
		Avoided processes - credits	virgin plastic production	virgin plastic production	virgin plastic production	virgin plastic production
		Material substitutes	/	/	/	/
		Carbon sequestration issue taken into account?	/	/	/	/
	Waste characteristics					
		Heating value	/	/	/	/
		Degradation rate (over 100 years)	/	/	/	/
	Incineration					
		Alternative use of incineration capacity included?	/	/	/	/
	Composting					
		Compost spreading for composting taken into account?	/	/	/	/
		Compost leaching after spreading taken into account?	/	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/	/
	Landfill					
		Methane emissions included?	/	/	/	/

Plastics- n°2

Title	LCA of management options for mixed waste plastics
Year	2008
Author	Shonfield

Impact assessment

Methodology CML 2001

Included stages disposal stage only
Functional unit 1000 kg of mixed plastic wastes arising from a materials recycling facility

	2 [MIX]			
	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)
Depletion of abiotic resources (kg Sb eq)	-13,74	-16,43	-13,46	-12,55
Climate change (kg CO_2 eq)	-464	-631	-397	-300
Cumulative energy demand (MJ)	-9753	-10758	-7782	-6076
Water consumption (m^3)				
Eutrophication (kg PO4 eq)	0,152	-0,013	0,156	0,201
Acidification (kg SO2 eq)	-8,271	-10,087	-8,213	-7,694
Photochemical oxidation (kg ethylene eq)	-1,291	-1,585	-1,314	-1,253
Ozone depletion (kg CFC-11 eq)	-6,10E-07	1,50E-06	1,90E-06	3,00E-06
Human toxicity (kg 1,4-DB eq)	652,02	438,57	627,51	668,16

Indicator not included

Plastics- n°2

Title	LCA of management options for mixed waste plastics
Year	2008
Author	Shonfield

	Case	2 [MIX]				
	Material composition	plastics mix (40% PP, 17% PET, 15% PE, 11% PVC, 6% PS, others)				
	Sub-scenario	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)
Material production	Virgin material					
	Material marginal: which?	No inf.	No inf.	No inf.	No inf.	No inf.
	Electricity marginal: which?	average UK electricity mix	average UK electricity mix	average UK electricity mix	average UK electricity mix	average UK electricity mix
	Steam marginal: which?	No inf.	No inf.	No inf.	No inf.	No inf.
	Co-products dealt with?	No inf.	No inf.	No inf.	No inf.	No inf.
	Recovered material					
	Material marginal: which?	No inf.	No inf.	No inf.	No inf.	No inf.
	Electricity marginal: which?	average UK electricity mix	average UK electricity mix	average UK electricity mix	average UK electricity mix	average UK electricity mix
	Steam marginal: which?	No inf.	No inf.	No inf.	No inf.	No inf.
	Co-products dealt with?	No inf.	No inf.	No inf.	No inf.	No inf.
Material recovery	Material recovery included?	Yes	Yes	Yes	Yes	Yes
	Type of recycling	Mechanical recycling, closed loop	Mechanical recycling, closed loop	Mechanical recycling, closed loop	Mechanical recycling, closed loop	Mechanical recycling, closed loop
	In which ratio does recycled material substitute virgin material?	1	1	1	1	1
Material disposal	General					
	Technology	Density separation, shredding, cleaning and extruding	Pre-treatment, cleaning, extruding	Pre-treatment, cleaning, extruding	Density separation, shredding, cleaning and extruding	Density separation, shredding, cleaning and extruding
	Infrastructures taken into account?	No	No	No	No	No
	Transport included?	Yes	Yes	Yes	Yes	Yes
	Energy production	Yes	Yes	Yes	Yes	Yes
	Produced energy substitutes electricity?	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues	gas-fired power plant for the incineration of residues
	Produced energy substitutes steam?	No	No	No	No	No
	Avoided processes - credits	virgin plastic production	virgin plastic production	virgin plastic production	virgin plastic production	virgin plastic production
	Material substitutes	/	/	/	/	/
	Carbon sequestration issue taken into account?	/	/	/	/	/
	Waste characteristics					
	Heating value	/	/	/	/	/
	Degradation rate (over 100 years)	/	/	/	/	/
	Incineration					
	Alternative use of incineration capacity included?	/	/	/	/	/
	Composting					
	Compost spreading for composting taken into account?	/	/	/	/	/
	Compost leaching after spreading taken into account?	/	/	/	/	/
	Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/	/	/
	Landfill					
	Methane emissions included?	/	/	/	/	/

Plastics- n°2

Title	LCA of management options for mixed waste plastics
Year	2008
Author	Shonfield

Impact assessment

Methodology CML 2001

Included stages	disposal stage only
Functional unit	1000 kg of mixed plastic wastes arising from a materials recycling facility

	2 [MIX]				
	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)	Recycling of PE and PP(residue: 84% to landfill, 16% to incineration)
Depletion of abiotic resources (kg Sb eq)	-13,74	-16,43	-13,46	-12,55	-13,63
Climate change (kg CO_2 eq)	-464	-631	-397	-300	-434
Cumulative energy demand (MJ)	-9753	-10758	-7782	-6076	-8897
Water consumption (m^3)					
Eutrophication (kg PO4 eq)	0,152	-0,013	0,156	0,201	0,153
Acidification (kg SO2 eq)	-8,271	-10,087	-8,213	-7,694	-8,254
Photochemical oxidation (kg ethylene eq)	-1,291	-1,585	-1,314	-1,253	-1,302
Ozone depletion (kg CFC-11 eq)	-6,10E-07	1,50E-06	1,90E-06	3,00E-06	5,00E-07
Human toxicity (kg 1,4-DB eq)	652,02	438,57	627,51	668,16	641,18

Indicator not included

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

		Case	3[PE]		
		Material composition	PE		
		Sub-scenario	recycling (40% of plastics rejected and incinerated)	incineration	landfill
Material production	Virgin material				
		Material marginal: which?	No inf.	/	/
		Electricity marginal: which?	European mix	/	/
		Steam marginal: which?	No inf.	/	/
		Co-products dealt with?	No inf.	/	/
	Recovered material				
		Material marginal: which?	No inf.	/	/
		Electricity marginal: which?	coal power plants	/	/
		Steam marginal: which?	No inf.	/	/
		Co-products dealt with?	No inf.	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	Mechanical recycling, closed loop	/	/
		In which ratio does recycled material substitute virgin material?	1	/	/
Material disposal	General				
		Technology	sorting, washing and conversion to PE granules	modern technology with flue gas condensation	captation of 50% of the biogas, treatment of 80% of the leakage water
		Infrastructures taken into account?	No	No	No
		Transport included?	Yes	Yes	Yes
		Energy production	No	Yes, used for district heating	Yes, 60% heat, 30% electricity, 10% lost
		Produced energy substitutes electricity?	/	No (except that the gas from the landfill of ashes is used to produce electricity)	electricity from coal
		Produced energy substitutes steam?	/	replaces heat from forest residues	replaces heat from forest residues
		Avoided processes - credits	replaces same plastic types produced from virgin raw materials	/	/
		Material substitutes	HDPE	HDPE	HDPE
		Carbon sequestration issue taken into account?	/	/	No sequestration
	Waste characteristics				
		Heating value	/	46 MJ/ton	/
		Degradation rate	/	/	full degradation (hypothetical infinite time period)
	Incineration				
		Alternative use of incineration capacity included?	/	No inf.	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

Impact assessment

Methodology EDIP

Included stages disposal stage only

Functional unit 1 ton of waste

	3[PE]		
	recycling	incineration	landfill
Depletion of abiotic resources (MJ)	-4,5E+04	-4,1E+02	-1,5E+02
Climate change (kg CO_2 eq)	2,7E+02	3,0E+03	3,2E+03
Cumulative energy demand (MJ)	-5,5E+04	-4,0E+04	-1,5E+04
Water consumption (m^3)			
Eutrophication (**kg O2 eq**)*	5,2E+01	2,5E+01	5,1E-01
Acidification (kg SO2 eq)**	-4,7E-03	-1,8E-01	-4,2E-03
Photochemical oxidation (kg ethylene eq)	-5,5E+00	-8,5E-01	2,0E-01
Ozone depletion (kg CFC-11 eq)			
Human toxicity (**SEK/year**)	-3,0E+03	-5,9E+02	8,7E+01
Ecotoxicity (**SEK/year**)	-5,1E+01	-3,6E+01	9,1E+00

* Aquatic eutrophcation excl Nox

** Acidification (excl Sox and Nox)

[grey box] Indicator not included

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

		Case	3[PP]		
		Material composition	PP		
		Sub-scenario	recycling (40% of plastics rejected and incinerated)	incineration	landfill
Material production	Virgin material				
		Material marginal: which?	No inf.	/	/
		Electricity marginal: which?	electricity mix	/	/
		Steam marginal: which?	No inf.	/	/
		Co-products dealt with?	No inf.	/	/
	Recovered material				
		Material marginal: which?	No inf.	/	/
		Electricity marginal: which?	coal power plants	/	/
		Steam marginal: which?	No inf.	/	/
		Co-products dealt with?	No inf.	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	Mechanical recycling, closed loop	/	/
		In which ratio does recycled material substitute virgin material?	1	/	/
Material disposal	General				
		Technology	based on PET and HDPE data	modern technology with flue gas condensation	captation of 50% of the biogas, treatment of 80% of the leakage water
		Infrastructures taken into account?	No	No	No
		Transport included?	Yes	Yes	Yes
		Energy production	No	Yes, used for district heating	Yes, 60% heat, 30% electricity, 10% lost
		Produced energy substitutes electricity?	/	No (except that the gas from the landfill of ashes is used to produce electricity)	electricity from coal
		Produced energy substitutes steam?	/	replaces heat from forest residues	replaces heat from forest residues
		Avoided processes - credits	replaces same plastic types produced from virgin raw materials	/	/
		Material substitutes	/	HDPE	HDPE
		Carbon sequestration issue taken into account?	/	/	No sequestration
	Waste characteristics				
		Heating value	/	46,5 MJ/ton	/
		Degradation rate	/	/	full degradation (hypothetical infinite time period)
	Incineration				
		Alternative use of incineration capacity included?	/	No inf.	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

Impact assessment

Methodology EDIP

Included stages disposal stage only

Functional unit 1 ton of waste

	3[PP]		
	recycling	incineration	landfill
Depletion of abiotic resources (MJ)	-3,3E+05	-3,1E+03	-1,1E+03
Climate change (kg CO_2 eq)	2,0E+03	2,2E+04	2,4E+04
Cumulative energy demand (MJ)	-4,1E+05	-2,9E+05	-1,1E+05
Water consumption (m^3)			
Eutrophication (**kg O2 eq**)*	3,9E+02	1,8E+02	3,8E+00
Acidification (kg SO2 eq)**	-3,5E-02	-1,3E+00	-3,2E-02
Photochemical oxidation (kg ethylene eq)	-4,1E+01	-6,3E+00	1,5E+00
Ozone depletion (kg CFC-11 eq)			
Human toxicity (**SEK/year**)	-2,3E+04	-4,4E+03	6,4E+02
Ecotoxicity (**SEK/year**)	-3,8E+02	-2,7E+02	6,8E+01

* Aquatic eutrophcation excl Nox

** Acidification (excl Sox and Nox)

[grey box] Indicator not included

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

		Case	3[PS]		
		Material composition	PS		
		Sub-scenario	recycling (40% of plastics rejected and incinerated)	incineration	landfill
Material production	Virgin material				
		Material marginal: which?	No inf.	/	/
		Electricity marginal: which?	electricity mix	/	/
		Steam marginal: which?	No inf.	/	/
		Co-products dealt with?	No inf.	/	/
	Recovered material				
		Material marginal: which?	No inf.	/	/
		Electricity marginal: which?	coal power plants	/	/
		Steam marginal: which?	No inf.	/	/
		Co-products dealt with?	No inf.	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	Mechanical recycling, closed loop	/	/
		In which ratio does recycled material substitute virgin material?	1	/	/
Material disposal	General				
		Technology	sorting, washing and conversion to PE granules	modern technology with flue gas condensation	captation of 50% of the biogas, treatment of 80% of the leakage water
		Infrastructures taken into account?	No	No	No
		Transport included?	Yes	Yes	Yes
		Energy production	No	Yes, used for district heating	Yes, 60% heat, 30% electricity, 10% lost
		Produced energy substitutes electricity?	/	No (except that the gas from the landfill of ashes is used to produce electricity)	electricity from coal
		Produced energy substitutes steam?	/	replaces heat from forest residues	replaces heat from forest residues
		Avoided processes - credits	replaces same plastic types produced from virgin raw materials	/	/
		Material substitutes	/	HDPE	HDPE
		Carbon sequestration issue taken into account?	/	/	No sequestration
	Waste characteristics				
		Heating value	/	40,6 MJ/ton	/
		Degradation rate	/	/	full degradation (hypothetical infinite time period)
	Incineration				
		Alternative use of incineration capacity included?	/	No inf.	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

Impact assessment

Methodology EDIP

Included stages disposal stage only

Functional unit 1 ton of waste

	3[PS]		
	recycling	incineration	landfill
Depletion of abiotic resources (MJ)	-4,2E+05	-3,9E+03	-1,4E+03
Climate change (kg CO_2 eq)	2,6E+03	2,8E+04	3,0E+04
Cumulative energy demand (MJ)	-5,2E+05	-3,7E+05	-1,4E+05
Water consumption (m^3)			
Eutrophication (**kg O2 eq**)*	4,9E+02	2,3E+02	4,7E+00
Acidification (kg SO2 eq)**	-4,4E-02	-1,7E+00	-4,0E-02
Photochemical oxidation (kg ethylene eq)	-5,2E+01	-7,9E+00	1,9E+00
Ozone depletion (kg CFC-11 eq)			
Human toxicity (**SEK/year**)	-2,8E+04	-5,5E+03	8,1E+02
Ecotoxicity (**SEK/year**)	-4,7E+02	-3,4E+02	8,5E+01

* Aquatic eutrophcation excl Nox

** Acidification (excl Sox and Nox)

[grey box] Indicator not included

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

	Case	3[PET]		
	Material composition	PET		
	Sub-scenario	recycling (40% of plastics rejected and incinerated)	incineration	landfill
Material production	Virgin material			
	Material marginal: which?	No inf.	/	/
	Electricity marginal: which?	electricity mix	/	/
	Steam marginal: which?	No inf.	/	/
	Co-products dealt with?	No inf.	/	/
	Recovered material			
	Material marginal: which?	No inf.	/	/
	Electricity marginal: which?	coal power plants	/	/
	Steam marginal: which?	No inf.	/	/
	Co-products dealt with?	No inf.	/	/
Material recovery	Material recovery included?	Yes	/	/
	Type of recycling	Mechanical recycling, closed loop	/	/
	In which ratio does recycled material substitute virgin material?	1	/	/
Material disposal	General			
	Technology	baling of bottles and conversion to PET resin	modern technology with flue gas condensation	captation of 50% of the biogas, treatment of 80% of the leakage water
	Infrastructures taken into account?	No	No	No
	Transport included?	Yes	Yes	Yes
	Energy production	No	Yes, used for district heating	Yes, 60% heat, 30% electricity, 10% lost
	Produced energy substitutes electricity?	/	No (except that the gas from the landfill of ashes is used to produce electricity)	electricity from coal
	Produced energy substitutes steam?	avoids virgin PET production	replaces heat from forest residues	replaces heat from forest residues
	Avoided processes - credits	replaces same plastic types produced from virgin raw materials	/	/
	Material substitutes	/	HDPE	HDPE
	Carbon sequestration issue taken into account?	/	/	No sequestration
	Waste characteristics			
	Heating value	/	29 MJ/ton	/
	Degradation rate	/	/	full degradation (hypothetical infinite time period)
	Incineration			
	Alternative use of incineration capacity included?	/	No inf.	/
	Composting			
	Compost spreading for composting taken into account?	/	/	/
	Compost leaching after spreading taken into account?	/	/	/
	Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill			
	Methane emissions included?	/	/	Yes

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

Impact assessment

Methodology EDIP

Included stages disposal stage only

Functional unit 1 ton of waste

	3[PET]		
	recycling	incineration	landfill
Depletion of abiotic resources (MJ)	-8,3E+05	-7,7E+03	-2,8E+03
Climate change (kg CO_2 eq)	5,1E+03	5,6E+04	6,0E+04
Cumulative energy demand (MJ)	-1,0E+06	-7,4E+05	-2,7E+05
Water consumption (m^3)			
Eutrophication (**kg O2 eq**)*	9,7E+02	4,6E+02	9,4E+00
Acidification (kg SO2 eq)**	-8,8E-02	-3,3E+00	-7,9E-02
Photochemical oxidation (kg ethylene eq)	-1,0E+02	-1,6E+01	3,7E+00
Ozone depletion (kg CFC-11 eq)			
Human toxicity (**SEK/year**)	-5,7E+04	-1,1E+04	1,6E+03
Ecotoxicity (**SEK/year**)	-9,4E+02	-6,7E+02	1,7E+02

