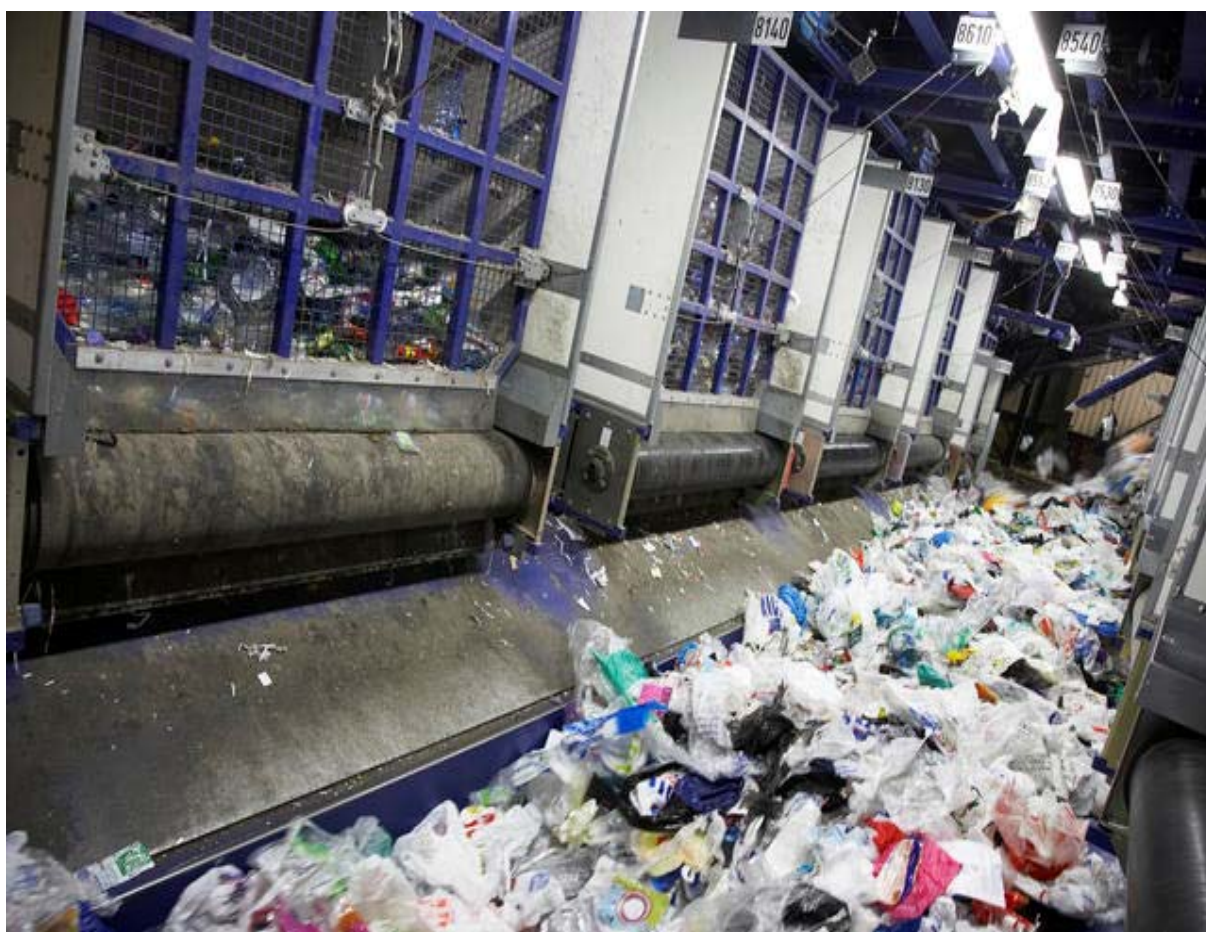


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Final Report

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# LCA of Management Options for Mixed Waste Plastics



WRAP helps individuals, businesses and local authorities to reduce waste and recycle more, making better use of resources and helping to tackle climate change.

**Written by:** Dr Peter Shonfield

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**Front cover photography:** Mixed Plastics in a materials recycling facility © WRAP

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# Executive summary

## Introduction

This report details an environmental life cycle assessment (LCA) study of a range of recycling technologies and includes comparison with a selection of alternative disposal options for domestic mixed waste plastic.

The study has been commissioned by WRAP to identify whether waste plastic recycling has the potential to deliver significant environmental benefits over existing waste management options. The work will inform WRAP's strategic planning process and determine whether this should be a priority area for further work. It is expected that recyclers and other stakeholders will also find this study useful in shaping their decisions regarding technology options for managing domestic mixed plastic waste.

Trials of mixed plastic waste recycling technologies from a wide range of organisations have been carried out as described in detail in the main report. Several alternative disposal/recovery technologies have also been assessed based on data obtained from published literature and life cycle inventory databases.

To enable comparisons to be made between the various technologies a series of scenarios have been developed to build up complete supply chains for the recycling process—each accepting the same mix of input materials. Where necessary, several technologies have been combined to produce a complete supply chain. These are described in the table below.

## Functional Unit

The basis for comparison between the various recycling technologies and alternative disposal routes is the recycling, reprocessing or disposal of 1 tonne of mixed plastic (and other residual materials) arising as waste from a typical UK materials recycling facility (MRF).

## Study boundaries

This life cycle assessment relates only to waste management options for mixed plastics. An assessment of the potential effect of managing mixed plastics as part of a mixed municipal waste stream was outside of the scope of this study.

For each recycling scenario the boundaries of the LCA study range from the point at which this mixed plastic waste leaves the MRF through to the production of granulate material ready to be made into “new” products. Non-recycled fractions are modelled up to the point at which the material is considered to be disposed of (e.g. in landfill) or to the point where it can substitute for a primary material (e.g. after the agglomeration process for producing a redox agent for blast furnace injection). In the case of recycled/recovered products the assessment also includes the avoided production of material or energy from primary sources. It should be noted that the chosen study boundaries mean that the process of collecting the mixed plastic waste is not included in the assessment.

The technologies included in this study are either already in use in sorting facilities or have been proven in principle in pilot plants and could be scaled up and deployed in the near future. As such the study represents the current situation or that which could exist within the next few years. Geographically, the work aims to reflect the situation in the UK.

## Impact assessment categories and relevant metrics

The following impact categories have been assessed:

- Global warming potential (GWP)
- Photochemical ozone creation potential (POCP)
- Eutrophication potential (EP)
- Acidification potential (AP)
- Human toxicity potentials (HTP)
- Ozone layer depletion potential (OLDP)
- Abiotic depletion potential (ADP)

Further metrics reported in the impact assessment include primary energy consumption and landfilled solid waste. The priority issues for WRAP are global warming potential and solid waste arising.

## Allocation procedures

A system expansion approach has been used to calculate the overall environmental performance of each scenario as follows:

$$\text{Environmental Performance} = \text{Process Impacts} - \text{Avoided Impacts of Primary Production}$$

“Process impacts” relate to the environmental impacts from operating each waste management option. The “avoided impacts of primary production” are the environmental benefit derived by replacing the need to produce functionally equivalent products from primary materials.

**Table 1** Key processes included in the modelled scenarios

Scenario	Key processes
A	■ Landfill (all materials)
B	■ Municipal incineration with energy recovery (all materials)
C	■ Near infra-red (NIR) sorting (Titech) ■ Conversion to solid recovered fuel (SRF) for cement kilns (non-PVC fraction) ■ Mechanical recycling of PVC fraction
D	■ Film removal (Stadler) ■ NIR sorting of rigids (Titech) ■ Pyrolysis of PP and PE fractions (BP polymer cracking process) ■ Mechanical recycling of PVC and PET fractions
E	■ Film removal (Stadler) ■ NIR sorting of rigids (Titech) ■ Pyrolysis of PP, PE and PS fractions (Ozmotech process) ■ Mechanical recycling of PVC and PET fractions
F	■ Film removal (Stadler) ■ NIR sorting of rigids (Titech) ■ Conversion of PE and PP fractions for use as redox agent in blast furnace ■ Mechanical recycling of PVC and PET fractions
G	■ Film removal (Stadler) ■ NIR sorting of rigids (Titech) ■ Mechanical recycling of PE, PP, PET and PVC fractions
H	■ Film removal (Stadler) ■ NIR sorting of rigids (Pellenc) ■ Mechanical recycling of PE, PP, PET and PVC fractions
I	■ Film removal (Stadler) ■ NIR sorting of rigids (Qinetiq) ■ Mechanical recycling of PE, PP, PET and PVC fractions
J	■ Film removal (Stadler) ■ NIR sorting of rigids (Sims) ■ Mechanical recycling of PE, PP, PET and PVC fractions
K	■ Film removal (KME) ■ NIR sorting of rigids (Titech) ■ Mechanical recycling of PE, PP, PET and PVC fractions
L	■ Film removal (Stadler) ■ Density separation (TLT) ■ Mechanical recycling of PE and PP fractions
M	■ Sorting and cleaning PE and PP fractions (Swiss Polymera) ■ Mechanical recycling of PE and PP fractions (Swiss Polymera)
N	■ Sorting and cleaning PE and PP fractions (B+B) ■ Mechanical recycling of PE and PP fractions
O	■ Film removal (Stadler) ■ Density separation (Herbold) ■ Mechanical recycling of PE and PP fractions
P	■ Film removal (Flottweg) ■ Density separation (TLT) ■ Mechanical recycling of PE and PP fractions

## Results

The summary table below gives the overall ranking of the scenarios in each impact category. The priority given to each impact category is based on an assessment of WRAP's own organisational targets and on the results of a normalisation exercise (nevertheless it should be recognised that all rankings of this type are based on subjective judgement rather than objective analysis).