* Aquatic eutrophcation excl Nox

** Acidification (excl Sox and Nox)

[grey box] Indicator not included

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

		Case	3[PVC]		
		Material composition	PVC		
		Sub-scenario	recycling (40% of plastics rejected and incinerated)	incineration	landfill
Material production	Virgin material				
		Material marginal: which?	No inf.	/	/
		Electricity marginal: which?	electricity mix	/	/
		Steam marginal: which?	No inf.	/	/
		Co-products dealt with?	No inf.	/	/
	Recovered material				
		Material marginal: which?	No inf.	/	/
		Electricity marginal: which?	coal power plants	/	/
		Steam marginal: which?	No inf.	/	/
		Co-products dealt with?	No inf.	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	Mechanical recycling, closed loop	/	/
		In which ratio does recycled material substitute virgin material?	1	/	/
Material disposal	General				
		Technology	based on PET and HDPE data	modern technology with flue gas condensation	captation of 50% of the biogas, treatment of 80% of the leakage water
		Infrastructures taken into account?	No	No	No
		Transport included?	Yes	Yes	Yes
		Energy production	No	Yes, used for district heating	Yes, 60% heat, 30% electricity, 10% lost
		Produced energy substitutes electricity?	/	No (except that the gas from the landfill of ashes is used to produce electricity)	electricity from coal
		Produced energy substitutes steam?	/	replaces heat from forest residues	replaces heat from forest residues
		Avoided processes - credits	replaces same plastic types produced from virgin raw materials	/	/
		Material substitutes	/	HDPE	HDPE
		Carbon sequestration issue taken into account?	/	/	No sequestration
	Waste characteristics				
		Heating value	/	21 MJ/PVC	/
		Degradation rate	/	/	full degradation (hypothetical infinite time period)
	Incineration				
		Alternative use of incineration capacity included?	/	No inf.	/
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill				
		Methane emissions included?	/	/	Yes

Plastics- n°3

Title	Life Cycle Assessment of energy from solid waste
Year	2000
Author	Finnveden

Impact assessment

Methodology EDIP

Included stages disposal stage only

Functional unit 1 ton of waste

	3[PVC]		
	recycling	incineration	landfill
Depletion of abiotic resources (MJ)	-1,1E+06	-1,0E+04	-3,7E+03
Climate change (kg CO_2 eq)	6,7E+03	7,3E+04	7,9E+04
Cumulative energy demand (MJ)	-1,3E+06	-9,6E+05	-3,6E+05
Water consumption (m^3)			
Eutrophication (**kg O2 eq**)*	1,3E+03	6,0E+02	1,2E+01
Acidification (kg SO2 eq)**	-1,2E-01	-4,3E+00	-1,0E-01
Photochemical oxidation (kg ethylene eq)	-1,4E+02	-2,1E+01	4,9E+00
Ozone depletion (kg CFC-11 eq)			
Human toxicity (**SEK/year**)	-7,4E+04	-1,4E+04	2,1E+03
Ecotoxicity (**SEK/year**)	-1,2E+03	-8,7E+02	2,2E+02

* Aquatic eutrophcation excl Nox

** Acidification (excl Sox and Nox)

(grey box) Indicator not included

Plastics- n°4

Title	A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes
Year	2005
Author	Perugini

		Case	4[MIX]			
		Material composition	mix of PE/PET			
		Sub-scenario	Landfill	Incineration with energy recovery	Recycling	Pyrolysis
Material production	Virgin material					
		Material marginal: which?	/	/	No inf.	No inf.
		Electricity marginal: which?	/	/	No inf.	No inf.
		Steam marginal: which?	/	/	No inf.	No inf.
		Co-products dealt with?	/	/	No inf.	No inf.
	Recovered material					
		Material marginal: which?	/	/	No inf.	No inf.
		Electricity marginal: which?	/	/	No inf.	No inf.
		Steam marginal: which?	/	/	No inf.	No inf.
		Co-products dealt with?	/	/	No inf.	No inf.
Material recovery		Material recovery included?	/	/	Yes	Yes for the PET fraction
		Type of recycling	/	/	Mechanical recycling, closed loop	Mechanical recycling, closed loop
		In which ratio does recycled material substitute virgin material?	/	/	1	1
Material disposal	General					
		Technology	No inf.	electric efficiciency of 25%	No inf.	bubbling fluidized bed reactor where a low-temperature cracking reaction takes place
		Infrastructures taken into account?	No inf.	No inf.	No inf.	No inf.
		Transport included?	Yes	Yes	Yes	Yes
		Energy production	No	Yes	Yes, from the incineration of scraps	Yes, from the incineration of scraps
		Produced energy substitutes electricity?	/	Italian grid	Italian grid	Italian grid
		Produced energy substitutes steam?	/	No	No	No
		Avoided processes - credits	No	/	production of virgin PET and PE	credits from petrochemical products resulting from pyrolysis (atmospheric residues, C3/C4 compounds, naphta)
		Material substitutes	/	/	/	/
		Carbon sequestration issue taken into account?	/	/	/	/
	Waste characteristics					
		Heating value	/	27 MJ/kg		
		Degradation rate (over 100 years)	No degradation	/		
	Incineration					
		Alternative use of incineration capacity included?	/	/	/	/
	Composting					
		Compost spreading for composting taken into account?	/	/	/	/
		Compost leaching after spreading taken into account?	/	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/	/
	Landfill					
		Methane emissions included?	No	/	/	/

Plastics- n°4

Title	A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes
Year	2005
Author	Perugini

Impact assessment

Methodology CML 2002

Included stages	disposal stage only
Functional unit	disposal of 2,35 kg of plastic waste and production of 1 kg of PET flakes and 0,39 kg of PE flakes

	4[MIX]			
	Landfill	Incineration with energy recovery	Recycling	Pyrolysis
Depletion of abiotic resources (kg Sb eq)				
Climate change (kg CO_2 eq)	5,31	7,31	1,37	1,73
Cumulative energy demand (MJ)	51,59	6,45	-5,41	12,14
Water consumption (m^3)	47,11	45,92	3,48	14,06
Eutrophication (kg PO4 eq)				
Acidification (kg SO2 eq)				
Photochemical oxidation (kg ethylene eq)				
Ozone depletion (kg CFC-11 eq)				
Human toxicity (kg 1,4-DB eq)				
Crude oil consumption (g)	1462	995	-74,76	-145,86
Air emissions of organic compounds (g)	26,8	14,3	-0,05	1,42
Waste production (kg)	2,49	0,19	0,09	0,2

Indicator not included

Plastics- n°5

Title	LCA: a tool for evaluating and comparing different treatment options for plastic wastes from old television sets
Year	2007
Author	Dodbiba

		Case	5[MIX]	
		Material composition	mix of PE/PS/PVC	
		Sub-scenario	Incineration with energy recovery	Recycling (33% residue incinerated)
Material production	Virgin material			
		Material marginal: which?	No inf.	No inf.
		Electricity marginal: which?	Japanese electricity mix	Japanese electricity mix
		Steam marginal: which?	No inf.	No inf.
		Co-products dealt with?	No inf.	No inf.
	Recovered material			
		Material marginal: which?	No inf.	No inf.
		Electricity marginal: which?	Japanese electricity mix	Japanese electricity mix
		Steam marginal: which?	No inf.	No inf.
		Co-products dealt with?	No inf,	No inf.
Material recovery		Material recovery included?	No	Yes
		Type of recycling	/	Mechanical recycling, closed loop
		In which ratio does recycled material substitute virgin material?	/	No inf.
Material disposal	General			
		Technology	15% efficiency	separation (triboelectric separation and air tabling)
		Infrastructures taken into account?	No inf,	No inf.
		Transport included?	No	No
		Energy production	Yes	Yes for the residue
		Produced energy substitutes electricity?	Japanese electricity mix	Japanese electricity mix
		Produced energy substitutes steam?	No	No
		Avoided processes - credits	/	avoided plastic production
		Material substitutes	/	/
		Carbon sequestration issue taken into account?	/	/
	Waste characteristics			
		Heating value	PS: 40,24 KJ/kg PVC: 18,02 kJ/kg PE: 46,68 kJ/kg	/
		Degradation rate (over 100 years)	/	/
	Incineration			
		Alternative use of incineration capacity included?	/	/
	Composting			
		Compost spreading for composting taken into account?	/	/
		Compost leaching after spreading taken into account?	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/
	Landfill			
		Methane emissions included?	/	/

Plastics- n°5

Title	LCA: a tool for evaluating and comparing different treatment options for plastic wastes from old television sets
Year	2007
Author	Dodbiba

Impact assessment

Methodology CML 2002

Included stages full life cycle

Functional unit 10 years use of color TV sets

	5[MIX]	
	Incineration with energy recovery	Recycling (33% residue incinerated)
Depletion of abiotic resources (kg Sb eq)	1,14E+06	6,98E+05
Climate change (kg CO_2 eq)	4,52E+08	3,35E+08
Cumulative energy demand (MJ)		
Water consumption (m^3)		
Eutrophication (kg PO4 eq)		
Acidification (kg SO2 eq)		
Photochemical oxidation (kg ethylene eq)		
Ozone depletion (kg CFC-11 eq)		
Human toxicity (kg 1,4-DB eq)		
Crude oil consumption (g)		
Air emissions of organic compounds (g)		
Waste production (kg)		

Indicator not included

Plastics- n°6

Title	Solid Waste Management and Greenhouse Gases
Year	2006
Author	US EPA

	Case	6[HDPE]		
	Material composition	HDPE		
	Sub-scenario	Recycling	Incineration with energy recovery	Landfill
Material production	Virgin material			
	Material marginal: which?	No inf.	No inf.	No inf.
	Electricity marginal: which?	US average grid mix	US average grid mix	US average grid mix
	Steam marginal: which?	No inf.	No inf.	No inf.
	Co-products dealt with?	No	No	No
	Recovered material			
	Material marginal: which?	No inf.	/	/
	Electricity marginal: which?	US average fossil fuel mix	/	/
	Steam marginal: which?	No inf.	/	/
	Co-products dealt with?	No	/	/
Material recovery	Material recovery included?	Yes	/	/
	Type of recycling	Mechanical closed-loop recycling	/	/
	In which ratio does recycled material substitute virgin material?	1	/	/
Material disposal	General			
	Technology	National average	National average	National average
	Infrastructures taken into account?	No inf.	No inf.	No inf.
	Transport included?	Yes	Yes	Yes
	Energy production	No	Yes	Yes, for the proportion of US landfills with energy recovery
	Produced energy substitutes electricity?	/	Yes, US average grid mix	Yes, US average grid mix
	Produced energy substitutes steam?	/	No	No
	Avoided processes - credits	virgin HDPE production	/	/
	Material substitutes	/	/	/
	Carbon sequestration issue taken into account?	/	HDPE 84% carbon, 98% of carbon converted to CO2	/
	Waste characteristics			
	Heating value	/	18 687 BTU per pound	/
	Degradation rate (over 100 years)	/	/	
	Incineration			
	Alternative use of incineration capacity included?		No inf.	
	Composting			
	Compost spreading for composting taken into account?	/	/	/
	Compost leaching after spreading taken into account?	/	/	/
	Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill			
	Methane emissions included?	/	/	No methane emissions

Plastics- n°6

Title	Solid Waste Management and Greenhouse Gases
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

Included stages disposal stage only

Functional unit 1 short ton of material

	6[HDPE]		
	Recycling	Incineration with energy recovery	Landfill
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq)	-380	250	10
Cumulative energy demand (million BTU*)	-50,90	-6,37	0,53
Water consumption (m^3)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxidation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)			
Crude oil consumption (g)			
Air emissions of organic compounds (g)			
Waste production (kg)			

* 1 million BTU = 1055,056 MJ

(grey box) Indicator not included

Plastics- n°6

Title	Solid Waste Management and Greenhouse Gases
Year	2006
Author	US EPA

		Case	6[LDPE]		
		Material composition	LDPE		
		Sub-scenario	Recycling	Incineration with energy recovery	Landfill
Material production	Virgin material				
		Material marginal: which?	No inf.	No inf.	No inf.
		Electricity marginal: which?	US average grid mix	US average grid mix	US average grid mix
		Steam marginal: which?	No inf.	No inf.	No inf.
		Co-products dealt with?	No	No	No
	Recovered material				
		Material marginal: which?	No inf.	/	/
		Electricity marginal: which?	US average fossil fuel mix	/	/
		Steam marginal: which?	No inf.	/	/
		Co-products dealt with?	No	/	/
Material recovery		Material recovery included?	Yes	/	/
		Type of recycling	Mechanical closed-loop recycling	/	/
		In which ratio does recycled material substitute virgin material?	1	/	/
Material disposal	General				
		Technology	National average	National average	National average
		Infrastructures taken into account?	No inf.	No inf.	No inf.
		Transport included?	Yes	Yes	Yes
		Energy production	No	Yes	Yes, for the proportion of US landfills with energy recovery
		Produced energy substitutes electricity?	/	Yes, US average grid mix	Yes, US average grid mix
		Produced energy substitutes steam?	/	No	No
		Avoided processes - credits	virgin LDPE production	/	/
		Material substitutes	/	/	/
		Carbon sequestration issue taken into account?	/	LDPE 84% carbon, 98% of carbon converted to CO2	/
	Waste characteristics				
		Heating value	/	18 687 BTU per pound	/
		Degradation rate (over 100 years)	/	/	
	Incineration				
		Alternative use of incineration capacity included?			
	Composting				
		Compost spreading for composting taken into account?	/	/	/
		Compost leaching after spreading taken into account?	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill				
		Methane emissions included?	/	/	No methane emissions

Plastics- n°6

Title	Solid Waste Management and Greenhouse Gases
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

Included stages disposal stage only

Functional unit 1 short ton of material

	6[LDPE]		
	Recycling	Incineration with energy recovery	Landfill
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq)	-460	250	10
Cumulative energy demand (million BTU*)	-56,01	-6,37	0,53
Water consumption (m^3)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxidation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)			
Crude oil consumption (g)			
Air emissions of organic compounds (g)			
Waste production (kg)			

* 1 million BTU = 1055,056 MJ

Indicator not included

Plastics- n°6

Title	Solid Waste Management and Greenhouse Gases
Year	2006
Author	US EPA

	Case	6[PET]		
	Material composition	PET		
	Sub-scenario	Recycling	Incineration with energy recovery	Landfill
Material production	Virgin material			
	Material marginal: which?	No inf.	No inf.	No inf.
	Electricity marginal: which?	US average grid mix	US average grid mix	US average grid mix
	Steam marginal: which?	No inf.	No inf.	No inf.
	Co-products dealt with?	No	No	No
	Recovered material			
	Material marginal: which?	No inf.	/	/
	Electricity marginal: which?	US average fossil fuel mix	/	/
	Steam marginal: which?	No inf.	/	/
	Co-products dealt with?	No	/	/
Material recovery	Material recovery included?	Yes	/	/
	Type of recycling	Mechanical closed-loop recycling	/	/
	In which ratio does recycled material substitute virgin material?	1	/	/
Material disposal	General			
	Technology	National average	National average	National average
	Infrastructures taken into account?	No inf.	No inf.	No inf.
	Transport included?	Yes	Yes	Yes
	Energy production	No	Yes	Yes, for the proportion of US landfills with energy recovery
	Produced energy substitutes electricity?	/	Yes, US average grid mix	Yes, US average grid mix
	Produced energy substitutes steam?	/	No	No
	Avoided processes - credits	virgin PET production	/	/
	Material substitutes	/	/	/
	Carbon sequestration issue taken into account?	/	PET 57% carbon, 98% of carbon converted to CO2	/
	Waste characteristics			
	Heating value	/	9 702 BTU per pound	/
	Degradation rate (over 100 years)	/	/	
	Incineration			
	Alternative use of incineration capacity included?			
	Composting			
	Compost spreading for composting taken into account?	/	/	/
	Compost leaching after spreading taken into account?	/	/	/
	Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/
	Landfill			
	Methane emissions included?	/	/	No methane emissions

Plastics- n°6

Title	Solid Waste Management and Greenhouse Gases
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

Included stages disposal stage only

Functional unit 1 short ton of material

	6[PET]		
	Recycling	Incineration with energy recovery	Landfill
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq)	-420	300	10
Cumulative energy demand (million BTU*)	-52,83	-3,16	#REF!
Water consumption (m^3)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxidation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)			
Crude oil consumption (g)			
Air emissions of organic compounds (g)			
Waste production (kg)			

* 1 million BTU = 1055,056 MJ

(grey box) Indicator not included

Plastics- n°7

Title	Report for Life Cycle Assessment for paper and packaging waste management scenarios in Victoria
Year	2001
Author	Grant

		Case	7[PET]	
		Material composition	PET	
		Sub-scenario	Recycling (10% residue to landfill)	Landfill
Material production	Virgin material			
		Material marginal: which?	No inf.	/
		Electricity marginal: which?	grid Southeast Australia (mainly coal)	/
		Steam marginal: which?	No inf.	/
		Co-products dealt with?	No inf.	/
	Recovered material			/
		Material marginal: which?	No inf.	/
		Electricity marginal: which?	grid Southeast Australia (mainly coal)	/
		Steam marginal: which?	No inf.	/
		Co-products dealt with?	No inf.	/
Material recovery		Material recovery included?	Yes	/
		Type of recycling	Mechanical recycling, closed loop	/
		In which ratio does recycled material substitute virgin material?	No inf.	/
Material disposal	General			
		Technology	Sorting, washing and extruding of pelletised PET recyclate	55% biogas captation, leachate collection and treatment
		Infrastructures taken into account?		
		Transport included?	Yes	Yes
		Energy production	No	Yes
		Produced energy substitutes electricity?	/	grid Southeast Australia (mainly coal)
		Produced energy substitutes steam?	/	/
		Avoided processes - credits	avoided bottle grade PET	
		Material substitutes	/	/
		Carbon sequestration issue taken into account?	/	/
	Waste characteristics			
		Heating value	/	/
		Degradation rate (over 100 years)	/	5%
	Incineration			
		Alternative use of incineration capacity included?	/	/
	Composting			
		Compost spreading for composting taken into account?	/	/
		Compost leaching after spreading taken into account?	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/
	Landfill			
		Methane emissions included?	/	Yes,50% of the non-captured methane is oxidised to CO2, rest emitted as methane

Plastics- n°7

Title	Report for Life Cycle Assessment for paper and packaging waste management scenarios in Victoria
Year	2001
Author	Grant

Impact assessment

Methodology Specific methodology

Included stages disposal stage only

Functional unit disposal of 1 kg of material

	7[PET]	
	Recycling (10% residue to landfill)	Landfill
Depletion of abiotic resources (kg Sb eq)		
Climate change (kg CO_2 eq)	-0,76	0,19
Cumulative energy demand (MJ)	-46,00	2,80
Water consumption (m^3)	5,24E-02	0,00E+00
Eutrophication (kg PO4 eq)		
Acidification (kg SO2 eq)		
Photochemical oxidation (kg ethylene eq)	-2,47E-03	1,40E-04
Ozone depletion (kg CFC-11 eq)		
Human toxicity (kg 1,4-DB eq)		
Crude oil consumption (g)		
Air emissions of organic compounds (g)		
Waste production (kg)	0,34	0,95

(grey box) Indicator not included

Plastics- n°7

Title	Report for Life Cycle Assessment for paper and packaging waste management scenarios in Victoria
Year	2001
Author	Grant

		Case	7[PE]	
		Material composition	HDPE	
		Sub-scenario	Recycling (10% residue to landfill)	Landfill
Material production	Virgin material			
		Material marginal: which?	No inf.	/
		Electricity marginal: which?	grid Southeast Australia (mainly coal)	/
		Steam marginal: which?	No inf.	/
		Co-products dealt with?	No inf.	/
	Recovered material			/
		Material marginal: which?	No inf.	/
		Electricity marginal: which?	grid Southeast Australia (mainly coal)	/
		Steam marginal: which?	No inf.	/
		Co-products dealt with?	No inf.	/
Material recovery		Material recovery included?	Yes	/
		Type of recycling	Mechanical recycling, closed loop	/
		In which ratio does recycled material substitute virgin material?	1	/
Material disposal	General			
		Technology	Sorting, washing and extruding of granulated HDPE recyclate	55% biogas captation, leachate collection and treatment
		Infrastructures taken into account?		
		Transport included?	Yes	Yes
		Energy production	No	Yes
		Produced energy substitutes electricity?	/	grid Southeast Australia (mainly coal)
		Produced energy substitutes steam?	/	/
		Avoided processes - credits	avoided virgin HDPE granulates production	
		Material substitutes	/	/
		Carbon sequestration issue taken into account?	/	/
	Waste characteristics			
		Heating value	/	/
		Degradation rate (over 100 years)	/	5%
	Incineration			
		Alternative use of incineration capacity included?	/	/
	Composting			
		Compost spreading for composting taken into account?	/	/
		Compost leaching after spreading taken into account?	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/
	Landfill			
		Methane emissions included?	/	Yes,50% of the non-captured methane is oxidised to CO2, rest emitted as methane

Plastics- n°7

Title	Report for Life Cycle Assessment for paper and packaging waste management scenarios in Victoria
Year	2001
Author	Grant

Impact assessment

Methodology Specific methodology

Included stages disposal stage only

Functional unit disposal of 1 kg of material

	7[PE]	
	Recycling (10% residue to landfill)	Landfill
Depletion of abiotic resources (kg Sb eq)		
Climate change (kg CO_2 eq)	-0,37	0,22
Cumulative energy demand (MJ)	-45,50	3,27
Water consumption (m^3)	7,54E-02	0,00E+00
Eutrophication (kg PO4 eq)		
Acidification (kg SO2 eq)		
Photochemical oxidation (kg ethylene eq)	-9,23E-03	1,60E-04
Ozone depletion (kg CFC-11 eq)		
Human toxicity (kg 1,4-DB eq)		
Crude oil consumption (g)		
Air emissions of organic compounds (g)		
Waste production (kg)	0,27	0,95

Indicator not included

Plastics- n°7

Title	Report for Life Cycle Assessment for paper and packaging waste management scenarios in Victoria
Year	2001
Author	Grant

	Case		7[PVC]	
	Material composition		PVC	
	Sub-scenario		Recycling (10% residue to landfill)	Landfill
Material production	Virgin material			
		Material marginal: which?	No inf.	/
		Electricity marginal: which?	grid Southeast Australia (mainly coal)	/
		Steam marginal: which?	No inf.	/
		Co-products dealt with?	No inf.	/
	Recovered material			/
		Material marginal: which?	No inf.	/
		Electricity marginal: which?	grid Southeast Australia (mainly coal)	/
		Steam marginal: which?	No inf.	/
		Co-products dealt with?	No inf.	/
Material recovery		Material recovery included?	Yes	/
		Type of recycling	Mechanical recycling, closed loop	/
		In which ratio does recycled material substitute virgin material?	1	/
Material disposal	General			
		Technology	Sorting, washing and extruding of PVC powder	55% biogas captation, leachate collection and treatment
		Infrastructures taken into account?		
		Transport included?	Yes	Yes
		Energy production	No	Yes
		Produced energy substitutes electricity?	/	grid Southeast Australia (mainly coal)
		Produced energy substitutes steam?	/	/
		Avoided processes - credits	avoided virgin PVC granulates production	
		Material substitutes	/	/
		Carbon sequestration issue taken into account?	/	/
	Waste characteristics			
		Heating value	/	/
		Degradation rate (over 100 years)	/	5%
	Incineration			
		Alternative use of incineration capacity included?	/	/
	Composting			
		Compost spreading for composting taken into account?	/	/
		Compost leaching after spreading taken into account?	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/
	Landfill			
		Methane emissions included?	/	Yes,50% of the non-captured methane is oxidised to CO2, rest emitted as methane

Plastics- n°7

Title	Report for Life Cycle Assessment for paper and packaging waste management scenarios in Victoria
Year	2001
Author	Grant

Impact assessment

Methodology Specific methodology

Included stages disposal stage only

Functional unit disposal of 1 kg of material

	7[PVC]	
	Recycling (10% residue to landfill)	Landfill
Depletion of abiotic resources (kg Sb eq)		
Climate change (kg CO_2 eq)	-1,49	0,21
Cumulative energy demand (MJ)	-17,60	3,03
Water consumption (m^3)	-4,56E-02	0,00E+00
Eutrophication (kg PO4 eq)		
Acidification (kg SO2 eq)		
Photochemical oxidation (kg ethylene eq)	4,10E-04	1,50E-04
Ozone depletion (kg CFC-11 eq)		
Human toxicity (kg 1,4-DB eq)		
Crude oil consumption (g)		
Air emissions of organic compounds (g)		
Waste production (kg)	0,18	0,95

(grey box) Indicator not included

Plastics- n°8

Title	Kunststoffe aus nachwachsenden Rohstoffen: Vergleichende Ökobilanz für Loose-fill-Packmittel aus Stärke bzw. Polystyrol
Year	2002
Author	BIfA/IFEU/Flo-Pak

		Case	8 [PS]			
		Material composition	Secondary polystyrene from polystyrene production wastes			
		Sub-scenario	Incineration with energy recovery	Feedstock recycling	Mechanical closed-loop recycling	Mechanical open-loop recycling
Material production	Virgin material					
		Material marginal: which?	/	/	/	/
		Electricity marginal: which?	/	/	/	/
		Steam marginal: which?	/	/	/	/
		Co-products dealt with?	/	/	/	/
	Recovered material					
		Material marginal: which?	No inf.	No inf.	No inf.	No inf.
		Electricity marginal: which?	German electricity mix	German electricity mix	German electricity mix	German electricity mix
		Steam marginal: which?	German average heat	German average heat	German average heat	German average heat
		Co-products dealt with?	No co-products	No co-products	No co-products	No co-products
Material recovery		Material recovery included?	No	Yes	Yes	Yes
		Type of recycling	/	Use as reducing agent in blast furnaces	Closed loop	Open loop (product sold on the market for different applications)
		In which ratio does recycled material substitute virgin material?	/	/	1	1
Material disposal	General					
		Technology	Cogeneration, 65% efficiency	Plastics recovery in blast furnaces	Mechanical recycling: regranulation to produce similar products	Mechanical recycling: regranulation to produce similar products
		Infrastructures taken into account?	No	No	No	No
		Transport included?	Included up to the treatment facilities	Included up to the treatment facilities	Included up to the treatment facilities	Included up to the treatment facilities
		Energy production	10% electricity, 55% heat	No	No	No
		Produced energy substitutes electricity?	German grid	/	/	/
		Produced energy substitutes steam?	German heat	/	/	/
		Avoided processes - credits	/	/	Avoids production of secondary polystyrol	No crediting included
		Material substitutes	/	/	/	/
		Carbon sequestration issue taken into account?	/	/	/	/
	Waste characteristics					
		Heating value	No inf.	37 MJ/kg	/	/
		Degradation rate (over 100 years)	/	/	/	/
	Incineration					
		Alternative use of incineration capacity included?	No	No inf.	No inf.	No inf.
	Composting					
		Compost spreading for composting taken into account?	/	/	/	/
		Compost leaching after spreading taken into account?	/	/	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	/	/
	Landfill					
		Methane emissions included?	/	/	/	/

Plastics- n°8

Title	Kunststoffe aus nachwachsenden Rohstoffen: Vergleichende Ökobilanz für Loose-fill-Packmittel aus Stärke bzw. Polystyrol
Year	2002
Author	BIfA/IFEU/Flo-Pak

Impact assessment

Methodology CML

Full life cycle
100 m^3 of PS

	8 [PS]			
	Incineration with energy recovery	Feedstock recycling (recycling scenario from case PS1)	Mechanical closed-loop recycling (recycling scenario from case PS2)	Mechanical open-loop recycling (recycling scenario from case PS3)
Depletion of abiotic resources (kg Sb eq)				
Climate change (kg CO_2 eq)	1970	1770	1230	970
Cumulative energy demand (MJ)*	25000	27000	16000	10000
Water consumption (m^3)				
Terrestrial eutrophication (kg PO4 eq)	0,74	0,82	0,43	0,30
Aquatic eutrophication (kg PO4 eq)	0,0063	0,0061	0,0016	-0,0002
Acidification (kg SO2 eq)	6,20	8,80	4,90	3,40
Photochemical oxidation (kg ethylene eq)	10,50	10,50	10,10	10,10
Ozone depletion (kg N2O eq)	-0,078	0,036	0,033	0,039
Toxicity (kg 1-4-dichlorobenzene)				

* The energy demand in this study corresponds to the consumption of fossil energy resources

(grey box) Indicator not included

Appendix 4 Summary of key elements from the studies on biopolymers

Biopolymers- n°1

Title	Life Cycle Assessment (LCA) of Biopolymers for single-use carrier bags
Year	2008
Author	Murphy (DEFRA)

		Case	1 [MB] (MB = Mater-Bi)		
		Material composition	50% starch (corn) , 50% polycaprolactone		
		Sub-scenario	Incineration with energy recovery	Landfill	Composting
Material production	Virgin material				
		Material marginal: which?	No inf.	No inf.	No inf.
		Electricity marginal: which?	No inf.	No inf.	No inf.
		Steam marginal: which?	No inf.	No inf.	No inf.
		Co-products dealt with?	No	No	No
	Recovered material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	No	No	No
		Type of recycling	/	/	/
		In which ratio does recycled material substitute virgin material?	/	/	/
Material disposal	General				
		Technology	No inf.	19,6% water sanitary landfill	No inf.
		Infrastructures taken into account?	No inf.	No	No inf.
		Transport included?	Yes	Yes	Yes
		Energy production	Yes	No inf.	No
		Produced energy substitutes electricity?	grid electricity UK	/	/
		Produced energy substitutes steam?	No	/	/
		Avoided processes - credits	paper and PE incineration	/	no fertiliser substitution
		Material substitutes	paper for starch, PE for polycaprolactone	cardboard	
		Carbon sequestration issue taken into account?	/	Yes	Yes
	Waste characteristics				
		Heating value	No inf.	/	/
		Degradation rate (over 100 years)	/	32%	90%
	Incineration				
		Alternative use of incineration capacity included?	No inf.	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	No inf.
		Compost leaching after spreading taken into account?	/	/	No inf.
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	Yes
	Landfill				
		Methane emissions included?	/	No inf.	/

Biopolymers- n°1

Title	Life Cycle Assessment (LCA) of Biopolymers for single-use carrier bags
Year	2008
Author	Murphy (DEFRA)

Impact assessment

Methodology CML 2002

Included stages: full life cycle

Functional unit: carrying 10 000 litres of grocery items : 5,72 kg of Mater-Bi, 7,70 kg of Octopus

	1 [MB]		
	Incineration with energy recovery	Landfill	Composting
Depletion of abiotic resources (kg Sb eq)	0,179	0,195	0,197
Climate change (kg CO2 eq)	21,1	13,6	24,3
Cumulative energy demand (MJ)			
Water consumption (m3)			
Eutrophication (kg PO4 eq)	0,0236	0,0391	0,0239
Acidification (kg SO2 eq)	0,116	0,13	0,13
Photochemical oxidation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			

[grey box] Indicator not included

Biopolymers- n°1

Title	Life Cycle Assessment (LCA) of Biopolymers for single-use carrier bags
Year	2008
Author	Murphy (DEFRA)

		Case	1 [OCT] (OCT = Octopus)		
		Material composition	60% PLA, Ecofoil 40%		
		Sub-scenario	Incineration with energy recovery	Landfill	Composting
Material production	Virgin material				
		Material marginal: which?	No inf.	No inf.	No inf.
		Electricity marginal: which?	No inf.	No inf.	No inf.
		Steam marginal: which?	No inf.	No inf.	No inf.
		Co-products dealt with?	No	No	No
	Recovered material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	No	No	No
		Type of recycling	/	/	/
		In which ratio does recycled material substitute virgin material?	/	/	/
Material disposal	General				
		Technology	No inf.	19,6% water sanitary landfill	No inf.
		Infrastructures taken into account?	No inf.	No	No inf.
		Transport included?	Yes	Yes	Yes
		Energy production	Yes	No inf.	No
		Produced energy substitutes electricity?	grid electricity UK	/	/
		Produced energy substitutes steam?	No	/	/
		Avoided processes - credits	paper and PP incineration	/	no fertiliser substitution
		Material substitutes	paper for PLA, PP for Ecofoil	cardboard	
		Carbon sequestration issue taken into account?	/	Yes	Yes
	Waste characteristics				
		Heating value	No inf.	/	/
		Degradation rate (over 100 years)	/	32%	90%
	Incineration				
		Alternative use of incineration capacity included?	No inf.	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	No inf.
		Compost leaching after spreading taken into account?	/	/	No inf.
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	Yes
	Landfill				
		Methane emissions included?	/	No inf.	/

Biopolymers- n°1

Title	Life Cycle Assessment (LCA) of Biopolymers for single-use carrier bags
Year	2008
Author	Murphy (DEFRA)

Impact assessment

Methodology CML 2002

Included stages: full life cycle

Functional unit: carrying 10 000 litres of grocery items : 5,72 kg of Mater-Bi, 7,70 kg of Octopus

	1 [OCT]		
	Incineration with energy recovery	Landfill	Composting
Depletion of abiotic resources (kg Sb eq)	0,238	0,258	0,262
Climate change (kg CO2 eq)	23,1	13,7	27,4
Cumulative energy demand (MJ)			
Water consumption (m3)			
Eutrophication (kg PO4 eq)	0,0464	0,0672	0,0466
Acidification (kg SO2 eq)	0,207	0,225	0,224
Photochemical oxidation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			

[grey box] Indicator not included

Biopolymers- n°2

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

		Case	2 [PLA]		
		Material composition	PLA		
		Sub-scenario	Incineration with energy recovery	Landfill	Composting
Material production	Virgin material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	/	/	/
		Type of recycling	/	/	/
		In which ratio does recycled material substitute virgin material?	/	/	/
Material disposal	General				
		Technology	cogeneration 1/2 humid 32% efficiency	captation of 50% of the biogas	windrow composting
		Infrastructures taken into account?	Yes	Yes	Yes
		Transport included?	not the transport for waste collection	not the transport for waste collection	not the transport for waste collection
		Energy production	Yes	Yes	No
		Produced energy substitutes electricity?	average France 2000	average France 2000	/
		Produced energy substitutes steam?	37,5% gas, 30,2% coal,	No	/
		Avoided processes - credits	production of steel, aluminium and	/	production of inorganic fertilizers
		Material substitutes	No	No	No
		Carbon sequestration issue taken into account?	/	97 kg C/t	339 kg C/t
	Waste characteristics				
		Heating value	18 MJ/kg	/	/
		Degradation rate (over 100 years)	/	80%	30%
	Incineration				
		Alternative use of incineration capacity included?	No inf.	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	Yes
		Compost leaching after spreading taken into account?	/	/	No
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	No
	Landfill				
		Methane emissions included?	/	Yes	/