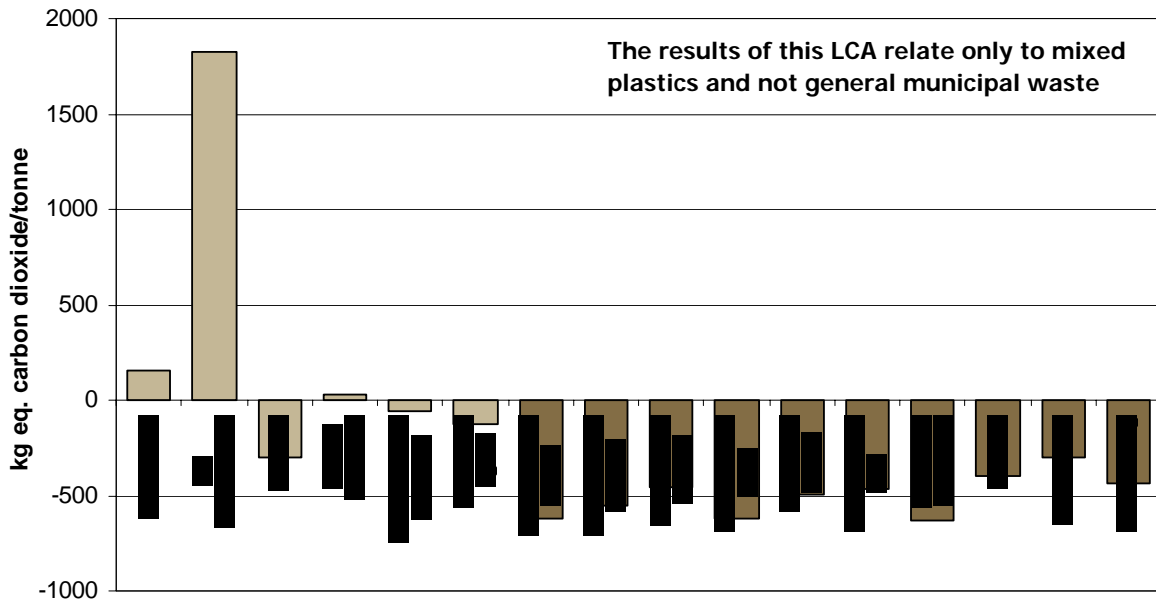
**Table 5.2** Summary of results showing relative ranking of the scenarios against each impact category (rank 1 = best, rank 16 = worst), green = top 25%, red = bottom 25%

Scenario	High priority				Low priority					
	Global Warming Potential	Solid Waste	Energy	Human Toxicity Potential	Eutrophication Potential	Photochemical Ozone Creation Potential	Acidification Potential	Abiotic Depletion Potential	Ozone Layer Depletion Potential	
A (Landfill)	15	16	16	16	16	16	16	16	16	
B (Incineration)	16	1	8	15	10	15	15	15	2	
C (SRF)	11	2	1	14	2	12	11	1	10	
D (BP pyrolysis)	14	12	4	2	8	13	13	14	3	
E (Ozmotech pyrolysis)	13	15	3	3	1	11	12	13	1	
F (Redox agent)	12	4	2	4	13	14	14	5	9	
G (Stadler & Titech)	1	5	5	5	3	6	4	3	6	
H (Stadler & Pellenc)	4	7	7	11	5	8	8	7	4	
I (Stadler & Qinetiq)	7	14	10	13	7	10	10	12	5	
J (Stadler & Sims)	2	6	6	6	4	7	5	4	7	
K (KME & Titech)	5	8	9	12	6	9	9	9	8	
L (Stadler & TLT)	6	10	12	8	11	3	2	6	11	
M (Swiss Polymera)	3	3	11	1	9	1	1	2	13	
N (B+B)	9	13	14	10	14	5	6	10	14	
O (Stadler & Herbold)	10	11	15	9	15	4	7	11	15	
P (Stadler & Flottweg)	8	9	13	7	12	2	3	8	12	

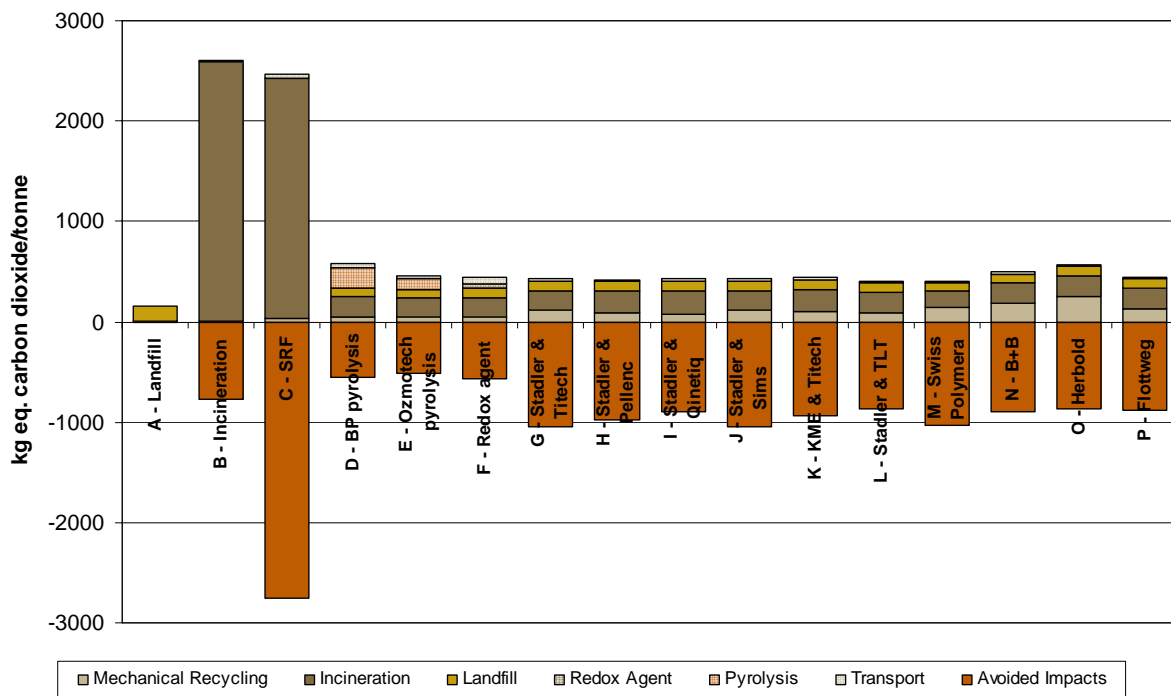
From this table it is clear that scenario A (landfill) is the option with the least favourable environmental performance followed by B (incineration) – although interestingly incineration has the best performance for solid waste arising, the second ranked impact category. The recycling scenarios (G – P) tend to have the best environmental performance if all impact categories are taken into account, but if the “WRAP priority impact categories” are studied then C (SRF) ranks in the middle of the recycling options.

Charts showing more detailed results for global warming potential and landfill (WRAP's priority impact categories) are given below. When reading the charts, positive values signify negative environmental impacts arising from the recycling/reprocessing supply chain. Negative values signify an environmental benefit and are due to avoided processes (e.g. avoiding the need to produce primary plastic).