Biopolymers- n°2

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

Impact assessment

Methodology CML 2002

disposal stage only

1000 kg of material

	2 [PLA]		
	Incineration with energy recovery	Landfill	Composting
Depletion of abiotic resources (kg Sb eq)	-3,19	0,0394	0,05
Climate change (kg CO_2 eq)	-437	-355	-1009
Cumulative energy demand (MJ) *	-9277	106	217
Water consumption (m^3)			
Eutrophication (kg PO4 eq)	0,52	0,0126	0,0102
Acidification (kg SO2 eq)	-0,63	0,0433	0,05
Photochemical oxidation (kg ethylene eq)	3,41	0,06	0,13
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)	-15,2	0,51	0,92
Ecotoxicity in water (kg 1,4-DB eq)	-10,72	0,0902	0,15
Exoctoxicity in sediments (kg 1,4-DB eq)	-24,43	0,201	0,34
Ecotoxicity in soil (kg 1,4-DB eq)	12,24	0,00391	0,00863

* The energy demand in this study corresponds to the consumption of non-renewable energy resources

[grey box] Indicator not included

Biopolymers- n°2

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

		Case	2 [MB] (MB = Mater-Bi)			
		Material composition	Mater-Bi			
		Sub-scenario	Incineration with energy recovery	Landfill	Composting	Recycling
Material production	Virgin material					
		Material marginal: which?	/	/	/	/
		Electricity marginal: which?	/	/	/	/
		Steam marginal: which?	/	/	/	/
		Co-products dealt with?	/	/	/	/
	Recovered material					
		Material marginal: which?	/	/	/	Mater-Bi
		Electricity marginal: which?	/	/	/	No inf.
		Steam marginal: which?	/	/	/	No inf.
		Co-products dealt with?	/	/	/	No inf.
Material recovery		Material recovery included?	/	/	/	Yes
		Type of recycling	/	/	/	mechanical recycling
		In which ratio does recycled material substitute virgin material?	/	/	/	1
Material disposal	General					
		Technology	cogeneration 1/2 humid 32% efficiency	captation of 50% of the biogas		grinding, granulation, extrusion
		Infrastructures taken into account?	Yes	Yes	Yes	No
		Transport included?	not the transport for waste collection	not the transport for waste collection	not the transport for waste collection	not the transport for waste collection
		Energy production	Yes	Yes	No	No
		Produced energy substitutes electricity?	average France 2000	average France 2000	/	/
		Produced energy substitutes steam?	37,5% gas, 30,2% coal,	No	/	/
		Avoided processes - credits	production of steel, aluminium and	/	production of inorganic fertilizers	manufacturing of Mater-Bi
		Material substitutes	No	No	No	based on the recycling process for PE
		Carbon sequestration issue taken into account?	/	44 kg C/t	152 kg C/t	/
	Waste characteristics					
		Heating value	22 MJ/kg	/	/	/
		Degradation rate (over 100 years)	/	80%	30%	/
	Incineration					
		Alternative use of incineration capacity included?	No inf.	/	/	/
	Composting					
		Compost spreading for composting taken into account?	/	/	Yes	/
		Compost leaching after spreading taken into account?	/	/	No	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	No	/	/
	Landfill					
		Methane emissions included?	/	Yes	/	/

Biopolymers- n°2

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

Impact assessment

Methodology CML 2002

disposal stage only

1000 kg of material

	2 [MB] (MB = Mater-Bi)			
	Incineration with energy recovery	Landfill	Composting	Recycling
Depletion of abiotic resources (kg Sb eq)	-3,88	0,04	0,05	-33,71
Climate change (kg CO_2 eq)	618	-156,7	28,61	-2623,46
Cumulative energy demand (MJ) *	-11424	106	217	-79647
Water consumption (m^3)				
Eutrophication (kg PO4 eq)	0,63	0,01	0,01	-1,78
Acidification (kg SO2 eq)	-0,79	0,04	0,05	-11,41
Photochemical oxidation (kg ethylene eq)	4,12	0,06	0,14	-7,7
Ozone depletion (kg CFC-11 eq)				
Human toxicity (kg 1,4-DB eq)	-19,24	0,51	0,92	-48,21
Ecotoxicity in water (kg 1,4-DB eq)	-13,06	0,09	0,15	-4,54
Exoctoxicity in sediments (kg 1,4-DB eq)	-29,77	0,2	0,34	-9,81
Ecotoxicity in soil (kg 1,4-DB eq)	14,76	0,004	0,01	-0,77

* The energy demand in this study corresponds to the consumption of non-renewable energy resources

[grey box] Indicator not included

Biopolymers- n°2

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

		Case	2 [BIO] (BIO = Biolice)		
		Material composition	Biolice		
		Sub-scenario	Incineration with energy recovery	Landfill	Composting
Material production	Virgin material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	/	/	/
		Type of recycling	/	/	/
		In which ratio does recycled material substitute virgin material?	/	/	/
Material disposal	General				
		Technology	cogeneration 1/2 humid 32% efficiency	capatation of 50% of the biogas	windrow composting
		Infrastructures taken into account?	Yes	Yes	Yes
		Transport included?	not the transport for waste collection	not the transport for waste collection	not the transport for waste collection
		Energy production	Yes	Yes	No
		Produced energy substitutes electricity?	average France 2000	average France 2000	/
		Produced energy substitutes steam?	37,5% gas, 30,2% coal,	No	/
		Avoided processes - credits	production of steel, aluminium and	/	production of inorganic fertilizers
		Material substitutes	No	No	No
		Carbon sequestration issue taken into account?	/	48 kg C/t	166 kg C/t
	Waste characteristics				
		Heating value	confidential	/	/
		Degradation rate (over 100 years)	/	80%	30%
	Incineration				
		Alternative use of incineration capacity included?	No inf.	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	Yes
		Compost leaching after spreading taken into account?	/	/	No
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	/	No
	Landfill				
		Methane emissions included?	/	Yes	/

Biopolymers- n°2

Title	Bilan environnemental de filières de traitement de plastiques de différentes origines
Year	2006
Author	Bio Intelligence Service

Impact assessment

Methodology CML 2002

disposal stage only

1000 kg of material

	2 [BIO] (BIO = Biolice)		
	Incineration with energy recovery	Landfill	Composting
Depletion of abiotic resources (kg Sb eq)	-3,3	0,0394	0,05
Climate change (kg CO_2 eq)	351	-172,27	-156,87
Cumulative energy demand (MJ) *	-9620	106	207
Water consumption (m^3)			
Eutrophication (kg PO4 eq)	0,54	0,0126	0,0528
Acidification (kg SO2 eq)	-0,65	0,0433	0,24
Photochemical oxidation (kg ethylene eq)	3,52	0,06	0,13
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)	-15,85	0,51	0,91
Ecotoxicity in water (kg 1,4-DB eq)	-11,11	0,0902	0,15
Exoctoxicity in sediments (kg 1,4-DB eq)	-25,32	0,201	0,34
Ecotoxicity in soil (kg 1,4-DB eq)	12,64	0,00391	0,00863

* The energy demand in this study corresponds to the consumption of non-renewable energy resources

[grey box] Indicator not included

Biopolymers- n°3

Title	Life Cycle Assessment pf polylactide (PLA)
Year	2006
Author	IFEU

		Case	3[PLA]			
		Material composition	100% PLA			
		Sub-scenario	Feedstock recycling (+ 20% incineration)	Composting (+ 11,5% incineration + 8,5% for recycling)	Anaerobic digestion (+ 31,4 % incineration)	Chemical recycling (+ 31,4% incineration)
Material production	Virgin material					
		Material marginal: which?	No inf.	No inf.	No inf.	No inf.
		Electricity marginal: which?	No inf.	No inf.	No inf.	No inf.
		Steam marginal: which?	No inf.	No inf.	No inf.	No inf.
		Co-products dealt with?	No inf.	No inf.	No inf.	No inf.
	Recovered material					
		Material marginal: which?	virgin polymer	virgin polymer	virgin polymer	virgin polymer
		Electricity marginal: which?	No inf.	No inf.	No inf.	No inf.
		Steam marginal: which?	No inf.	No inf.	No inf.	No inf.
		Co-products dealt with?	No inf.	No inf.	No inf.	No inf.
Material recovery		Material recovery included?	Yes	Yes	No	Yes
		Type of recycling	mechanical recycling	mechanical recycling	/	chemical recycling
		In which ratio does recycled material substitute virgin material?	no substituted product	no substituted product	/	no substituted product
Material disposal	General					
		Technology	plastics recovery in blast furnaces + gasification	encapsulated system for composting + roofed clamp for the after-composting step	biogas combustion in a gas-motor	hydrolysis process followed by a purification step with lactic acid monomers being the final product of the recycling process
		Infrastructures taken into account?	No inf.	No inf.	No inf.	No inf.
		Transport included?	Yes	Yes	Yes	Yes
		Energy production	Yes	Not for the composted part	Yes	Yes
		Produced energy substitutes electricity?	average German grid electricity	(average German grid electricity if incinerated)	average German grid electricity	average German grid electricity
		Produced energy substitutes steam?	average German thermal energy	(average German thermal energy if incinerated)	(average German thermal energy if incinerated)	average German thermal energy
		Avoided processes - credits	production of methanol + substitutes hard coal as secondary fuel in a blast furnace	production of methanol + production of compost that displaces mineral fertilizers and peat	production of compost that displaces mineral fertilizers and peat	substitutes lactic acid from sugar ferlentation as an input for the PLA polymerisation process
		Material substitutes	No inf.	No inf.	No inf.	No inf.
		Carbon sequestration issue taken into account?	/	No inf.	/	/
	Waste characteristics					
		Heating value	18 MJ/kg	18 MJ/kg	18 MJ/kg	18 MJ/kg
		Degradation rate (over 100 years)	/	95%	95%	/
	Incineration					
		Alternative use of incineration capacity included	No inf.	No inf.	No inf.	No inf.
	Composting					
		Compost spreading for composting taken into account?	/	No	/	/
		Compost leaching after spreading taken into account?	/	No	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?				
	Landfill					
		Methane emissions included?	/	/	/	/

Biopolymers- n°3

Title	Life Cycle Assessment pf polylactide (PLA)
Year	2006
Author	IFEU

Impact assessment

Methodology CML 1992, 2002

Full life cycle

1000 clam shells (12,2 g each)

	3[PLA]			
	Feedstock recycling (+ 20% incineration) (recycling scenario from case PLA1)	Composting (+ 11,5% incineration + 8,5% for recycling)	Anaerobic digestion (+ 31,4 % incineration)	Chemical recycling (+ 31,4% incineration) (recycling scenario from case PLA2)
Depletion of abiotic resources (kg Sb eq)				
Climate change (kg CO_2 eq)	48,2	57,3	48,1	34,1
Cumulative energy demand (kg crude oil eq)	4,08	7,24	6,84	5,34
Water consumption (m^3)				
Terrestrial eutrophication (kg PO4 eq)	0,0238	0,035	0,0237	0,0139
Aquatic eutrophication (kg PO4 eq)	0,00403	0,00458	0,00471	0,00248
Acidification (kg SO2 eq)	0,25	0,256	0,253	0,144
Photochemical oxidation (kg ethylene eq)	0,01287	0,06256	0,01934	0,00769
Ozone depletion (kg CFC-11 eq)				
Human toxicity (kg PM 10 eq)	0,257	0,261	0,259	0,147

* The energy demand in this study corresponds to the consumption of fossil energy resources expressed in kg crude oil (1 kg crude oil eq = 42 MJ)

(grey box) Indicator not included

Biopolymers- n°4

Title	Environmental assessment of biodegradable multilayer film derived from carbohydrate polymers
Year	2007
Author	Vidal

		Case	4[MUB1] (MUB = Multibio)		
		Material composition	68% starch with PCL/32% PLA		
		Sub-scenario	Incineration without energy recovery	Landfill	Composting
Material production	Virgin material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	/	/	/
		Type of recycling	/	/	/
		In which ratio does recycled material substitute virgin material?	/	/	/
Material disposal	General				
		Technology	no energy recovery	no gas control	windrow system
		Infrastructures taken into account?	No inf.	No inf.	No inf.
		Transport included?			
		Energy production	No	No	No
		Produced energy substitutes electricity?	/	/	/
		Produced energy substitutes steam?	/	/	/
		Avoided processes - credits	No	No	replaces peat does not replace inorganic fertilizers
		Material substitutes	No	No	No
		Carbon sequestration issue taken into account?	/	Yes	Yes
	Waste characteristics				
		Heating value	No inf.	/	/
		Degradation rate (over 100 years)	/	30%	30%
	Incineration				
		Alternative use of incineration capacity included?	No inf.	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	No
		Compost leaching after spreading taken into account?	/	/	No
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?			
	Landfill				
		Methane emissions included?	/	Yes	/

Biopolymers- n°4

Title	Environmental assessment of biodegradable multilayer film derived from carbohydrate polymers
Year	2007
Author	Vidal

Impact assessment

Methodology EU Commission_2001

End-of-life stage
1 kg of material

	4[MUB1]		
	Incineration without energy recovery	Landfill	Composting
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq)	0,023	1,209	-0,248
Cumulative energy demand (MJ)			
Water consumption (m^3)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxidation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)			
Summer smog (kg etene eq)			

Indicator not included

Biopolymers- n°4

Title	Environmental assessment of biodegradable multilayer film derived from carbohydrate polymers
Year	2007
Author	Vidal

		Case	4[MUB2](MUB = Multibio)		
		Material composition	68% starch with PCL/32% PLA		
		Sub-scenario	Incineration without energy recovery	Landfill	Composting
Material production	Virgin material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
	Recovered material				
		Material marginal: which?	/	/	/
		Electricity marginal: which?	/	/	/
		Steam marginal: which?	/	/	/
		Co-products dealt with?	/	/	/
Material recovery		Material recovery included?	/	/	/
		Type of recycling	/	/	/
		In which ratio does recycled material substitute virgin material?	/	/	/
Material disposal	General				
		Technology	no energy recovery	no gas control	windrow system
		Infrastructures taken into account?	No inf.	No inf.	No inf.
		Transport included?			
		Energy production	No	No	No
		Produced energy substitutes electricity?	/	/	/
		Produced energy substitutes steam?	/	/	/
		Avoided processes - credits	No	No	replaces peat does not replace inorganic fertilizers
		Material substitutes	No	No	No
		Carbon sequestration issue taken into account?	/	Yes	Yes
	Waste characteristics				
		Heating value	No inf.	/	/
		Degradation rate (over 100 years)	/	50%	50%
	Incineration				
		Alternative use of incineration capacity included?	No inf.	/	/
	Composting				
		Compost spreading for composting taken into account?	/	/	No
		Compost leaching after spreading taken into account?	/	/	No
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?			
	Landfill				
		Methane emissions included?	/	Yes	/

Biopolymers- n°4

Title	Environmental assessment of biodegradable multilayer film derived from carbohydrate polymers
Year	2007
Author	Vidal

Impact assessment

Methodology EU Commission_2001

End-of-life stage 1 kg of material

	4[MUB2]		
	Incineration without energy recovery	Landfill	Composting
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq)	0,023	3,452	-0,213
Cumulative energy demand (MJ)			
Water consumption (m^3)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxidation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Human toxicity (kg 1,4-DB eq)			
Summer smog (kg etene eq)			

[grey box] Indicator not included

Biopolymers- n°5

Title	Assessment of the environmental profile of PLA, PET and PES clamshell containers using LCA methodology
Year	2009
Author	Madival

		Case	5[PLA]				
		Material composition	100% PLA				
		Sub-scenario	40% recycling/30% incineration/30% landfill	100% Landfill	100% Recycling	50% incineration/50% landfill	23,5% incineration/76,5% landfill
Material production	Virgin material						
		Material marginal: which?	No inf.	No inf.	No inf.	No inf.	No inf.
		Electricity marginal: which?	No inf.	No inf.	No inf.	No inf.	No inf.
		Steam marginal: which?	No inf.	No inf.	No inf.	No inf.	No inf.
		Co-products dealt with?	No inf.	No inf.	No inf.	No inf.	No inf.
	Recovered material						
		Material marginal: which?	No inf.	/	No inf.	/	/
		Electricity marginal: which?	No inf.	/	No inf.	/	/
		Steam marginal: which?	No inf.	/	No inf.	/	/
		Co-products dealt with?	No inf.	/	No inf.	/	/
Material recovery		Material recovery included?	Yes	/	Yes	/	/
		Type of recycling	waiting for precisions	/	waiting for precisions	/	/
		In which ratio does recycled material substitute virgin material?	waiting for precisions	/	waiting for precisions	/	/
Material disposal	General						
		Technology	incineration with energy recovery	waiting for precisions	waiting for precisions	incineration with energy recovery	incineration with energy recovery
		Infrastructures taken into account?	No inf.	No inf.	No inf.	No inf.	No inf.
		Transport included?	Yes	Yes	Yes	Yes	Yes
		Energy production	Yes	No	No	Yes	Yes
		Produced energy substitutes electricity?	for incineration, crediting to the energy consumption used for the polymer manufacture	/	/	for incineration, crediting to the energy consumption used for the polymer manufacture	for incineration, crediting to the energy consumption used for the polymer manufacture
		Produced energy substitutes steam?	waiting for precisions	/	/	waiting for precisions	waiting for precisions
		Avoided processes - credits	waiting for precisions	waiting for precisions	waiting for precisions	waiting for precisions	waiting for precisions
		Material substitutes	mixed plastics	mixed plastics	mixed plastics	mixed plastics	mixed plastics
		Carbon sequestration issue taken into account?	Yes	Yes	Yes	Yes	Yes
	Waste characteristics						
		Heating value	waiting for precisions	/	/	waiting for precisions	waiting for precisions
		Degradation rate (over 100 years)	0% in landfill	0% in landfill	/	0% in landfill	0% in landfill
	Incineration						
		Alternative use of incineration capacity included?	No inf.	/	/	No inf.	No inf.
	Composting						
		Compost spreading for composting taken into account?	/	/	No inf.	/	/
		Compost leaching after spreading taken into account?	/	/	No inf.	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?					
	Landfill						
		Methane emissions included?	waiting for precisions	waiting for precisions	/	waiting for precisions	waiting for precisions