**Chart 5.3.1** Net global warming potential



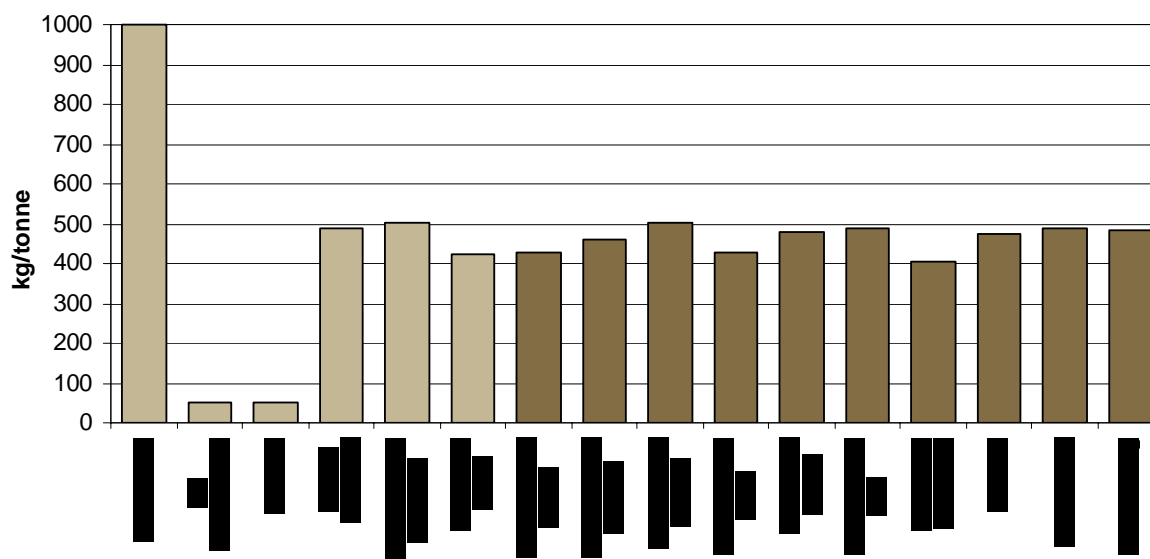
**Chart 5.3.2** Contribution to global warming potential by process stage



The results in most impact categories are dominated by the avoided emissions from substituted processes, as can be seen in the chart above showing the contribution to overall global warming potential from each process stage. This means that even quite large differences in process impacts are often obscured by the even larger benefits from avoiding the use of primary materials.

The chart showing solid waste arising is given below. Landfill, obviously, has the highest impacts in this category while the incineration scenarios (B and C) have the lowest impacts – plastic does not leave much residue when burnt. It is notable that all the other scenarios (D – P) result in broadly similar quantities of solid waste despite the diversity of technologies involved.

Chart 5.4.1 Solid waste arising



### Assumptions and uncertainties

A series of sensitivity analyses have been carried out to test the importance of some of the main assumptions on the results. Aspects that have been looked at include:

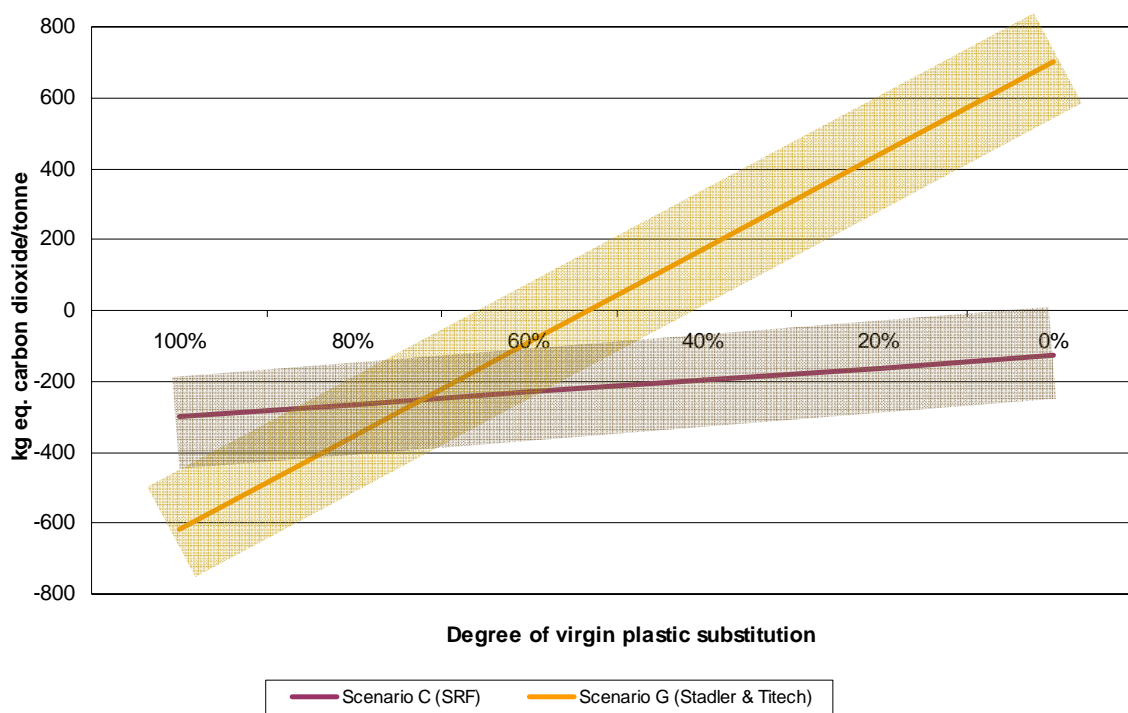
- feedstock composition (low polyolefin, default and high polyolefin mixes)
- thermal conversion efficiency of municipal incinerators
- choice of substituted power from municipal incineration
- choice of substituted material from recycling plastic

The sensitivity analyses show that all of these aspects do affect the environmental performance of the various scenarios assessed in this study. However, the most important issue is shown to be the choice of substituted material from recycling plastic. The default assumption in the study is that recycled plastic will substitute directly for virgin plastic on a 1:1 basis. This implies that high quality recyclates are obtained every time. The chart below plots the effects on global warming potential when increasing quantities of lower quality plastic is produced that can only substitute for wood or concrete rather than virgin plastic. Once the amount of virgin plastic substitution drops below about 70% scenario C (the SRF scenario) becomes favoured over scenario G (a recycling scenario based in NIR-sorting).

A cross-over in the preferred scenario also occurs for acidification potential (once the degree of virgin plastic substitution drops to below about 55%) and photochemical ozone creation potential impact categories (once the degree of virgin plastic substitution drops to below about 45%). Scenario G also shows large negative changes all in other impact categories other than human toxicity potential (which is more or less unchanged).

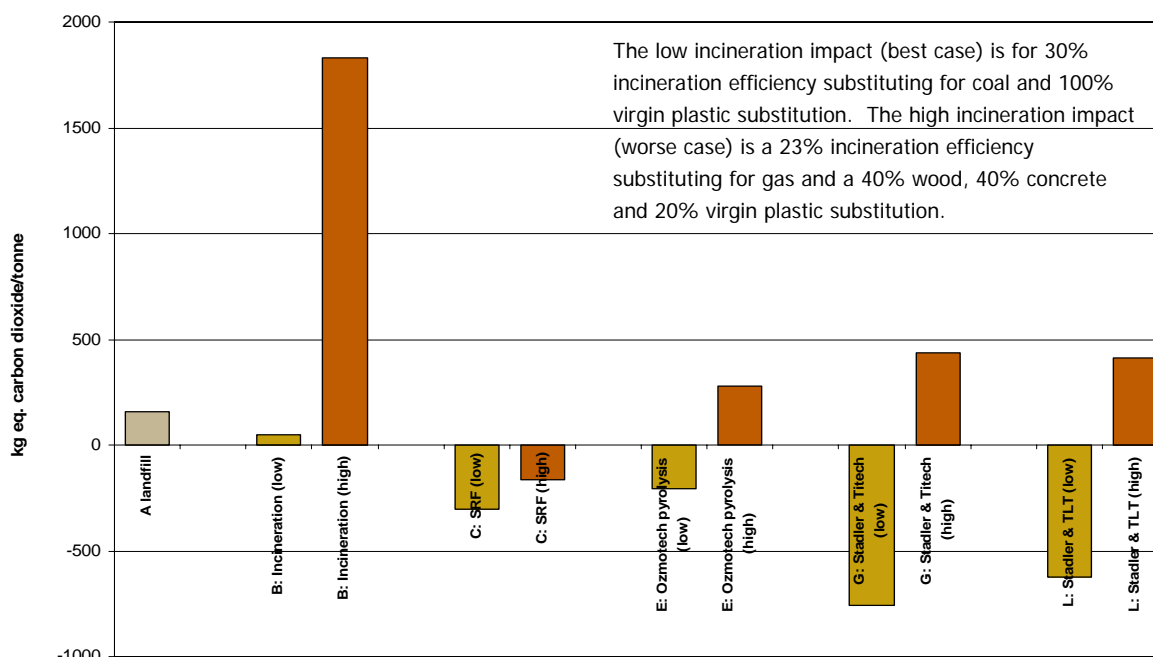
Due to the inherent uncertainties in LCA the “absolute” values presented here should be treated with some caution and there is likely to be considerable variation around the 70% figure due to the specific assumptions and datasets in this study. Nevertheless, despite this uncertainty the general principle holds that the quality of the recyclates is a very important aspect affecting the environmental performance of the recycling scenarios and that the best environmental performance is achieved when high quality recyclate is generated. If only lower quality recyclates are obtained then alternative disposal options may offer a better environmental solution.

**Figure 6.4.2** Sensitivity of substitution options for recycled plastic on global warming potential (comparison of scenarios C and G for varying degrees of substitution). Bands placed around each line to emphasise uncertainties in the data although these have not been quantified



This clearly is a critical issue for understanding the environmental performance of the recycling technologies – if a large proportion of the input material cannot be recycled to sufficient purity to replace virgin plastic then the contribution to total global warming potential of the recycling process is likely to become greater than that of alternative reprocessing/disposal options.

**Figure 6.5** Range of results for global warming potential when combining uncertainties associated with incinerator efficiency and for substitution options for power generation and recycling plastic.



These results have clear implications for the development of plastics recycling processes in the UK and shows that no single scenario is likely to provide a complete solution. Rather, waste plastics recycling plants should be designed to produce high quality recycled material. Lower quality recycled applications should not be considered – instead it is likely to be preferable for lower quality fractions to be sent for alternative reprocessing options such as SRF or use as a redox agent in blast furnaces.

The figure above shows the results of combining uncertainties associated with incinerator efficiency and for substitution options for plastic recycle and incinerator power generation. The effects of the different feedstock scenarios (high and low polyolefin content) have not been included in this assessment as they do not represent extremes but simply different material compositions (all of which are fairly likely and could represent typical output from the MRF). Given the number of components in the feedstock it is difficult to decide which “extreme” scenario (e.g. 100% PET output from the MRF) should be used and would end up modelling scenarios that are extremely unlikely to ever occur in practise.

The majority of the variation for scenarios E, G and L is due to substitution options for plastic recycling (ranging from 100% virgin plastic substitution through to 20% virgin plastic: 40% wood: 40% concrete). While for scenario B the key factor relates to substitution options for power generation at municipal incinerators (natural gas power vs. coal power). Scenario C (SRF) is largely insensitive to the aspects being considered in this assessment.

The results show that there are possible scenarios where incineration becomes preferable to recycling – when incineration substitutes for coal power and recycling does not produce high quality plastic recycle. However if it can be ensured that recycled plastic is of high quality then the recycling scenarios always have superior environmental performance to incineration for the global warming potential.

## Discussion and conclusions

This life cycle assessment relates only to waste management options for mixed plastics. An assessment of the potential effect of managing mixed plastics as part of a mixed municipal waste stream was outside of the scope of this study. The results only refer to the specific case where mixed plastic waste is sourced as output from a MRF and collection processes for the mixed waste plastic are not included within the study boundaries.

For most of the impact categories studied, landfill is less favourable than incineration of mixed plastics. However for global warming potential this study has found that incineration (with or without energy recovery) is the least favourable waste management option of those studied for domestic mixed plastics. On the basis of these results we can conclude that it is environmentally beneficial to remove mixed plastic from the waste stream prior to either landfilling or incineration. The diverted mixed plastics stream should be managed through a combination of mechanical recycling and SRF type processes.

Overall, the results of this LCA indicate that recycling scenarios are generally the environmentally preferable options for all impact categories considered in this study and with the assumptions made. However if one attempts to prioritise these impact categories and give more weight to the particular issues driving WRAP – global warming potential and solid waste – the results become more nuanced. The recycling options are favoured when considering global warming, but the Energy from Waste options (incineration and SRF) produce the least amount of solid waste.

This disparity is emphasised further by the high sensitivity of the results to the quality of the recycled plastic produced. The environmental performance of the recycling scenarios rapidly deteriorates as quality declines. Once the proportion of high quality recycle (that can substitute directly for virgin plastic) falls below a certain level it is likely that alternative waste management technologies will become the more favourable option. This assessment estimates the crossover point for global warming potential to occur once recycled plastic can only substitute for about 70% virgin plastic or less, but there is a large degree of uncertainty around this exact figure and the results differ for different impact categories.

The best environmental option will be to focus on developing facilities capable of delivering high quality recycled plastics that can substitute for virgin plastics. Where this quality cannot be achieved the material should be sent for use in alternative processing options such as SRF or for use as a redox agent in blast furnaces.

Another notable outcome of this assessment is that there is generally little to choose between the two main classes of recycling technologies – NIR sorting and density separation. NIR technologies can sort a wider variety of plastics, but density separation processes, while less flexible, tend to recover a higher proportion of their

selected plastics from the waste stream. Which technology is actually preferable from an environmental point of view may come down to whether markets can be found for the products from these recycling processes (this study assumes that such markets exist in all cases). Further discussion on the relative merits of the NIR sorting vs. density separation can be found in the main report, which includes assessment of the economic aspects of the various technologies.

The results relating to solid waste arisings are also interesting because they show that, for the individual recycling scenarios modelled, it is not possible to divert more than 60% of the material stream away from landfill. The same is true for the alternative reprocessing technologies, the exceptions being incineration and SRF to cement kilns (although the capacity of this latter option is limited in the UK). However it should be noted that by combining recycling technologies to give a full process a higher proportion can be recycled. This can be seen in the results for Process Design B (described in the main report) where a 67% recycling rate is achieved.

This happens for several reasons, a key one being the prevalence of landfill as the “default” disposal option for wastes that are difficult to recycle. For plastics-rich waste streams an increase in the use of incineration would help to reduce the quantities going to landfill. However a better approach would be to consider how to increase the amounts of recyclable wastes in the material stream. Understanding the strengths and weaknesses of the different recycling technologies can lead to the development of more sustainably designed plastic products.

For example, NIR-sorting technologies have difficulty sorting black plastics and can also get confused when packaging and their labels are made from different plastics (the sensor may “see” the label and so miss-sort the pack – a particular problem for shrink wrap labels that cover the whole bottle). Fairly simple design changes can overcome these problems.

For density separation technologies the main problems occur when the density ranges of different polymers overlap resulting in some inevitable mixing of polymer types in the overlapping region. This diversity in range is largely due to the use of additives and fillers to modify the properties of the polymers.

## Further considerations

No account is taken here of possible future changes in waste arisings (aside from noting in general terms the likely short-term trends in use of polymer types and consumption in Section 3.10), UK energy markets, technological advances and so on. To do so would require the development of a series of future scenarios subject to their own uncertainties. Purely in the interests of transparency, therefore, the analysis is based around current conditions. However, it is still informative to consider how things may change in the future, as it reflects on the long-term robustness of the results. To illustrate:

### ■ Waste arisings:

- The amount of plastic entering the waste stream will change
- The variety of plastics in the waste stream may reduce in response to the desire for recyclability
- Sorting speed and efficiency of technologies is likely to improve as they are utilised more widely
- The costs of these technologies will fall, again as experience with them increases

### ■ Energy technologies:

- The marginal technology for power generation (currently gas-fired CCGT) may change, possibly to less carbon intensive fuel cycles such as nuclear or renewables
- The efficiency of generation may improve
- In the medium to long term the fossil fuel cycles as developed in the UK may adopt carbon capture and storage, significantly reducing their greenhouse gas burdens

### ■ Incineration:

- There may be an increase in the efficiency of incineration processes, particularly if the utilisation of waste heat becomes more widespread
- The demand for plastic materials in incinerator feedstock may change in response to changes in the residual waste stream due to higher levels of recycling

### ■ Availability of alternative processes for handling plastic wastes:

- Cement kilns and blast furnaces may not have the capacity to take a significant fraction of plastic waste. WRAP could consider undertaking further work to assess which wastes are best disposed of through cement kilns and blast furnaces

■ Environmental technologies:

- Revision of the Large Combustion Plant and IPPC Directives may cause a reduction in emissions from various of the technologies considered in this report

More issues could be added, but the length of the list demonstrates that it is not possible to develop a clear idea of changes into the future. It is therefore recommended that WRAP keep the conclusions of this study (and others like it) under review as the waste management and other relevant sectors develop in the years to come.