Biopolymers- n°5

Title	Assessment of the environmental profile of PLA, PET and PES clamshell containers using LCA methodology
Year	2009
Author	Madival

Impact assessment

Methodology Impact 2002 +

Full life cycle

1000 containers of capacity 0,4536 kg

	5[PLA]				
	40% recycling/30% incineration/30% landfill	100% Landfill	100% Recycling	50% incineration/50% landfill	23,5% incineration/76,5% landfill
Depletion of abiotic resources (kg Sb eq)					
Climate change (kg CO_2 eq)	1,65E+02	1,75E+02	1,10E+02	2,05E+02	1,80E+02
Cumulative energy demand (MJ)	3,15E+03	4,00E+03	1,80E+03	4,00E+03	4,00E+03
Water consumption (m^3)					
Eutrophication (kg PO4 eq)					
Acidification (kg SO2 eq)					
Photochemical oxidation (kg ethylene eq)					
Ozone depletion (kg CFC-11 eq)					
Toxicity (kg 1-4-dichlorobenzene)					

[grey box] Indicator not included

Biopolymers- n°6

Title	Miljøvurdering af alternative bortskaffelsesveje for bionedbrydelig emballage
Year	2002
Author	Nielsen

		Case	6 [PLA]	
		Material composition	100% PLA	
		Sub-scenario	Incineration with energy recovery	Composting
Material production	Virgin material			
		Material marginal: which?	/	/
		Electricity marginal: which?	/	/
		Steam marginal: which?	/	/
		Co-products dealt with?	/	/
	Recovered material			
		Material marginal: which?	/	/
		Electricity marginal: which?	/	/
		Steam marginal: which?	/	/
		Co-products dealt with?	/	/
Material recovery		Material recovery included?	/	/
		Type of recycling	/	/
		In which ratio does recycled material substitute virgin material?	/	/
Material disposal	General			
		Technology	incineration with electricity and heat production	in vessel
		Infrastructures taken into account?	No	No
		Transport included?	No	No
		Energy production	electricity and heat for district heating	No
		Produced energy substitutes electricity?	Yes; Natural gas	/
		Produced energy substitutes steam?	yes, oil/gas-fired	/
		Avoided processes - credits	Yes	No
		Material substitutes	/	No
		Carbon sequestration issue taken into account?	/	No
	Waste characteristics			
		Heating value	No inf.	
		Degradation rate (over 100 years)		98%
	Incineration			
		Alternative use of incineration capacity included?	No	No
	Composting			
		Compost spreading for composting taken into account?	/	No
		Compost leaching after spreading taken into account?	/	No
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	Yes
	Landfill			
		Methane emissions included?	/	/

Biopolymers- n°6

Title	Miljøvurdering af alternative bortskaffelsesveje for bionedbrydelig emballage
Year	2002
Author	Nielsen

Impact assessment

Methodology EDIP

End-of-life stage
1 kg of material

	6 [PLA]	
	Incineration with energy recovery	Composting
Depletion of abiotic resources (kg Sb eq)		
Climate change (kg CO_2 eq)	5,61E-01	1,48E+00
Cumulative energy demand (MJ)		
Water consumption (m^3)		
Eutrophication (kg PO4 eq)		
Acidification (kg SO2 eq)	-4,20E-04	5,60E-05
Photochemical oxidation (kg ethylene eq)	1,80E-04	4,50E-07
Ozone depletion (kg CFC-11 eq)		
Toxicity (kg 1-4-dichlorobenzene)	9,00E-12	2,00E-17

[grey box] Indicator not included

Biopolymers- n°6

Title	Miljøvurdering af alternative bortskaffelsesveje for bionedbrydelig emballage
Year	2002
Author	Nielsen

		Case	6 [CE] (CE = Cellulose)	
		Material composition	100% cellulose	
		Sub-scenario	Incineration with energy recovery	Composting
Material production	Virgin material			
		Material marginal: which?	/	/
		Electricity marginal: which?	/	/
		Steam marginal: which?	/	/
		Co-products dealt with?	/	/
	Recovered material			
		Material marginal: which?	/	/
		Electricity marginal: which?	/	/
		Steam marginal: which?	/	/
		Co-products dealt with?	/	/
Material recovery		Material recovery included?	/	/
		Type of recycling	/	/
		In which ratio does recycled material substitute virgin material?	/	/
Material disposal	General			
		Technology	inceneration with electricity and heat production	in vessel
		Infrastructures taken into account?	No	No
		Transport included?	No	No
		Energy production	electricity and heat for district heating	No
		Produced energy substitutes electricity?	Yes, natural gas	/
		Produced energy substitutes steam?	yes, oil/gas-fired	/
		Avoided processes - credits	yes	No
		Material substitutes	/	No
		Carbon sequestration issue taken into account?	/	No
	Waste characteristics			
		Heating value	No inf	
		Degradation rate (over 100 years)		98%
	Incineration			
		Alternative use of incineration capacity included?	No	No
	Composting			
		Compost spreading for composting taken into account?	/	No
		Compost leaching after spreading taken into account?	/	No
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	Yes
	Landfill			
		Methane emissions included?	/	/

Biopolymers- n°6

Title	Miljøvurdering af alternative bortskaffelsesveje for bionedbrydelig emballage
Year	2002
Author	Nielsen

Impact assessment

Methodology EDIP

End-of-life stage
1 kg of material

	6 [CE]	
	Incineration with energy recovery	Composting
Depletion of abiotic resources (kg Sb eq)		
Climate change (kg CO_2 eq)	6,30E-01	1,64E+00
Cumulative energy demand (MJ)		
Water consumption (m^3)		
Eutrophication (kg PO4 eq)		
Acidification (kg SO2 eq)	-5,60E-04	5,60E-05
Photochemical oxidation (kg ethylene eq)	2,00E-04	4,50E-07
Ozone depletion (kg CFC-11 eq)		
Toxicity (kg 1-4-dichlorobenzene)	9,00E-12	2,00E-17

Indicator not included

Biopolymers- n°7

Title	Vergleichende Ökobilanz für Loose-fill-Packmittel aus Stärke bzw. Polystyrol
Year	2002
Author	BIfA/IFEU/Flo-Pak

		Case	7 [MAS] (MAS= Maize Starch)			
		Material composition	Maize starch			
		Sub-scenario	Incineration with energy recovery	Composting	Anaerobic digestion	Feedstock recycling
Material production	Virgin material					
		Material marginal: which?	No	No	No	/
		Electricity marginal: which?	German electricity mix	German electricity mix	German electricity mix	/
		Steam marginal: which?	German heat	German heat	German heat	/
		Co-products dealt with?	Yes: gluten, pulp and biogas	Yes: gluten, pulp and biogas	Yes: gluten, pulp and biogas	/
	Recovered material					
		Material marginal: which?	/	/	/	No inf.
		Electricity marginal: which?	/	/	/	German electricity mix
		Steam marginal: which?	/	/	/	German average heat
		Co-products dealt with?				No co-products
Material recovery		Material recovery included?	No	No	No	Yes
		Type of recycling	/	/	/	Use as reducing agent in blast furnaces
		In which ratio does recycled material substitute virgin material?	/	/	/	/
Material disposal	General					
		Technology	Cogeneration, 65% efficiency	Average technology, enclosed composting reactor	Dry fermentation and biogas valorisation (400 m^3 per ton of organic matter), 89% efficiency	Plastics recovery in blast furnaces
		Infrastructures taken into account?	No	No	No	No
		Transport included?	Included up to the treatment facilities	Included up to the treatment facilities	Included up to the treatment facilities	Included up to the treatment facilities
		Energy production	10% electricity, 55% heat	No	Yes, by burning the biogas, valorisation 33% electricity, 56% thermal	No
		Produced energy substitutes electricity?	German grid	/	German grid	/
		Produced energy substitutes steam?	German heat	/	German heat	/
		Avoided processes - credits	/	/	/	/
		Material substitutes	/	/	/	/
		Carbon sequestration issue taken into account?	/	No inf.	No inf.	/
	Waste characteristics					
		Heating value	No inf.	/	/	16 MJ/kg
		Degradation rate (over 100 years)	/	83%	No inf.	
	Incineration					
		Alternative use of incineration capacity included?	No inf.	/	/	No inf.
	Composting					
		Compost spreading for composting taken into account?	/	No	/	/
		Compost leaching after spreading taken into account?	/	No	/	/
		Reference to EN 13432:2000 (Requirements for Packaging Recoverable Through Composting and Biodegradation)?	/	No	/	/
	Landfill					
		Methane emissions included?	/	/	/	/

Biopolymers- n°7

Title	Vergleichende Ökobilanz für Loose-fill-Packmittel aus Stärke bzw. Polystyrol
Year	2002
Author	BIfA/IFEU/Flo-Pak

Impact assessment

Methodology CML

Full life cycle

100 m^3 of biopolymer

	7 [MAS] (MAS= Maize Starch)			
	Incineration with energy recovery	Composting	Anaerobic digestion	Feedstock recycling
Depletion of abiotic resources (kg Sb eq)				
Climate change (kg CO_2 eq)	1020	2360	910	1270
Cumulative energy demand (MJ)*	14000	29000	17000	17000
Water consumption (m^3)				
Terrestrial eutrophication (kg PO4 eq)	0,94	1,00	1,02	1,05
Aquatic eutrophication (kg PO4 eq)	0,0154	0,0190	0,0732	0,0153
Acidification (kg SO2 eq)	5,68	9,29	5,99	9,03
Photochemical oxidation (kg ethylene eq)	0,49	0,63	0,51	0,52
Ozone depletion (kg N2O eq)	0,645	0,802	0,768	0,798
Toxicity (kg 1-4-dichlorobenzene)				

* The energy demand in this study corresponds to the consumption of fossil energy resources

(grey box) Indicator not included

Appendix 5 Summary of key elements from the studies on food & garden waste

Food & garden - n°1

Title	Using LCA to evaluate impacts and resources conservation potential of composting: A case study of the Asti District in Italy
Year	2008
Author	Blengini et al

		Case	1[OR]	
		Material composition	Bio-waste from Households	
		Sub-scenario	Composting	Landfill
Material production	Virgin material			
		Material marginal: which?	/	/
		Electricity marginal: which?	/	/
		Heat marginal: which?	/	/
		Co-products dealt with?	/	/
	Recovered material			
		Material marginal: which?	/	/
		Electricity marginal: which?	/	/
		Heat marginal: which?	/	/
		Co-products dealt with?	Yes	Yes
Material recovery		Material recovery included?	Yes	No
		Type of recycling	Open loop	/
		In which ratio does recycled material substitute virgin material?	/	/
Material disposal	General			
		Technology		
		Infrastructures taken into account?	waste containers and bags	waste containers and bags, landfill facility construction
		Transport included?	Yes	Yes
		Energy production		
		Produced energy substitutes electricity?	/	No
		Produced energy substitutes heat?	/	No
		Avoided processes - credits	fertiliser, steel	/
		Material substitutes	fertiliser, steel	/
		Carbon sequestration issue taken into account?	Yes (173 kg of CO2-eq/ton of waste)	/
	Waste characteristics			
		Heating value	/	/
		Degradation rate (over 100 years)	/	/
	Incineration			
		Alternative use of incineration capacity included?	/	/
	Composting			
		Compost spreading for composting taken into account?	No	/
		Compost leaching after spreading taken into account?	No	/
		Carbon binding of compost included?	Yes	/
		% of carbon remaining in compost after 100 uears	/	/
	Landfill			
		Methane emissions included?	Yes	Yes
		LFG efficiency	/	0,00%

Food & garden - n°1

Title	Using LCA to evaluate impacts and resources conservation potential of composting: A case study of the Asti District in Italy
Year	2008
Author	Blengini et al

Impact assessment

Methodology Ecoindicator 99

disposal stage only

1 kg of input bio-waste, thought as a mix of household organic waste and green/wooden waste.

	1[OR]	
	Composting	Landfill
Depletion of abiotic resources		
Climate change (kg CO2-eq/ton)	130,00	951,00
Cumulative enerhy demand (MJ/ton)	959,00	800,00
Water consumption (m^3)		
Eutrophication (kg O2 eq/ton)	3,64	21,40
Acidification (mol H+/ton)	18,00	23,00
Photochemical oxydation (kg ethylene eq/ton)	0,000578	0,184788
Ozone depletion (kg CFC-11 eq)	0,000027	0,000021
Toxicity (kg 1-4-dichlorobenzene)		

(grey box) Indicator not included

Food & garden - n°2

Title	Environmental assessment of garden waste management in Århus Kommune
Year	2009
Author	Boldrin

		Case	2[GW] (GW=Garden Waste)					
		Material composition	Fine stuff, branches, wood, hard materials and foreign items					
		Sub-scenario	Windrow composting	Composting and incineration of rejects	Composting and seasonal incineration of waste	Max incineration of waste	Home composting	Home composting and max incineration
Material production	Virgin material							
		Material marginal: which?	peat, inorganic fertiliser	peat, inorganic fertiliser	peat, inorganic fertiliser	peat, inorganic fertiliser	peat, inorganic fertiliser	peat, inorganic fertiliser
		Electricity marginal: which?	coal	coal	coal	coal	coal	coal
		Heat marginal: which?	coal	coal	coal	coal	coal	coal
		Co-products dealt with?	Yes	Yes	Yes	Yes	Yes	Yes
	Recovered material							
		Material marginal: which?	mature compost	mature compost	mature compost	mature compost	mature compost	mature compost
		Electricity marginal: which?	coal	coal	coal	coal	coal	coal
		Heat marginal: which?	coal	coal	coal	coal	coal	coal
		Co-products dealt with?	/	/	/	/	/	/
Material recovery		Material recovery included?	Yes	Yes	Yes	Yes	Yes	Yes
		Type of recycling	open loop	open loop	open loop	open loop	open loop	open loop
		In which ratio does recycled material substitute virgin material?	1000:131.5 compost:peat/fertiliser	1000:131.5 compost:peat/fertiliser	1000:131.5 compost:peat/fertiliser	1000:131.5 compost:peat/fertiliser	1000:131.5 compost:peat/fertiliser	1000:131.5 compost:peat/fertiliser
Material disposal	General							
		Technology	current	current	current	current	current	current
		Infrastructures taken into account?	No	No	No	No	No	No
		Transport included?	Yes	Yes	Yes	Yes	Yes	Yes
		Energy production						
		Produced energy substitutes electricity?	Yes	Yes	Yes	Yes	Yes	Yes
		Produced energy substitutes heat?	Yes	Yes	Yes	Yes	Yes	Yes
		Avoided processes - credits	energy, peat and inorganic fertiliser	energy, peat and inorganic fertiliser	energy, peat and inorganic fertiliser	energy, peat and inorganic fertiliser	energy, peat and inorganic fertiliser	energy, peat and inorganic fertiliser
		Material substitutes	peat and inorganic fertiliser	peat and inorganic fertiliser	peat and inorganic fertiliser	peat and inorganic fertiliser	peat and inorganic fertiliser	peat and inorganic fertiliser
		Carbon sequestration issue taken into account?	Yes	Yes	Yes	Yes	Yes	Yes
	Waste characteristics							
		Heating value	/	/	/	/	/	/
		Degradation rate (over 100 years)	according to subfraction	according to subfraction	according to subfraction	according to subfraction	according to subfraction	according to subfraction
	Incineration							
		Alternative use of incineration capacity included?	No	No	No	No	No	No
	Composting							
		Compost spreading for composting taken into account?	/	/	/	/	/	/
		Compost leaching after spreading taken into account?	/	/	/	/	/	/
		Carbon binding of compost included?	Yes	Yes	Yes	Yes	Yes	Yes
		% of carbon remaining in compost after 100 uears	15%	15%	15%	15%	15%	15%
	Landfill							
		Methane emissions included?	/	/	/	/	/	/

Food & garden - n°2

Title	Environmental assessment of garden waste management in Århus Kommune
Year	2009
Author	Boldrin

Impact assessment

Methodology EDIP97

disposal stage only

Handling and treatment of 16,220 tonnes of garden waste produced in Århus municipality and treated at Århus Affaldscenter

	2[GW]		
	Windrow Composting (Composting scenario from case GW1)	Incineration with energy recovery	Home Composting (Composting scenario from case GW2)
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	-31,19415661	-443,8705646	-87,75001206
Cumulative enerhy demand (MJ)			
Water consumption (m^3)			
Eutrophication (kg NO3 eq/ton)	0,875688252	0,88458764	0,742777975
Acidification (kg SO2 eq/ton)	0,532968787	0,430590364	0,476618144
Photochemical oxydation (kg ethylene eq/ton)	0,043858483	-0,001985871	0,012710197
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Ecotoxicity in Water (m3/ton)	2899,441711	-270,3642013	-25,11618029
Human Toxicity via Soil (m3/ton)	43,63298253	-0,232179958	54,74043569
Human Toxicity via Air (m3/ton)	108577893,6	5467513,615	-404747,9168
Human Toxicity via Water (m3/ton)	6314,76782	-294,0949988	7921,065633
Ecotoxicity in Soil (m3/ton)	14663,51605	-1,911687901	18402,39258

Indicator not included

Food & garden - n°3

Title	Life cycle assessment of food waste management options
Year	2005
Author	Lundie and Peters

		Case	3[FW] (FW= Food waste)				
		Material composition	Food Waste				
		Sub-scenario	Home Composting (aerobic)	Home Composting (unaerobic)	Centralised composting	Co-disposal with MSW (Landfil without energy recovery)	In-Sink_Erator
Material production	Virgin material						
		Material marginal: which?					
		Electricity marginal: which?	Australian mix	Australian mix	Australian mix	Australian mix	Australian mix
		Heat marginal: which?	Australian mix	Australian mix	Australian mix	Australian mix	Australian mix
		Co-products dealt with?					
	Recovered material						
		Material marginal: which?	cow manure	cow manure	cow manure	/	/
		Electricity marginal: which?	Australian mix	Australian mix	Australian mix	Australian mix	Australian mix
		Heat marginal: which?	Australian mix	Australian mix	Australian mix	Australian mix	Australian mix
		Co-products dealt with?	No	No	No	No	No
Material recovery		Material recovery included?	Yes	Yes	Yes	No	No
		Type of recycling					
		In which ratio does recycled material substitute virgin material?	/	/	/	/	/
Material disposal	General						
		Technology	Sydney specific	Sydney specific	Sydney specific	Sydney specific	Sydney specific
		Infrastructures taken into account?	Yes	Yes	Yes	Yes	Yes
		Transport included?	Yes	Yes	Yes	Yes	Yes
		Energy production					
		Produced energy substitutes electricity?	/	/	/	/	/
		Produced energy substitutes heat?	/	/	/	/	/
		Avoided processes - credits	cow manure	cow manure	cow manure	/	/
		Material substitutes	cow manure	cow manure	cow manure	/	/
		Carbon sequestration issue taken into account?	No	No	No	No	No
	Waste characteristics						
		Heating value	/	/	/	/	/
		Degradation rate (over 100 years)	/	/	/	/	/
	Incineration						
		Alternative use of incineration capacity included?	/	/	/	/	/
	Composting						
		Compost spreading for composting taken into account?	No	No	No	No	No
		Compost leaching after spreading taken into account?	No	No	No	No	No
		Carbon binding of compost included?	No	No	No	No	No
		% of carbon remaining in compost after 100 uears	/	/	/	/	/
	Landfill						
		Methane emissions included?	Yes	Yes	Yes	Yes	Yes
		LFG efficiency	/	/	/	Flaring/No energy recovery	/

Food & garden - n°3

Title	Life cycle assessment of food waste management options
Year	2005
Author	Lundie and Peters

Impact assessment

Methodology Specific methodology

disposal stage only
The management of the average amount of food waste produced by a household in 1 year. In the Waverley Council area, this amounts to 182 kg (wet) per annum

	3[FW]				
	Home Composting (aerobic) (case FW2)	Home Composting (unaerobic) (case FW3)	Centralised composting (case FW1)	Co-disposal with MSW (Landfil without energy recovery)	In-Sink_Erator (not inlcuded in the comparison)
Depletion of abiotic resources					
Climate change (kg CO2-eq/ton)	16.00	1500.00	285.70	450.50	71.40
Cumulative enerhy demand (MJ/ton)	219.80	219.80	3631.90	1197.80	802.20
Water consumption (m^3)	54.90	54.90	104.40	263.70	12829.70
Eutrophication (kg P eq/ton)	0.05	0.05	0.66	0.30	0.99
Acidification (kg SO2 eq/ton)	0.02	0.02	3.24	0.82	0.60
Photochemical oxydation (kg ethylene eq)					
Ozone depletion (kg CFC-11 eq)					
Toxicity (kg 1-4-dichlorobenzene)					
Terrestrial Ecotoxicity (kg DCB-eq/ton)	-1.10	-1.10	10.99	28.57	20.33
Acuatic Ecotoxicity (kg DCB-eq/ton)	0.00	0.00	0.04	0.01	0.04
Human Toxicity (kg DCB-eq/ton)	0.00	0.00	1.70	0.52	5.05

(grey box) Indicator not included

Food & garden - n°4

Title	Life cycle assessment of energy from solid waste
Year	2000
Author	Finnveden et al

		Case	4[FW] (FW= Food Waste)				
		Material composition	Food Waste				
		Sub-scenario	Incineration	Landfilling	Composting	Anaerobic Digestion 1	Anaerobic Digestion 2
Material production	Virgin material						
		Material marginal: which?	/	/	fertiliser	fertiliser	fertiliser
		Electricity marginal: which?	/	/	fertiliser	fertiliser	fertiliser
		Heat marginal: which?	/	/	fertiliser	fertiliser	fertiliser
		Co-products dealt with?	/	/	fertiliser	fertiliser	fertiliser
	Recovered material						
		Material marginal: which?	/	/	Compost	Compost	Compost
		Electricity marginal: which?	Hard coal	Hard coal	Hard coal	Hard coal	Hard coal
		Heat marginal: which?	Forest residues	Forest residues	Forest residues	Forest residues	Forest residues
		Co-products dealt with?	/	/	/	/	/
Material recovery		Material recovery included?	Yes	Yes	Yes	Yes	Yes
		Type of recycling	/	/	/	/	/
		In which ratio does recycled material substitute virgin material?	1:1	1:1	1:1	1:1	1:1
Material disposal	General						
		Technology					
		Infrastructures taken into account?	No	No	No	No	No
		Transport included?	Yes	Yes	Yes	Yes	Yes
		Energy production					
		Produced energy substitutes electricity?	Yes	Yes	Yes	Yes	fuel for vehicles
		Produced energy substitutes heat?	Yes	Yes	Yes	Yes	fuel for vehicles
		Avoided processes - credits	energy	energy	compost	energy/compost	energy/compost
		Material substitutes	/	/	/	compost	compost
		Carbon sequestration issue taken into account?	No	No	No	No	No
	Waste characteristics						
		Heating value		/	/	/	/
		Degradation rate (over 100 years)		/	/	/	/
	Incineration						
		Alternative use of incineration capacity included?	No	No	No	No	No
	Composting						
		Compost spreading for composting taken into account?	/	/	/	/	/
		Compost leaching after spreading taken into account?	/	/	/	/	/
		Carbon binding of compost included?	/	/	No	No	No
		% of carbon remaining in compost after 100 uears	/	Modeled	Modeled	/	/
	Landfill						
		Methane emissions included?	/	Yes	Yes	Yes	Yes

Food & garden - n°4

Title	Life cycle assessment of energy from solid waste
Year	2000
Author	Finnvenden et al

Impact assessment

Methodology EDIP, USES-LCA, Ecoindicator 99

disposal stage only

Treatment of the amount of the included waste fractions collected in Sweden during one year

	4[FW]				
	Incineration	Landfilling	Composting	Anaerobic Digestion (case FW1)	Anaerobic (case FW2)
Depletion of abiotic resources (kg Sb eq/ton)	723.60	-4824.03	2371.81	-7638.04	-8442.05
Climate change (kg CO2-eq/ton)	133.86	2281.63	109.52	-699.70	-760.54
Cumulative enerhy demand (MJ/ton)	-15195.69	-6753.64	2420.05	-12381.67	-8442.05
Water consumption (m^3)					
Eutrophication (kg PO4 eq)*	544.04	806.68	0.94	-30.02	-30.02
Acidification (kg SO2 eq)**	0.03	0.18	1.54	-0.07	0.00
Photochemical oxydation (kg ethylene eq)	-0.27	1.72	0.52	0.38	0.54
Ozone depletion (kg CFC-11 eq)					
Toxicity (kg 1-4-dichlorobenzene)					
Ecotoxicity (SEK/ton) EDIP	-15.76	-2.53	2.19	11.26	16.32
Human Toxicity (SEK/ton) EDIP	-196.98	-196.98	219.49	-73.16	180.10

* without effect from Nox

** without effect from Sox and Nox

Indicator not included

Food & garden - n°5

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

	Case	5[OR] (OR=Organic Municipal Waste)		
	Material composition	Mixed Organics		
	Sub-scenario	Composting	Incineration	Landfilling
Material production	Virgin material			
	Material marginal: which?	/	/	/
	Electricity marginal: which?	/	/	/
	Steam marginal: which?	/	/	/
	Co-products dealt with?	/	/	/
	Recovered material			
	Material marginal: which?	Compost	/	/
	Electricity marginal: which?	/	fossil	fossil
	Steam marginal: which?	/	/	/
	Co-products dealt with?	/	/	/
Material recovery	Material recovery included?	No	/	/
	Type of recycling	/	/	/
	Alternative use of land/wood included?	/	/	/
	In which ratio does recycled material substitute virgin material?	/	/	/
Material disposal	General			
	Technology	USA	USA	USA
	Infrastructures taken into account?	/	/	/
	Transport included?	Yes	Yes	Yes
	Energy production			
	Produced energy substitutes electricity?	/	Yes	Yes
	Produced energy substitutes heat?	/	No	No
	Avoided processes - credits	/	Electricity production	Electricity production
	Material substitutes	/	/	/
	Carbon sequestration issue taken into account?	Yes	No	No
	Waste characteristics			
	Heating value	/	5.2 million Btu per ton	/
	Degradation rate (over 100 years)	/	/	/
	Incineration			
	Alternative use of incineration capacity included?	No	No	No
	Efficiency	/	/	/
	Composting			
	Compost spreading for composting taken into account?	Yes	/	/
	Compost leaching after spreading taken into account?	No	/	/
	Carbon storage taken into account?	Yes	/	/
	Landfill			
	Methane emissions included?	/	/	Yes
	Efficiency	/	/	/
	Carbon storage taken into account?	/	/	/

Food & garden - n°5

Title	Solid waste management and greenhouse gases: A life cycle assessment of emissions and sinks
Year	2006
Author	US EPA

Impact assessment

Methodology IPCC

disposal stage only

1 short ton of material

	5[OR]		
	Composting	Incineration	Landfilling
Depletion of abiotic resources (kg Sb eq)			
Climate change (kg CO_2 eq/ton)	-50	-50	60
Cumulative enerhy demand (MBtu/t)	0,58	-0,58	0,37
Water consumption (kg/t)			
Eutrophication (kg PO4 eq)			
Acidification (kg SO2 eq)			
Photochemical oxydation (kg ethylene eq)			
Ozone depletion (kg CFC-11 eq)			
Toxicity (kg 1-4-dichlorobenzene)			
Waste (kg/t)			

Indicator not included

Food & garden - n°6

Title	Klimaregnskap for avfallshåndtering
Year	2009
Author	Raandal

		Case	7[OR]			
		Material composition	Organic			
		Sub-scenario	Landfill	Incineration	Composting	Anaerobic Digestion
Material production	Virgin material					
		Material marginal: which?	/	/	/	/
		Electricity marginal: which?	/	/	/	/
		Steam marginal: which?	/	/	/	/
		Co-products dealt with?	/	/	/	/
	Recovered material					
		Material marginal: which?	/	/	30% peat, 60% fertiliser	fertiliser and peat
		Electricity marginal: which?	Scandinavian mix	Scandinavian mix	/	Scandinavian mix
		Steam marginal: which?	Norwegian mix	Norwegian mix	/	Norwegian mix
		Co-products dealt with?	/	/	/	/
Material recovery		Material recovery included?	/	/	Yes	Yes
		Type of recycling	/	/	/	/
		Alternative use of land/wood included?	/	/	/	/
		In which ratio does recycled material substitute virgin material?	/	/	/	/
Material disposal	General					
		Technology				
		Infrastructures taken into account?	/	/	/	/
		Transport included?	Yes	Yes	Yes	Yes
		Energy production				
		Produced energy substitutes electricity?	Yes	Yes	/	Yes
		Produced energy substitutes heat?	Yes	Yes	/	Yes
		Avoided processes - credits	energy production	energy production	fertiliser	energy production, fertiliser and peat production
		Material substitutes	/	/	fertiliser	fertiliser and peat
		Carbon sequestration issue taken into account?	No	No	No	No
	Waste characteristics					
		Heating value	/	2.3 MJ/kg	/	/
		Degradation rate (over 100 years)	/	/	/	/
	Incineration					
		Alternative use of incineration capacity included?	/	No	/	/
		Efficiency	/	/	/	/
	Composting					
		Compost spreading for composting taken into account?	/	/	/	/
		Compost leaching after spreading taken into account?	/	/	/	/
		Carbon storage taken into account?	/	/	Yes	/
	Landfill / AD					
		Methane emissions included?	Yes	/	Yes	Yes
		Efficiency	25% methane recovery, 38% used for electricity (35% conversion), 20% heat (64% conversion) and 42% flared	/	/	Recovered energy replaces 18% electricity, 53% heat, 19% flared, 2% loss and 9% unknown
		Carbon storage taken into account?	/	/	Yes	Yes

Food & garden - n°6

Title	Klimaregnskap for avfallshåndtering
Year	2009
Author	Raandal

Impact assessment

Methodology IPCC

disposal stage only

Management of 1 kg of waste and associated transport and substitution of energy and/or material which is generated from waste management

	6[OR]			
	Landfill	Incineration	Composting	Anaerobic Digestion
Depletion of abiotic resources (kg Sb eq)				
Climate change (kg CO_2 eq/ton)	0,89	0,01	-0,02	-0,09
Cumulative enerhy demand (MBtu/t)				
Water consumption (kg/t)				
Eutrophication (kg PO4 eq)				
Acidification (kg SO2 eq)				
Photochemical oxydation (kg ethylene eq)				
Ozone depletion (kg CFC-11 eq)				
Toxicity (kg 1-4-dichlorobenzene)				
Waste (kg/t)				

Indicator not included

Food & garden - n°7

Title	Environmental assessment of waste systems for municipal waste in Århus Kommune
Year	2004
Author	Kikerby

		Case	7[OR]	
		Material composition	Organic municipal waste	
		Sub-scenario	Incineration	Anaerobic Digestion
Material production	Virgin material			
		Material marginal: which?	/	fertiliser
		Electricity marginal: which?	/	/
		Steam marginal: which?	/	/
		Co-products dealt with?	/	/
	Recovered material			
		Material marginal: which?	/	fertiliser
		Electricity marginal: which?	coal	coal
		Steam marginal: which?	coal	coal
		Co-products dealt with?	Yes	Yes
Material recovery		Material recovery included?	/	Yes
		Type of recycling	/	open loop
		Alternative use of land/wood included?	/	/
		In which ratio does recycled material substitute virgin material?	/	70% N, 100% P and K
Material disposal	General			
		Technology		
		Infrastructures taken into account?	No	No
		Transport included?	Yes	Yes
		Energy production		
		Produced energy substitutes electricity?	Yes	Yes
		Produced energy substitutes heat?	Yes	Yes
		Avoided processes - credits	energy	fertiliser and energy
		Material substitutes	/	fertliser
		Carbon sequestration issue taken into account?	/	/
	Waste characteristics			
		Heating value	3.4 MJ/kg	/
		Degradation rate (over 100 years)	/	/
	Incineration			
		Alternative use of incineration capacity included?	No	/
		Efficiency	80% (69% heat and 11% electricity)	/
	Composting			
		Compost spreading for composting taken into account?	/	Yes
		Compost leaching after spreading taken into account?	/	Yes
		Carbon storage taken into account?	/	No
	Landfill / AD			
		Methane emissions included?	/	Yes
		Efficiency	/	97% methane recovery, 70% energy efficiency (32% electricity and 38% heat)
		Carbon storage taken into account?	/	/

Food & garden - n°7

Title	Environmental assessment of waste systems for municipal waste in Århus Kommune
Year	2004
Author	Kikerby

Impact assessment

Methodology EDIP

disposal stage only

1 ton of waste

	7[OR]	
	Incineration	Anaerobic Digestion
Depletion of abiotic resources (kg Sb eq)		
Climate change (kg CO_2 eq)	-278,53	-178,28
Cumulative enerhy demand (MJ)		
Water consumption (kg)		
Eutrophication (kg PO4 eq)	1,35	0,91
Acidification (kg SO2 eq)	1,28	0,50
Photochemical oxydation (kg ethylene eq)	0,01	0,06
Ozone depletion (kg CFC-11 eq)	0,00	0,00
Toxicity (kg 1-4-dichlorobenzene)		
Waste (kg/t)		
Human Toxicity water (m3)	997,59	1526,93
Human Toxicity air (m3)	12668642,15	-2239269,36
Human Toxicity soil (m3)	0,83	26,35
Ecotoxicity water chronic (m3)	333,16	-1786,68
Ecotoxicity water acc (m3)	19,24	-205,85
Ecotoxicity soil (m3)	0,01	-0,10