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Carrying out LCA studies is a notoriously data intensive activity and this study could not have been completed without the assistance of a large number of project partners and data providers who have kindly contributed their time and expertise to help make the results of this assessment as robust and reliable as possible.

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Boustead Consulting	Ian Boustead	Peer review
ERM	Bernie Thomas	Peer review

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## 1.0 Introduction

Recent growth in local authority collection activity for a wider range of plastics packaging has highlighted the need for more sustainable waste management options to be developed for the non-bottle, mixed plastic packaging fraction.

Currently this material is normally landfilled or incinerated. WRAP has commissioned a project to assess the effectiveness of potential solutions to this problem. Plant trials of a range of sorting and recycling technologies for recycling domestic mixed waste plastic have been carried out using representative samples of mixed waste plastic arising from UK MRFs as described in detail in the main report. These trials have been supplemented with environmental and economic analyses.

This report comprises the environmental life cycle assessment (LCA) study of the chosen technologies including comparison with a range of alternative disposal options for domestic mixed waste plastic.

## 2.0 Goal

This study aims to inform the debate on which technologies offer the most environmentally friendly and cost effective solutions for dealing with domestic mixed plastics waste. A selection of leading plastics recycling technologies have been assessed along with a range of alternative disposal/recovery options. The study considers both the impacts from the recycling process (or alternative disposal route) and the benefits from producing the recycled materials and other recovered products.

In conjunction with a parallel economic assessment the results of the LCA study will be published and made publicly available. The work has been commissioned by WRAP to identify whether waste plastic recycling has the potential to deliver significant environmental benefits over existing waste management options. The results will inform WRAP's strategic planning process and determine whether this should be a priority area for further work. It is expected that recyclers and other stakeholders will also find this study useful in shaping their decisions regarding technology options for managing domestic mixed plastic waste.

The study complies with the ISO 14040 series of standards governing the use of LCA <sup>1,2</sup>, and has been critically reviewed (see Appendix 5).

## 3.0 Scope

### 3.1 Product Systems

Trials of a wide range of technologies suitable for recycling mixed plastic waste have been undertaken as described in detail in the main report.

Several alternative disposal/recovery technologies have also been assessed based on data obtained from the published literature and life cycle inventory databases (no trials were run on these processes). The options considered include:

- landfill
- incineration with energy recovery (energy from waste)
- use as solid recovered fuel (SRF) in cement kilns
- pyrolysis technologies (feedstock recycling; conversion to diesel)
- redox agent for blast furnace injection (coke substitute)

A number of previously published reports <sup>3-12</sup> have looked at some or several of these technologies and have been drawn upon to assist with this assessment.

### 3.2 Scenarios

A key challenge in this study is to ensure that the technologies are compared on a fair basis. This is complicated by the varying capabilities of the chosen technologies. Some offer comprehensive solutions

taking the mixed plastic waste and converting it to recycled material, others can deal with only part of the recycling process or require specific input materials (e.g. separating film from rigid, or sorting plastics from a rigid waste stream).

To enable a comparison to be made between the technologies a series of scenarios have been developed to build up complete supply chains for the recycling process—each accepting the same mix of input materials. Where necessary, several technologies have been combined to produce a complete supply chain. The scenarios are described in detail in Sections 4 and 5 and were selected in discussion with Scott Wilson, RECOUP and Bowman Process Technology. They were developed with the aims of:

- allowing a fair comparison between technologies by ensuring the study boundaries are consistently applied for all the options
- enabling a clear comparison to be made between different technologies
- examining a broad range of management options for treating mixed plastic

### *3.2.1 Recycling technologies*

The recycling scenarios are intended to model the situation where the major polymer types in the waste stream are separated and mechanically recycled. These scenarios are also modelled in the parallel economic assessment and some consideration has been taken of the commercial viability of the recycling options (e.g. most scenarios assume that polystyrene is not recovered as it is present in only small quantities in the waste stream).

The non-recycled materials – non-sorted plastics, fibres and labels, cans and other residues – are assumed to be disposed of using the UK average mix of landfill and incineration with energy recovery.

### *3.2.2 Alternative reprocessing/disposal options*

A series of alternative options have also been included in this study to provide comparison with the recycling technologies.

These include landfill, incineration with energy recovery and conversion to solid recovered fuel (SRF) all of which are established routes for dealing with mixed plastic wastes. Landfill and incineration are modelled very simply with no pre-processing or sorting required. Conversion to SRF requires a low chlorine content feedstock so this scenario assumes a NIR sorter is used to separate the PVC from the rest of the waste material.

Two less mature options for the UK market have also been assessed – pyrolysis (two versions: feedstock recycling and conversion to diesel) and use of plastic as a redox agent in the steelmaking process. These applications are restricted in the range of materials they can take – polyolefins only for feedstock recycling and redox agent applications, and polyolefins plus polystyrene for conversion to diesel – so pre-sorting of the plastic waste is required in each case. The other sorted plastic fractions (PVC, PET, etc.) are assumed to be sent for recycling.

## 3.3 Functional Unit

The basis for comparison between the various recycling technologies and alternative disposal routes is the recycling, reprocessing or disposal of 1 tonne of mixed plastic (and other residual materials) arising as waste from a materials recycling facility.

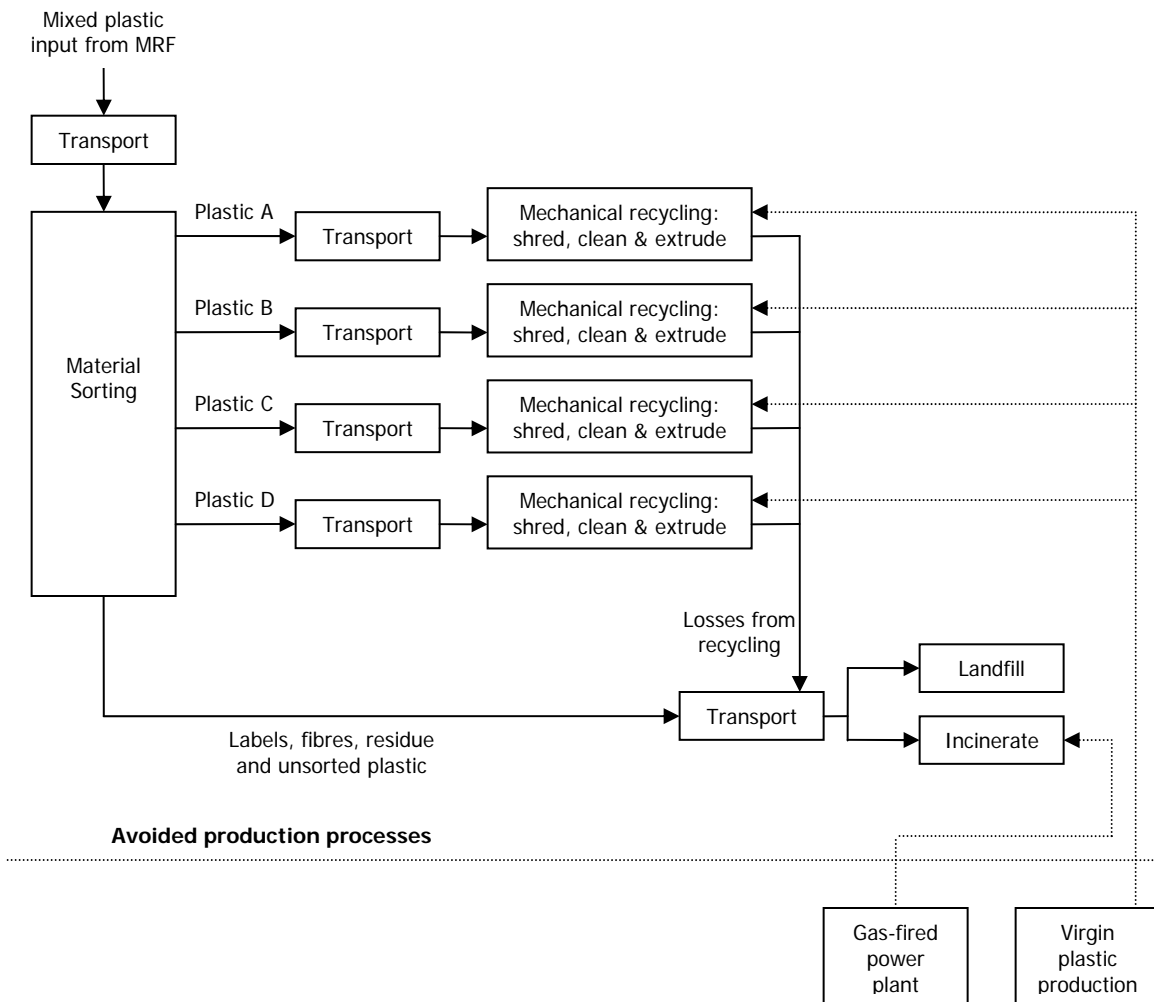
## 3.4 Study boundaries

The technologies included in this study are either already in use in sorting facilities or have been proven in principle in pilot plants and could scaled up and deployed in the near future. As such the study represents the current situation or that which could exist within the next few years.