Indicator not included

Appendix 6 List of selected studies

Material	Title of the publication	Journal/Publisher	Volume and pages of the journal	Authors	Year
Paper & cardboard	Analyse du Cycle de Vie comparative d'emballage pour magazines et imprimés adressés par voie postale	ADEME		BIOIS	2007
	Environmental Assessment of Paper Waste Management Options by Means of LCA Methodology	Industrial & Engineering Chemistry Research	pp. 5702-5714	Arena, Mastellone,Perugini, Clift	2004
	Life cycle assessment of energy from solid waste	Journal of Cleaner Production	vol. 13 -pp. 213–240	Finnveden, Johansson, Lind, Moberg	2005
	Solid Waste Management and Greenhouse Gases: A life Cycle Assessment of Emissions and Sinks	US EPA		US EPA	2006
	Klimaregnskap for avfallshåndtering			Raandal	2009
Plastics	Bilan environnemental de filières de traitement de plastiques de différentes origines			BIOIS	2006
	LCA of Management Options for Mixed Waste Plastics	WRAP		Shonfield	2008
	Life cycle assessment of energy from solid waste	Journal of Cleaner Production	vol. 13 -pp. 213–240	Finnveden, Johansson, Lind, Moberg	2005
	A Life Cycle Assessment of Mechanical and Feedstock Recycling Options for Management of Plastic Packaging Wastes	Environmental Progress	vol.24 - n°. 2 - pp. 137-154	Perugini, Mastellone, Arena	2005
	Life Cycle Assessment: a tool for evaluating and comparing different treatment options for plastic wastes from old television sets	Data Science Journal	vol. 6 - pp. S39-S50	Dodbiba, Furuyama , Takahashi, Sadaki, Fujita	2007
	Solid Waste Management and Greenhouse Gases: A life Cycle Assessment of Emissions and Sinks	US EPA		US EPA	2006

Material	Title of the publication	Journal/Publisher	Volume and pages of the journal	Authors	Year
Plastics	Stage 2 Report for Life Cycle Assessment for Paper and Packaging Waste Management Scenarios in Victoria	EcoRecycle Victoria		Grant, James, Lundie, Sonneveld	2001
	Kunststoffe aus nachwachsenden Rohstoffen: Vergleichende Ökobilanz für Loose-fill-Packmittel aus Stärke bzw. Polystyrol			BIFA, IFEU/FLO-pak	2002
Biopolymers	Life Cycle Assessment (LCA) of Biopolymers for single-use Carrier Bags	UK National Non-Food Crops Centre		Murphy, Davis, Payne	2008
	Bilan environnemental de filières de traitement de plastiques de différentes origines			BIOIS	2006
	Life Cycle Assessment of polylactide (PLA)	IFEU_Institute for Energy and Environmental Research		Detzel, Krüger	2006
	Environmental assessment of biodegradable multilayer film derived from carbohydrate polymers	Journal of Polymers and the Environment	vol. 15 - pp. 159–168	Vidal, Martınez, Mulet, Gonzalez ,Lopez-Mesa, Fowler, Fang	2007
	Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology	Journal of Cleaner Production	vol. 17 - pp. 1183–1194	Madival, Auras, Singh, Narayan	2009
	Miljøvurdering af alternative bortskaffelsesveje for bionedbrydelig emballage	Miljøstyrelsen (Danish EPA)		Nielsen, Weidema	2002
	Kunststoffe aus nachwachsenden Rohstoffen: Vergleichende Ökobilanz für Loose-fill-Packmittel aus Stärke bzw. Polystyrol			BIFA, IFEU/FLO-pak	2002

Material	Title of the publication	Journal/Publisher	Volume and pages of the journal	Authors	Year
Food & garden waste	Using LCA to evaluate impacts and resources conservation potential of composting: A case study of the Asti District in Italy	Resources, Conservation and Recycling	vol. 52 - pp. 1373–1381	Blengini	2008
	Environmental assessment of garden waste management in Århus Kommune	Technical University of Denmark		Boldrin, Andersen, Christensen	2009
	Life cycle assessment of food waste management options	Journal of Cleaner Production	13 275–286	Lundie, Peters	2005
	Life cycle assessment of energy from solid waste	Journal of Cleaner Production	vol. 13 -pp. 213–240	Finnveden, Johansson, Lind, Moberg	2005
	Solid Waste Management and Greenhouse Gases: A life Cycle Assessment of Emissions and Sinks	US EPA		US EPA	2006
	Klimaregnskap for avfallshåndtering			Raandal	2009
	Environmental assessment of waste systems for municipal waste in Århus Kommune			Kirkeby	2004

Appendix 7 List of rejected studies

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Paper & cardboard	Combining ecological and economic assessment of options for newspaper waste management	Resources, Conservation and Recycling	vol. 51 - pp. 42–63	Dahlbo, Ollikainen, Peltola, Myllymaaa, Melanen	2007
	Comparative LCAs for Curbside Recycling Versus Either Landfilling or Incineration with Energy Recovery	International Journal of Life Cycle Assessment	vol. 10 n°. 4	Morris	2005
	Förenklad livscykelanalys (LCA) och livscykelkostnad (LCC) för en kvällstidning	Kungliga Tekniska Högskolan	vol. 23	Atterhög	2008
	LCIs for Newspaper with Different Waste Management Options – Case Helsinki Metropolitan Area	Proc. of the "Advances in Waste Management and Recycling" symposium, September 9 - 11.2003, University of Dundee, Scotland		Dahlbo, Myllymaa, Laukka, Koskela, Jouttijärvi, Melanen	2003
	Life Cycle Assessment and Economic Analysis of Organic Waste Management and Greenhouse Gas Reduction Options	California Integrated Waste Management Board		RTI International,	2009
	Life cycle assessment for optimising the level of separated collection in integrated MSW management systems	Waste Management	vol. 29 - pp.934–944	Rigamonti, Grosso, Giugliano	2009
	Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration	Resources, Conservation and Recycling	vol. 52 - pp. 1391–1398	Merrild, Damgaard, Christensen	2008
	Paper and cardboard — recovery or disposal? Review of life cycle assessment and cost-benefit analysis on the recovery and disposal of paper and cardboard	European Environment Agency		European Environment Agency	2006
	Paper waste – Recycling, incineration or landfilling? A review of existing life cycle assessments	Waste Management	vol. 27 - pp.S29–S46	Villanueva, Wenzel	2007
	Quantification of Greenhouse Gases at Visy Industries using Life Cycle Assessment	Swinburne University of Technology		Wiegard	2001
	The Relationship between Waste Paper and Other Inputs in the Swedish Paper Industry	Environmental and Resource Economics	vol.25 - pp.191–212	Samakovlis	2003

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Paper & cardboard	Waste management from pulp and paper production in the European Union	Waste Management	vol. 29 - pp. 293–308	Monte, Fuente, Blanco, Negro	2009
	Waste management options for discarded newspaper in the Helsinki Metropolitan Area	Finnish Environment Institute		Dahlbo, Laukka, Myllymaa, Koskela, Tenhunen, Seppälä, Jouttijärvi, Melanen	2005
	Life cycle assessment of the waste hierarchy – A Danish case study on waste paper	Waste Management	vol. 27 - pp.1519–1530	Schmidt, Holm, Merrild, Christensen	2007
	Life Cycle Assessment of Tissue Products	Kimberly-Clark		ERM	2007
	Life cycle inventory analyses for five waste management options for discarded newspaper	Waste Management Resources	vol. 23 - pp. 291–303	Dahlbo, Koskela, Laukka, Myllymaa, Jouttijärvi, Melanen, Tenhunen	2005
Plastics	Life Cycle Assessment (LCA) of PET bottles and comparative LCA of three disposal options in Mauritius	International Journal of Environment and Waste Management	vol. 2 - n°. 1/2 - pp. 125-138	Foolmaun, Ramjeawon	2008
	Life Cycle Assessment of PVC and of principal competing materials	European Commission		PE Europe GmbH, IKP, IPU, RANDA GROUP	2004
	Biodegradation of Agricultural Plastic Films: A Critical Review	Journal of Polymers and the Environment	vol. 15 - pp. 125–150	Kyrikou, Briassoulis	2007
	Comparative environmental analysis of waste brominated plastic thermal treatments	Waste Management	vol. 29 - pp. 1095–1102	Bientinesi, Petarca	2009
	Life Cycle Inventory for five products produced from polylactide (PLA) and petroleum based resins	Athena Institute International		Franklin Associates	2006
	Miljøanalyse av ulike behandlingsformer for plastemballasje fra husholdninger	Grønt Punkt Norge (GPN)/Østfoldforskning		Raadal, Brekke and Modahl	2008
	Reducing Greenhouse Gas Emissions by Recycling Plastics and Textiles into Products	Finnish Environment Institute		Korhonen, Dahlbo	2007

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Plastics	Comparative LCAs for Curbside Recycling Versus Either Landfilling or Incineration with Energy Recovery	International Journal of Life Cycle Assessment	vol.10 - n°.4 - pp. 273-284	Morris	2005
	Life cycle assessment of fossil and bio based materials for 3D shell applications			Johansson	2005
	LCA of thermoplastics recycling	3rd International Conference on Life Cycle Management,Zurich, August 27 to 29, 2007		Garrain, Martínez, Vidal, Bellés	2007
	LCA of one way PET bottles and recycled products			IFEU_Institute for Energy and Environmental Research	2004
	Life Cycle Assessment of a Plastic Packaging Recycling System	International Journal of Life Cycle Assessment	vol. 8 - n°.2 - pp. 92-98	Arena, Mastellone, Perugini	2003
	Life Cycle Inventory and Analysis of Re-usable Plastic Containers and Display-ready Corrugated Containers Used for Packaging Fresh Fruits and Vegetables	Packaging Technology and science	(in press)	Singh, Chonhenchob	2006
	Comparison between material and energy recovery of municipal waste from an energy perspective - A study of two Swedish municipalities	Resources, Conservation and Recycling	vol. 43 - pp. 51–73	Holmgren, Henning	2004
	Reducing Greenhouse Gas Emissions by Recycling Plastics and Textiles into Products	Finnish Environment Institute		Korhonen, Dahlbo	2007
	Comparative LCAs for Curbside Recycling Versus Either Landfilling or Incineration with Energy Recovery	International Journal of Life Cycle Assessment	vol.10 - n°.4 - pp. 273-284	Morris	2005
	Life cycle assessment of fossil and bio based materials for 3D shell applications			Johansson	2005
Biopolymers	Perspective Compostability of polymers	Polymer International	vol. 57 - pp. 793–804	Kijchavengkul, Auras	2008
	LCA of biodegradable multilayer film from biopolymers	3rd International Conference on Life Cycle Management,Zurich, August 27 to 29, 2007		Garrain, Vidal, Martínez,Franco, Cebrián-Tarrasón	2007

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Biopolymers	Biodegradable Polymers: Past, Present, and Future	The Society for engineering in agricultural, food and biological systems		Kolybaba, Tabil, Panigrahi, Crerar, Powell, Wang	2003
	Biodegradable Polymers and Sustainability: Insights from Life Cycle Assessment	UK National Non-Food Crops Centre		Murphy, Bartle	2003
	Biodegradable packaging based on raw materials from crops and their impact on waste management	Industrial Crops and Products	vol. 23 - pp. 147–161	Davis, Song	2006
	LCA of biocomposites versus conventional products	3rd International Conference on Life Cycle Management,Zurich, August 27 to 29, 2007		Martinez, Garraín, Vidal	2007
	Biodegradability of biodegradable/degradable plastic materials under aerobic and anaerobic conditions	Waste Management		Mohee, Unmar, Mudhoo,Khadoo	2007
	Applications of life cycle assessment to NatureWorksTM polylactide (PLA) production	Polymer Degradation and Stability	vol. 80 - pp. 403–419	Vink, Rabago, Glassner, Gruber	2003
	Biodegradable Packaging Life-Cycle Assessment	Environmental Progress	vol. 23 - n°.4 - pp. 342-346	Bohlmann,	2004
	Profils environnementaux de la production de plastiques de différentes origines			BIOIS,	2006
	Sustainable Packaging: Replacing Polyethylene with Biopolymers for Tetra Pak non-aseptic cartons in Sweden	Lund University and Tetra Pak		Dean,	2003
	Life Cycle Inventory for five products produced from polylactide (PLA) and petroleum based resins	Athena Institute International		Franklin Associates	2006
	Environmental assessment of bio-based polymers and natural fibres			Patel, Bastioli, Marini, Würdinger	XXXX

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Biopolymers	Life Cycle Assessment, comparison of biopolymer and traditional diaper systems	Technical Reserarch Center of Finland		Hakala, Virtanen, Meinander, Tanner	1997
	Life cycle assessment of composite materials made of recycled thermoplastics combined with rice husks and cotton linters	International Journal of Life Cycle Assessment	vol. 14 - pp. 73–82	Vidal, Martínez, Garraín	2009
	Life Cycle Assessment of Polysaccharide Materials: A Review	J Polym Environ	vol. 16 - pp. 154–167	Shen, Patel	2008
	LCA of Degradable Plastic Bags			James, Grant	2003
	Compostable cutlery and waste management: An LCA approach	Waste Management	vol. 29 - pp. 1424–1433	Razza, Fieschi, Innocenti, Bastioli	2009
	Life cycle assessment of fossil and bio based materials for 3D shell applications			Johansson,	2005
	Life Cycle Management in bioplastics production	3rd International Conference on Life Cycle Management,Zurich, August 27 to 29, 2007		Innocenti, Razza, Fieschi, Bastioli	2007
Food & garden waste	A Life Cycle Assessment for Vegetable, Fruit and Garden Waste	Netherlands association of Waste Companies		IVAM	2003
	Life cycle assessment of the use of compost from municipal organic waste for fertilization of tomato crops	Resources, Conservation and Recycling	53 340–351	Martinez-Blanco, Munoz, Antón, Rieradevall	2009
	Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems	New South Wales Department of Environment and Conservation		Recycled Organics Unit_University of New South Wales	2006
	Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems-2nd edition	New South Wales Department of Environment and Conservation		Recycled Organics Unit_University of New South Wales	2007
	Madaffald fra storkøkkener	Miljøstyrelsen (Danish EPA)		NIRAS	2004
	Life cycle assessment of two biowaste management systems for Barcelona, Spain	Resources, Conservation and Recycling	vol. 49 - pp. 32–48	Guereca, Gasso, Baldasano, Jimenez-Guerrero	2006

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Food & garden waste	A Life-Cycle Analysis of Alternatives for the Management of Waste Hot-Mix Asphalt, Commercial Food Waste, and Construction and Demolition Waste	North Carolina State University		Levis	2008
	A review of life cycle assessment (LCA) on some food products	Journal of Food Engineering	vol. 90 - pp.1–10	Roy, Nei, Orikasa, Xu, Okadome, Nakamura, Shiina	2009
	Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives	Bioresource Technology	vol. 74 - pp. 3-16	Mata-Alvarez, Mace	2000
	Assessment of food disposal options in multi-unit dwellings in Sydney	In-Sink-Erator		CRC for Waste Management and Pollution Control Limited	2000
	Assessment of the environmental impact of management measures for the biodegradable fraction of municipal solid waste in Sao Paulo City	Waste Management	vol. 23 - pp.403–409	Mendes, Aramaki, Hanaki	2003
	Biowaste Decision support tool for collection and treatment of source-sorted organic municipal solid waste	Nordic Council Tema Nord		Nordic Council Tema Nord,	2007
	Dealing with Food Waste in the UK	WRAP		Hogg, Barth, Schleiss, Favoino	2007
	Energianalys av biogassystem	Lund University, Institute of technology and society, department of environment and energy		Berglund, Börjesson	2003
	Environmental aspects of the anaerobic digestion of the organic fraction of municipal solid wastes and of agricultural wastes			Edelmann, Baier, Engeli	XXXX
	Evaluation of environmental burdens caused by changes of food waste management systems in Seoul, Korea	Science of the Total Environment	vol. 387 - pp. 42–53	Lee, Choi, Osako, Dong	2007
	Food Waste Diversion Greenhouse Gas Analysis: Portland, Oregon	City of Portland		Visse,	2004

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Food & garden waste	Förbränning eller biologisk behandling? -en miljösystemanalys av olika behandlingsmetoder för det lättnedbrytbara organiska avfallet i Gästrikeregionen	Högskolan i Gävle - Institutionen för teknik och byggd miljö		Jönsson,	2005
	GHG Savings from Biological Treatment and Application of Compost	ECN/ORBIT e.V. Workshop 2008 „The future for Anaerobic Digestion of Organic Waste in Europe“		Schleiss,	2008
	Home Composting : A Role in Sustainable Waste Management ?			Coggins,	2003
	Life Cycle Assessment and Economic Analysis of Organic Waste Management and Greenhouse Gas Reduction Options	California Integrated Waste Management Board		RTI International,	2009
	Life Cycle Assessment for foodwaste Recycling and Management			Hirai, Murata, Sakai, Takatsuki	XXXX
	Life cycle assessment for optimising the level of separated collection in integrated MSW management systems	Waste Management	vol. 29 - pp.934–944	Rigamonti, Grosso, Giugliano	2009
	Life cycle assessment of bagasse waste management options	Waste Management	vol. 29 - pp.1628-1633	Kiatkittipong, Wongsuchoto, Pavasant	2009
	Life Cycle Assessment Of Organic Diversion Alternatives And Economic Analysis For Greenhouse Gas Reduction Options	RTI International		Weitz,	2008
	Life cycle impact assessment of various waste conversion technologies	Waste Management	vol. 29 - pp.1892–1900	Khoo,	2009
	Managing Biowastes from Households in the UK:Applying Life-cycle Thinking in the Framework of Cost-benefit Analysis	WRAP		Eunomia,	2007
	Quantification of environmental effects from anaerobic treatment of source-sorted organic household waste	Technical University of Denmark		Hansen,	2005
	Recovery of organic wastes in the Spanish wine industry. Technical, economic and environmental analyses of the composting process	Journal of Cleaner Production	vol. 17- pp. 830–838	Ruggieri, Cadena, Martinez-Blanco, Gasol, Rieradevall, Gabarrell, Gea, Sort, Sanchez	2009
	Systems Analysis of Organic Waste Management in Denmark	Miljøstyrelsen (Danish EPA)		Wittgren, Baky, Eriksson	2003

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Food & garden waste	The potential role of compost in reducing greenhouse gases	Waste Management and Research	vol. 26 - n°.1 - pp. 61-69	Favoino, Hogg	2008
	Evaluation of a biogas plant from life cycle assessment (LCA)	International Congress Series	vol. 1293- pp. 230-233	Ishikawa, Hoshiba, Hinata, Hishinuma, Morita	2006
	Life cycle assessment of two biowaste management systems for Barcelona, Spain	Resources, Conservation and Recycling	vol. 49 - pp.32-48	Guereca, Gass´o, Baldasano, Guerrero	2006
	Evaluation of a biogas plant from life cycle assessment (LCA)	International Congress Series	vol. 1293 - pp. 230–233	Ishikawa, Hoshiba, Hinata, Hishinuma, Morita	2006
Wood	Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems	New South Wales Department of Environment and Conservation		Recycled Organics Unit_University of New South Wales	2006
	Life cycle assessment of wood wastes: A case study of ephemeral architecture	Science of the Total Environment	vol. 357 - pp. 1-11	Rivela, Moreiraa, Munoz, Rieradevallb, Feijooa	2006
	Life cycle assessment for optimising the level of separated collection in integrated MSW management systems	Waste Management	vol. 29 - pp. 934–944	Rigamonti, Grosso, Giugliano	2009
	Life Cycle Inventory of Particleboard: A Case Study in the Wood Sector	International journal of Life Cycle Assessment	vol. 11 - n°. 2 - pp. 106-113	Rivela_b, Hospido, Moreira, Feijoo	2006
	Life Cycle Assessment of Wood Floor Coverings: A Representative Study for the German Flooring Industry	International journal of Life Cycle Assessment	vol. 11 - n°.3 - pp.172-182	Nebel, Zimmer, Wegener	2006
	Life Cycle Assessment of a Biomass Gasification Combined-Cycle System	US National Renewable Energy Laboratory		Mann, Spath	1997
	Technical Approach for the Life Cycle Assessment and Economic Analysis of Organic Waste Management and Greenhouse Gas Reduction Options	California Integrated Waste Management Board		RTI International	2009
	Lifecycle assessment of biofuel production from wood pyrolysis technology	Educational Research and Review	vol. 2 - n°. 6 - pp. 141-150	Manyele	2007

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Wood	Dynamic life cycle assessment (LCA) of renewable energy technologies	Renewable Energy	vol. 31 - pp. 55–71	Pehnt	2006
	Carbon and energy balances for a range of biofuels options	Resources Research Unit Sheffield Hallam University		Elsayed, Matthews, Mortimer	2003
	CCA-Treated wood disposed in landfills and life-cycle trade-offs with waste-to-energy and MSW landfill disposal	Waste Management	vol. 27 - pp. S21–S28	Jambeck, Weitz, Solo-Gabriele, Townsend, Thorneloe	2007
	Life Cycle Assessment of Particleboards and Fibreboards			Frühwald, Hasch	1999
	Conservation of energy and natural resources by recycling building waste	Resources, Conservation and Recycling	vol.33 - pp.113-130	Thormark	2001
	Life cycle impact assessment of various waste conversion technologies	Waste Management	vol. 29 - pp. 1892–1900	Khoo	2009
	Evaluating synthesis gas based biomass to plastics (BTP) technologies	Chalmers University of Technology		Nouri, Tillman	2005
	Reuse, recycling and energy generation of recovered wood from building constructions	COST E31 Final Conference, Klagenfurt, May 2nd to 4th, 2007		Merl	2007
	Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives	Energy policy	vol. 28 - pp. 575-588	Börjesson, Gustavsson	2000
Textile	Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: An UK energy saving perspective	Resources, Conservation and Recycling	vol. 46 - pp. 94–103	Woolridge, Ward, Phillips, Collins, Gandy	2006
	Streamlined Life Cycle Assessment of Textile Recycling			ERM	2002
	Biomass gasification for the silk industry: India	Tata Energy Research Institute		Tata Energy Research Institute	2002
	Recycling of Low Grade Clothing Waste	Oakdene Hollins		Oakdene Hollins, Salvation Army Trading Company Ltd, Nonwovens Innovation & Research Institute Ltd	2006

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Textiles	EDIPTEX– Environmental Assessment of textiles	Danish Ministry of the Environment		Laursen, Hansen, Knudsen, Wenzel, Larsen	2007
	Well dressed?	University of Cambridge		Allwood, Laursen, Malvido de Rodriguez, Bocken	2006
	Clothing Take-Back for Recycling and Reuse: A Japanese Insight	Oakdene Hollins		Oakdene Hollins,	2007
	EU COST Action 628: life cycle assessment (LCA) of textile products, eco-efficiency and definition of best available technology (BAT) of textile processing	Journal of Cleaner Production	vol. 15 - pp. 1259-1270	Nieminen, Linke, Tobler, Vander Beke	2007
	Danish Initiatives on LCA and Textiles	LCA Center		LCA Center	2005
	Assessment of plasma gasification of high caloric waste streams	Waste Management	vol. 27 - pp. 1562–1569	Lemmens, Elslander, Vanderreydt, Peys, Diels, Oosterlinck, Joos	2007
	Life Cycle Assessment and evaluation of ecological recycling concepts for a textile PET fabric	Swiss Federal Institute of Technology Zurich		Mathieu, Tobler	XXXX
	Making The difference - Textile Recycling Today… Innovation For Tomorrow	Oakdene Hollins		Oakdene Hollins_b,	2007
	Influence of organofluorine-treated textiles on biowaste composting	Textile research Journal	vol. 1 - pp. 84-90	Hoppenheidt, Kotimair, Mucke	2000
	LCA Methodology Issues for Textile Products	Chalmers University of Technology		Dahllöf	2004
	Streamlined Life Cycle Assessment of Two Marks & Spencer plc Apparel Products	Marks & Spencer plc		ERM	2002
	Mapping of Evidence on Sustainable Development Impacts that Occur in the Life Cycles of Clothing	DEFRA		ERM	2007
	Analyse de cycle de vie d'un T-shirt			Pin	2004
	Environmental indicators of textile products for ISO (Type III)environmental product declaration	AUTEX Research Journal	vol. 3 - n°.4	Nieminen-Kalliala	2003

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
Textiles	Modelling of the textile chain for LCA	Textiltechnologie und Ökologie, Seminar Klippeneck 2001		Tobler-Rohr	2001
	From the cradle to the gate: a life cycle inventory on cotton trousers			Sundin	2002
	Environmental profile of cotton and polyester-cotton fabrics	AUTEX Research Journal	vol. 1 - n°.1	Kalliala, Nousiainen	1999
	Life cycle analysis of cotton towels: impact of domestic laundering and recommendations for extending periods between washing	The Royal Society of Chemistry	vol. 6	Blackburn, Payne	2004
	Life Cycle Assessment of Disposable and Reusable Nappies in the UK	Environment Agency		Aumonier, Collins	2005
	An approach to scenario analysis of the sustainability of an industrial sector applied to clothing and textiles in the UK	Journal of Cleaner Production	vol. 16 - pp. 1234–1246	Allwood, Laursen, Russell, Malvido de Rodrıguez, Bocken	2008
	Environmental benefits from reusing clothes	Technical University of Denmark		Farrant	2008
	Reducing Greenhouse Gas Emissions by Recycling Plastics and Textiles into Products	Finnish Environment Institute		Korhonen, Dahlbo	2007
	Analyse de Cycle de Vie comparée d'une chemise en lin et d'une chemise en coton			BIOIS	2007
	Analyse de Cycle de Vie d'un Pantalon en Jean	ADEME		BIOIS	2006
	Aide à la prise en compte de l'environnement dans la conception des articles textiles			IFTH, BIOIS	2005
All fractions	Carbon Balances and Energy Impacts of the Management of UK Wastes	Defra		ERM	2006
	Benefits of Recycling	New South Wales Department of Environment and Conservation		Department of Environment and Conservation	2005
	Solid waste management and greenhouse gases A Life-Cycle Assessment of Emissions and Sinks	US EPA		US EPA	2002

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
All fractions	Comparison between material and energy recovery of municipal waste from an energy perspective - A study of two Swedish municipalities	Resources, Conservation and Recycling	vol. 43 - pp. 51–73	Holmgren, Henning	2004
	Technical Approach for the Life Cycle Assessment and Economic Analysis of Organic Waste Management and Greenhouse Gas Reduction Options	California Integrated Waste Management Board		RTI International,	2009
	Recycling revisited—life cycle comparisons of global warming impact and total energy use of waste management strategies	Resources, Conservation and Recycling	vol. 44 - pp. 309–317	Bjorklund, Finnveden	2005
	Life cycle assessment for optimising the level of separated collection in integrated MSW management systems	Waste Management	vol. 29 - pp. 934–944	Rigamonti, Grosso, Giugliano	2009
	Analyse du Cycle de Vie comparative d'emballage pour magazines et imprimés adressés par voie postale	ADEME		BIOIS	2007
	Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems	New South Wales Department of Environment and Conservation		Recycled Organics Unit_University of New South Wales	2006
	Comparaison des technologies et des scénarios de gestion des matières résiduelles	Communauté Métropolitaine de Montréal		Ciraig	2006
	Environmental Assessment of Municipal Waste Management Scenarios: Part I– Data collectionand preliminaryassessments for life cycle thinking pilotstudies	JRC		JRC	2007
	Environmental Assessment of Municipal Waste Management Scenarios: Part II– Detailed Life Cycle Assessments	JRC		JRC	2008
	The use of LCA in selecting the best MSW management system	Waste Management		DeFeo, Malvano	2009
	Comparison of energy and material recovery of household waste management from the environmental point of view – Case Kaunas, Lithuania	Applied Thermal Engineering	vol. 29 - pp. 938–944	Luoranen, Soukka, Denafas, Horttanainen	2009
	Aerobic in-vessel composting versus bioreactor landfilling using life cycle inventory models	Clean Techn Environ Policy	vol. 10 - pp. 39–52	Cabaraban, Khire, Alocilja	2008

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
All fractions	Assessment of environmental objectives of seven scenarios for Warwickshire County Council	Warwickshire County Council		AEA Technology	XXXX
	Life cycle assessment of urban waste management: Energy performances and environmental impacts. The case of Rome, Italy	Waste Management	vol. 28 - pp. 2552–2564	Cherubini, Bargigli, Ulgiati	2008
	Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration	Energy	(in press)	Cherubini_b, Bargigli, Ulgiati	2008
	Greenhouse Gases and Waste Management Options	Friends of the Earth		Friends of the Earth,	2000
	Impact of Energy from Waste and Recycling Policy on UK Greenhouse Gas Emissions	Defra		ERM	2006
	Bioethanol from Waste: Estimation of Greenhouse Gas Saving Potential on a Life Cycle Basis			Stichnothe, Hau, Azapagic	XXXX
	Life Cycle Assessment of Waste and Resource Recovery Options (including energy from waste)	EcoRecycle Victoria		Grant, James, Partl	2003
	Life Cycle Assessment of municipal solid waste management - Cost, energy consumption, & CO2 emission -	Proceedings of International Symposium and Workshop on Environmental Pollution Control and Waste Management, 7-10 January 2002, Tunis		Matsuto	2002
	Life Cycle Based Cost-Benefit Assessment of Waste Management Options	ISWA Annual Congress 2006, 2006.10.1-5., Copenhagen		Weidema, Wesnæs, Christiansen, Koneczny	2006
	Life Cycle Assessment of Municipal Waste Management Options in Scotland	Scottish Government		Scottish Environment Protection Agency	2007
	Sustainable recycling of municipal solid waste in developing countries	Waste Management	vol. 29 - pp. 915–923	Troschinetz, Mihelcic	2009
	Life Cycle Assessment of waste management systems in Italian industrial areas:Case study of 1st Macrolotto of Prato	Energy		Tarantini, Loprieno, Cucchi, Frenquellucci	2007

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
All fractions	Waste gasification Impacts on the Environment and Public Health	The Blue Ridge Environmental Defense League		The Blue Ridge Environmental Defense League,	2009
	Life cycle impact assessment of various waste conversion technologies	Waste Management	vol. 29 - pp. 1892–1900	Khoo,	2009
	Sustainability Appraisal and Life Cycle Analysis of Strategic Waste Management Options	South West Wales Regional Group		Environment Agency Wales,	2006
	Maximizing Resource Recovery from Waste Streams	Environmental Progress	vol. 22 - n°.4 - pp.250-254	Grant_b,	2003
	Life cycle assessment of solid waste management options for Eskisehir, Turkey	Waste Management	vol. 29 - pp. 54–62	Banar, Cokaygil, Ozkan	2009
	The impact of municipal solid waste treatment methods on greenhouse gas emissions in Lahore, Pakistan	Waste Management	vol. 29 - pp. 63–69	Batool, Chuadhry	2009
	Carbon – Making the right choice for waste management in developing countries	Waste Management	vol. 28 - pp. 690–698	Barton, Issaias, Stentiford	2008
	Environmental and economic modelling: A case study of municipal solid waste management scenarios in Wales	Resources, Conservation and Recycling	vol. 49 - pp. 244–263	Emery, Davies, Griffiths, Williams	2007
	Life cycle assessment of waste to energy micro-pyrolysis system: Case study for an Italian town	International Journal of Energy Research	vol. 28 - pp. 449–461	Di Maria, Fantozzi	2004
	Biomass integrated gasification combined cycle with reduced CO2 emissions: Performance analysis and life cycle assessment (LCA)	Energy	vol. 29 - pp. 2109–2124	Corti, Lombardi	2004
	Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO2 removal	Energy Conversion and Management	vol. 46 - pp. 1790–1808	Carpentieri, Corti, Lombardi	2005
	Life cycle assessment of MSW-to-energy schemes in Thailand	Journal of Cleaner Production	vol. 15 - pp. 1463-1468	Chaya, Gheewala	2007
	Greenhouse gas emissions from composting and mechanical biological treatment	Waste Management & Research	vol. 26 - pp. 47–60	Amlinger, Peyr, Cuhls	2008
	Feasibility of energy recovery from municipal solid waste in an integrated municipal energy supply and waste management system	Waste Management & Research	vol. 25 - pp. 426–439	Luoranen, Horttanainen	2007

Material	Title of the publication	Journal/Publisher	Numero, page of the journal	Authors	Year
All fractions	Environmental impacts and costs of solid waste: a comparison of landfill and incineration	Waste Management Research	vol.26 - pp.147-162	Rabl, Spadaro, Zoughaib	2008
	Life cycle assessment of a national policy proposal – The case of a Swedish waste incineration tax	Waste Management	vol. 27 - pp. 1046–1058	Bjorklund, Finnveden	2007
	Flexible and robust strategies for waste management in Sweden	Waste Management	vol. 27 - pp. S1–S8	Finnveden, Bjorklund, Reich, Eriksson, Sorbom	2007
	Testing a SEA methodology for the energy sector: a waste incineration tax proposal	Environmental Impact Assessment Review	vol. 25 - pp. 1-32	Nilsson, Bjorklund, Finnveden, Johansson	2005
	Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion	Energy Policy	vol. 35 - pp. 1346–1362	Eriksson, Finnveden, Ekvall, Bjorklund	2007
	Analyse du Cycle de Vie des modes de valorisation du biogaz en France			RDC	2006
	Modelling of environmental impacts of solid waste landfilling within the life-cycle analysis program EASEWASTE	Waste Management	vol. 27 - pp. 961–970	Kirkeby, Birgisdottir, Bhander, Hauschild, Christensen	2007
	Life-cycle assessment of municipal solid wastes:Development of the WASTED model	Waste Management	vol. 26 - pp. 886-901	Diaz, Warith	2006
	Comparison between material and energy recovery of municipal waste from an energy perspective: A study of two Swedish municipalities	Resources, Conservation and Recycling	vol. 43 - pp. 51–73	Homgren, Henning	2004
	The impact of landfilling and composting on greenhouse gas emissions – A review	Bioresource Technology	doi:10.1016/j.biortech.2008.12.006	Lou, Nair	2008
	The use of LCA in selecting the best MSW management system	Waste Management	doi:10.1016/j.wasman.2008.12.021	De Feo, Malvano	2009
	LCA screening of waste treatment options for South Western Iceland			WSP	2008

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