Geographically, the study aims to reflect the situation in the UK – using UK-specific power generation mix, transport distances, municipal disposal options, etc. It is assumed that domestic waste is collected and processed through materials recycling facilities (MRFs). During this process most of the easily recycled/high value materials are removed leaving a remainder consisting mainly of mixed plastics with some other residual materials as described in Table 3.2.

It should be noted that collection processes for the mixed waste plastic lie outside the study boundaries and so have not been included in this assessment. The results only refer to the specific case where mixed plastic waste is sourced as output from a MRF and so may not be applicable to other sources of mixed plastic waste. However, with pressure in the UK to increase recycling and with more material passing through MRFs it seems inevitable that these will represent an increasingly important source of mixed waste plastics in future.

**Figure 3.4** Example process diagram showing the system boundaries\*



\* For clarity, provision of utilities (power, water, etc) are omitted from this diagram but would be included in the assessment.

For each scenario the boundaries of the LCA study range from the point at which this mixed plastic waste leaves the MRF through to the production of granulate material ready to be made into “new” products. Non-recycled fractions are modelled up to the point at which the material is considered to be disposed of (e.g. in landfill) or to the point where it can substitute for a primary material (e.g. after the agglomeration process

for use as a redox agent for blast furnace injection). It should be noted that the chosen study boundaries mean that the process of collecting the mixed plastic waste is not included in the assessment.

In the case of recycled/recovered products the assessment also includes the avoided production of material or energy from primary sources (see Figure 3.4). This follows system expansion methodology commonly applied in LCA studies, which, in this case, is used to account for the benefits of the recycling/recovery processes (see Section 3.10 on allocation methods for more information on this approach).

In general, the following processes are included within the study boundaries for the scenarios:

- Transport
  - from MRF to recycling facility
  - between sub-processes during recycling/reprocessing
  - to final disposal options for waste produced during the recycling process
- Production of ancillary inputs (e.g. sodium hydroxide for caustic wash processes)
- Production of electricity and other fuels
- Supply of water
- Shredding, cleaning and granulating processes required to produce granulate ready for extrusion into a “new” product
- Activities specific to alternative disposal processes (e.g. agglomeration for producing a redox agent for blast furnace injection)
- Production of displaced virgin material or energy from primary sources
- Disposal of waste products

The following processes are considered to lie outside the study boundaries and have not been included in the assessment:

- Production and maintenance of capital equipment (unless maintenance issues turn out to be potentially significant – e.g. requiring replacement parts on a weekly basis). It is expected that these impacts will be negligible compared to the impacts associated with running the equipment over its operational lifetime.
- Activities not specific to the plastics recycling process – e.g. building heating and water supply, impacts related to labour required to operate equipment. Impacts from these activities would be shared with other operations and would vary considerably depending on the size and complexity of the site. Including these aspects is not considered necessary with regards to the goal of this study.

## 3.5 Data requirements

### 3.5.1 Technology

Recycling technology is continually developing. This LCA study compares a range of leading technologies for recycling mixed plastic waste. In several cases the trials are taking place on pilot plants rather than full scale facilities. This leads to complications interpreting the data as full scale operations are likely to be optimised for efficiency relative to demonstration plants. Where possible the LCA study has developed results based on expected utilities requirements for running a full scale facility, but using the sorting/recycling performance data collected in the pilot plant trials.

### 3.5.2 Timescales and data sources

Trial data have been collected for the recycling processes modelled in this study and, as such, represent the most up to date data available. Data on alternative disposal options are taken from a variety of sources including published literature and life cycle inventory databases such as the Ecoinvent database<sup>13</sup>. In the

interests of transparency the analysis is based on current conditions with respect to waste arisings, technologies, etc. This issue is discussed further in Section 7.

Consideration of timescales also affects some aspects of the impact assessment. The relative contribution of greenhouse gases to the total global warming potential is assessed over a 100 year timescale. The Ecoinvent data on landfill used in the models assess leaching over a very long term (60,000 year) time horizon and, as such, represent a worst case scenario that is particularly noticeable when assessing eutrophication potential. The data assume that landfilled plastic will entirely decompose and that the landfill lining will be breached so nitrogen containing chemicals in the plastics can leach out into the environment. Over a shorter time horizon (say, 100 years), very little plastic will have decomposed and the landfill lining would be expected to remain in place meaning that actual eutrophication over this period would probably be near zero.

### *3.5.3 Geography*

The focus of this LCA study is to assess options for the UK situation. Where UK specific data are not available data representative of the situation in Western Europe have been used. Several of the recycling trial sites are located in other European countries (Germany, Switzerland & France). It is expected that the direct performance of the processes (energy consumption, recycling efficiency, etc) would not be affected by location and that the results of the recycling trials are directly applicable to the UK situation.

## 3.6 Key assumptions

### *3.6.1 Approach to modelling the scenarios*

The large number of different materials in the waste stream and the potential for cross-contamination of a recycled stream with other materials makes these scenarios very complex to model.

As such, a number of assumptions have been made to simplify the assessment. The approach taken bases the LCA modelling on the recycling efficiency of the sorting process (i.e. how much of each material type is extracted from the waste stream for recycling). The modelling also takes account of the purity of the sorted fractions as it is assumed that mis-sorted materials are, in fact, left as residue from the sorting process and disposed of to landfill and incineration with energy recovery. This is a conservative assumption, assigning impacts to the mis-sorted product and ensuring that the benefits of recycling a plastic – the avoided impacts of virgin production – are not attributed to impurities in the recyclates.

### *3.6.2 Feedstock composition*

Trial samples were secured from Valpak Recycling's MRF in Preston. To put the results of this LCA study in context it is important to understand how representative these MRFs are of the typical situation in the UK, the types of feedstock they accept, and what proportion of the total plastic waste arising might be expected to be obtained from these types of operation. These issues are discussed in detail in the main report.

Due to the nature of the MRF process the composition of this material is not consistent but can vary widely from batch to batch. NIR spectroscopic analysis of the feedstock at some of the trials showed that there is large variation even between bags of material collected at the same time.

This variation in feedstock clearly has implications for dealing with the data collected at the trials – as each will have been run using different mixes of material. To ensure consistency the following approach has been adopted:

- trial data are used to determine the recycling efficiency of each material stream (the proportion of that material extracted from the input feedstock)
- these efficiencies are then applied to a standardised “default input mix” that is applied to all the scenarios

A typical mix of materials leaving the MRF is given in Table 3.6.2 and labelled the Default Composition (again, based on NIR spectroscopic analysis from the trials). To examine the effect of variation in this composition two alternative material mixes have also been assessed. The first is a high polyolefin mix – with an increased proportion of PE and PP, and the second a low polyolefin mix – with higher proportions of PS, PVC and PET. The non-plastic components of the waste stream are unchanged in each case.

It is further assumed that 10% of the plastic is black (e.g. food trays). Due to its low reflectivity, black polymer is not well sorted by NIR technologies. The actual sort efficiency of each NIR technology with regard to black plastic was not assessed during the trials but is estimated at 50% in all cases for the purpose of this study. Based on an assessment of the black plastic by Axion following the trials at Titech, it is assumed that its composition of this material is 20% PS, 25% PE, 25% PP and 30% PET.

**Table 3.6.2** Composition of input material to recycling processes by material type

Material type	Default Composition, %	High Polyolefin Alternative, %	Low Polyolefin Alternative, %
Aluminium	1	1	1
Carton Board	1	1	1
Steel	1	1	1
Paper	3	3	3
Polyethylene (PE) – Film	5	6	0
Polyethylene (PE) – Rigid	10	20	5
Polyethylene terephthalate (PET) – Film	2	0	2
Polyethylene terephthalate (PET) – Rigid	15	5	35
Polylactic acid (PLA) - Rigid	3	3	3
Polypropylene (PP) - Rigid	40	50	10
Polystyrene (PS) – Film	1	0	2
Polystyrene (PS) – Rigid	5	3	10
Polyvinyl chloride (PVC) – Film	1	0	2
Polyvinyl chloride (PVC) – Rigid	10	5	23
Residue	2	2	2

### 3.6.3 Municipal waste disposal

Statistics from Defra <sup>14</sup> on management of municipal waste for 2006/7 show that of those waste streams that are not currently composted or recycled, 84% go to landfill and 16% to incineration. Energy is recovered from 99.8% of the incineration processes – in the LCA models it is assumed 100% of incineration processes are equipped for energy recovery.

### 3.6.4 Transport

A number of assumptions have been made regarding the structure of the supply chain, modes of transport and the distances traveled.

For the recycling scenarios it is assumed that all required sorting and cleaning processes are co-located so no transport (other than e.g. conveyor belts) is needed to move material between process stages,

Transport in all cases is assumed to be by 32 tonne (gross weight) lorries with a full outward load and an empty return trip. It is assumed that these lorries comply with Euro IV emissions standards. Transport distances used in the model are given in Table 3.6.4. It is not possible to determine the degree to which these assumptions are representative of actual waste movements. They represent a ‘best guess’ of the distances over which materials would be transported.

The only UK blast furnaces are run by Corus Group plc and are located at Port Talbot, Scunthorpe and Teesside. It may be the case that, in practice, steel works would only source plastic from areas local to the

blast furnaces. However, to maintain a fair comparison with other scenarios (which do not make allowance for location) a high transport distance has been assumed used for this scenario.

**Table 3.6.4** Transport distances used in the LCA models

Route	Distance, km
From MRF to polymer sorting facility	50
Typical distance to landfill site	20
Typical distance to incinerator (energy recovery facility)	50
Typical distance to mechanical recycler of plastic	50
Typical distance to blast furnace for redox agent injection	200
Typical distance to pyrolysis facility (diesel production)	50
Typical distance to pyrolysis facility (BP process)	100
Typical distance to cement kiln	100

### 3.6.5 Electricity consumption and generation

All electricity use is assumed to lead to emissions based upon UK average electricity generation. All electricity generation (from incineration with energy recovery) is assumed to displace gas-fired generation in a combined cycle plant – as this is the expected marginal electricity source. This approach follows UK Government guidelines on evaluation and appraisals of greenhouse gas policy<sup>15</sup> and has been applied elsewhere<sup>16, 17</sup>.

However it may also be argued that power generation from municipal incinerators should displace the use of UK grid electricity, produced from the mix of UK power sources. A sensitivity analysis of this option has been undertaken and is discussed in Section 6.4.

### 3.6.6 Mechanical recycling

The mechanical recycling process requires the waste plastic to be shredded and extruded to form recycled granulate ready for use in “new” products. Shredding processes designed to give a product less than 80 mm in diameter typically have a power requirement in the range 16 – 32 kWh/tonne<sup>18</sup>, and an average of 24 kWh/tonne has been used in the LCA models.

Extruders are considerably more energy intensive and typically require 240 – 300 kWh/tonne<sup>19</sup>, an average of 270 kWh/tonne is assumed in this assessment. Based on data from the Swiss Polymera trial it further is assumed that there is 2% material loss during this process. Possible emissions (e.g. of VOCs) resulting from the extrusion process have not been assessed due to lack of data. These would mainly be of relevance to the Photochemical Ozone Creation Potential impact category, which is not considered a priority category by WRAP.

Agglomerators required to process plastic in preparation for injection into a blast furnace are estimated to require 100 – 250 kWh/tonne<sup>20</sup>, an average value of 175 kWh/tonne has been used in this assessment.

A further important assumption in this study is that markets exist for the recycled plastics that are produced – PP, PE, PET, PVC and mixed PP/PE blend depending on the scenario. If markets are not available for some of these recycled plastics it has a large impact on the results as the credits received for substituting primary plastics will be reduced (see Section 3.9).

## 3.7 Inventory analysis

The life cycle inventories generated for each scenario are built up from the inputs and outputs of the component processes as described in Section 4. All energy and material flows crossing the system boundaries are quantities of environmental relevance (energy and material resources and wastes and emissions). These flows are recorded for each unit process and summarised across the entire system to

form the life cycle inventory. Some specific inventory items (e.g. solid wastes, energy consumption) are used directly as relevant metrics for assessing the scenarios (see Section 3.8).

GaBi 4 Professional LCA software <sup>21</sup> has been used to model the scenarios and generate the life cycle inventories and impact assessments on which the study conclusions are based. This software is a state-of-the-art tool for carrying out LCAs. The user can generate “processes” in the software to model the data collected from the plant trials. Where required, secondary datasets can be added to account for background processes such as power production, landfill, transport, etc. Many of these datasets including Ecoinvent v1.3 are fully integrated into the software.

The models developed in this way are easy to visualise using graphical user interface and can be parameterised to assist with scenario modelling and sensitivity analyses. GaBi 4 Professional also incorporates a range of options for impact assessment (including the CML 2 Baseline Methods described below), normalisation and weighting.

### 3.8 Impact assessment categories and relevant metrics

The CML 2 Baseline Method characterisation factors <sup>22, 23</sup> have been applied in this study. The following impact categories have been assessed:

- Global warming potential (GWP)
- Photochemical ozone creation potential (POCP)
- Eutrophication potential (EP)
- Acidification potential (AP)
- Human toxicity potentials (HTP)
- Ozone layer depletion potential (OLDP)
- Abiotic depletion potential (ADP)

The CML impact indicators focus on the so-called midpoints of the cause-effect chain. This means that they aggregate data on emissions (the starting points in the cause-effect chain) to *potential* impacts in various categories (e.g. global warming, acidification, etc.), but do not go as far as to assess the endpoints, such as loss of biodiversity, damage to human health, etc. caused by these impacts.

Further metrics reported in the impact assessment include primary energy consumption (measured as gross calorific value) and landfilled solid waste. The solid waste metric accounts for:

- all non-recycled/reprocessed fractions of the waste stream (i.e. impurities and non-recycled plastics) that go direct to landfill
- landfilled residues from incineration
- landfilled residues from reprocessing operations

The total solid waste will be influenced by the composition of the feedstock and by the effectiveness of the recycling processes.

The CML defined impact categories occur on different scales ranging from global (GWP, OLDP and ADP), regional (AP) and local (POCP, EP and HTP), and the relevance of the point of emission becomes more important as more local impacts are considered. A kg of carbon dioxide emitted anywhere in the UK will give the same contribution to global warming as a kg of carbon dioxide emitted in Australia, whereas for more regionally confined impact categories only emissions that occur nearby will have a real impact.

This issue is a general weakness of the LCA technique and so the results generating from using these impact categories should be considered to be worst-case *potential* impacts rather than actual impacts on the environment. However, WRAP has identified global warming potential as its priority issue, followed by solid waste arising, both of which can both be considered “global” in scale.

### 3.9 Allocation procedures

A common problem in LCA studies is how to allocate impacts from processes that produce multiple products. This allocation issue does not arise in this study as the functional unit is based on material input to the process rather than to a specific output. Thus, all impacts from the subsequent recycling, recovery and disposal processes are assigned to the input material.

However, there is a need for allocation to account for the *benefits* of recycling, reprocessing and energy recovery processes modelled in this study. Waste management technologies produce different types and quantities of recycled/reprocessed products—energy, fuel, secondary raw materials, etc. Therefore, a fair comparison of these technologies must account for both the impacts of the process and the benefits of the products. This LCA study uses a system expansion approach to calculate the overall environmental performance of each scenario as follows:

$$\text{Environmental Performance} = \text{Process Impacts} - \text{Avoided Impacts of Primary Production}$$

“Process impacts” will be assessed using standard LCA methodology to account for material and energy flows to get an understanding of the environmental impacts from operating each waste management option.

**Table 3.9.1** Impacts associated with primary production of 1 tonne of selected plastics (for calculating avoided impacts only the process energy required to produce the virgin material is considered as the energy of the feedstock is not depleted)

Impact Category	Units	PET	HDPE	PP	PS	PVC
Process energy (ex. feedstock energy)	MJ	43336	26399	24396	43587	38841
Abiotic Depletion Potential	kg eq. Sb	33	33	33	38	18
Acidification Potential	kg eq. SO <sub>2</sub>	12	21	20	17	10
Eutrophication Potential	kg eq. PO <sub>4</sub> <sup>+</sup>	3	1	1	2	1
Human Toxicity Potential	kg eq. DCB	735	67	50	55	151
Ozone Layer Depletion Potential	kg eq. R11	0	0	0	0	0
Photochemical Ozone Creation Potential	kg eq. C <sub>2</sub> H <sub>4</sub>	2	3	2	2	1
Global Warming Potential	kg eq. CO <sub>2</sub>	2468	1891	1999	2776	1336

The “avoided impacts of primary production” are the environmental benefits derived by replacing the need to produce functionally equivalent products from primary materials, e.g. production of 1 kWh of electricity from incinerating plastic will avoid emissions associated with producing 1 kWh of electricity from alternative sources. The impacts associated with producing virgin plastics are given in Table 3.9.1, recycling plastics will avoid these impacts. These figures are derived from datasets provided by Plastics Europe representing European average production. The full choice of “avoided processes” modelled in this study is given in Table 3.9.2.

It is recognised that plastics will undergo some degradation with each thermal recycling process and that impurities in the recyclate may become concentrated after subsequent recycling steps. This needs to be taken in to consideration when closed loop recycling is undertaken and multiple recycling loops are possible. However the mixed plastics plants envisaged in this work will not recycle plastics packaging back into packaging and so it is considered highly unlikely to result in multiple recycling loops. In addition the plant will divert a significant proportion of the input material in to energy recovery rather than recycling, further reducing the significance of dealing with multiple recycling loops. The output material from the technologies assessed in the trials (for a single recycling loop) was considered to be of high quality and suitable to substitute for virgin material (this is discussed in more detail in the main report).

**Table 3.9.2** Avoided impacts from recycling, reprocessing and energy recovery

Resource	Avoided Process	Basis for Substitution
Recycled plastic granulate	Production of virgin plastic powder or pellet	Recyclate performs the same function as virgin plastic – 1 kg recyclate substitutes for 1 kg virgin plastic
Power (from incineration with energy recovery)	Production of power using average UK electricity mix	Direct equivalence – 1 kWh power from incineration replaces 1 kWh power from a combined cycle gas power plant
Redox agent for blast furnace injection	Production of coal	Polyolefin fraction replaces coal based on reducing potential – 1 kg plastic replaces 1.58 kg coal (see explanation above)
Diesel oil replacement (Ozmotech pyrolysis process)	Production of diesel from crude oil	Direct equivalence – 1 kg pyrolysis-derived oil replaces 1 kg diesel from crude oil
Gas fraction (BP polymer cracking process)	Production of refinery gas from crude oil processing	Direct equivalence – 1 kg gas replaces 1 kg refinery gas from crude oil
Light fraction oil (BP polymer cracking process)	Production of naphtha from crude oil processing	Direct equivalence – 1 kg light fraction oil replaces 1 kg naphtha from crude oil
Heavy fraction oil (BP polymer cracking process)	Production of paraffin from crude oil processing	Direct equivalence – 1 kg heavy fraction oil replaces 1 kg paraffin from crude oil
Solid recovered fuel	Production and combustion of coal	Plastic replaces coal based on calorific value – 1 MJ from plastic replaces 1 MJ from coal

In the scenario where plastic (polyolefin) is used as reducing agent in a blast furnace it is assumed that the most likely situation for the UK situation would be for it to replace pulverised coal<sup>24, 25</sup>. In current practise the coal is injected into the bottom of the blast furnace via copper tuyeres and plastic would be added in the same way – correct material preparation is essential to avoid the material adhering to, or damaging, the tuyeres.

The substitution in this scenario is based on the relative reducing potential of coal and polyolefin. The chemistry of a blast furnace is very complicated so a simplified approach has been taken using the following assumptions:

- Each carbon atom reacts with oxygen in the air to form carbon monoxide. Each molecule of carbon monoxide then reacts with an atom of oxygen in the iron ore to form carbon dioxide – reducing the ore.
- Two atoms of hydrogen are required to react with each atom of oxygen in the ore, forming water.
- Direct reduction of iron ore with carbon has been ignored. This will have little effect on the results as both polyolefin and coal have very similar carbon content.
- Side reactions (e.g. where water formed from the reduction reaction donates oxygen to carbon to produce hydrogen and carbon monoxide that are then available for further reduction) also been ignored

With coal typically containing 84% carbon and 4% hydrogen (the remainder being coal ash)<sup>26</sup> this implies that 1 kg coal contains 70 moles of carbon and 40 moles of hydrogen – potentially reacting with 90 moles oxygen in the iron ore.

Polyolefins have a carbon:hydrogen ratio of 1:2 (ignoring fillers, additives, etc.) and so contain 85.8% carbon and 14.2% hydrogen. As such, 1 kg polyolefin contains 71.5 moles of carbon and 142 moles of hydrogen – potentially reacting with 142.5 moles oxygen in the iron ore. This leads to a substitution based on 1 kg polyolefin replacing 1.58 kg coal.

### 3.10 Uncertainty and sensitivity analyses

This study uses a number of assumptions for which only poor or conflicting data are available, or that that may open to interpretation depending on the point of view of the reader. The range of uncertainties in the LCA results is discussed in Appendix 4 and a series of analyses have been carried out to examine the sensitivity of the results to the most important of these uncertainties. The results are discussed in detail in Section 6 and the aspects that have been looked at include:

- **feedstock composition (low polyolefin, default and high polyolefin mixes).** There is considerable variation in the composition of the mixed waste plastic output from the MRFs. Sensitivity analysis has been carried out looking at compositions with high and low levels of polyolefin as detailed in Table 3.6.2.
- **thermal conversion efficiency of municipal incinerators.** There is significant variation in published values for the thermal conversion efficiency of municipal incinerators. As a default it is assumed that 23% of the input energy (net calorific value) is converted to electricity. Sensitivity analysis has been carried out to assess the impact of higher, 30% efficient plant, and lower, 15% efficient plant.
- **substituted material from recycling plastic.** The default assumption is that recycled plastic obtained from the recycling processes is of high quality and substitutes directly for virgin plastic on a 1:1 basis. The sensitivity of the results to this assumption has been tested by considering an alternative basis for substitution where only 20% of the recycle replaces virgin plastic. The remaining lower quality material is assumed to replace concrete (40%) and wood (40%), e.g. in applications such as fencing.
- **substituted power from municipal incineration.** The assumption that power generation from combustion of wastes at a municipal incinerator substitutes for that generated by a combined-cycle gas power plant is in line with UK Government guidelines on evaluation and appraisals of greenhouse gas policy as discussed in Section 3.6.5. However, an alternative choices assuming that this electricity substitutes for power from coal power plants and from the UK grid, (i.e. from the range of UK power suppliers including gas, oil, coal, nuclear, hydro, wind, etc.) have also been assessed.

Another uncertainty, and one that is very difficult to predict, is for how long the results of this study will remain valid. A key variable here is the composition of the waste stream. This could be affected by new legislation (e.g. banning or taxing certain plastics), technological developments leading to new plastic types entering the waste stream, and the cost of crude oil. Public acceptance of the use of recycled plastics (e.g. for packaging foodstuffs) may also play a role in this through developing markets for certain plastic types.

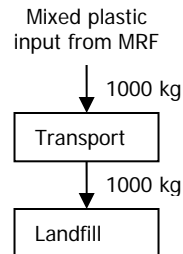
In discussion with WRAP the main predicted changes are a gradual increase in the use of polyolefins accompanied by a decrease in consumption of PVC. The outlook for bioplastics (e.g. PLA) is unclear given the competition for land with other uses such as food production and biofuels, which is pushing up raw material prices for these polymers. However, these currently comprise a very small quantity of the total plastic waste arising.

Overall, plastic waste in the UK is forecast to grow at an annual rate of between 2% and 5% over the next few years <sup>27</sup>.

## 4.0 Descriptions of Scenarios and Key Results

### 4.1 Scenario A – Landfill

**Figure 4.1** Process diagram for scenario A



The landfill scenario assesses impacts from transporting the mixed plastic waste to the landfill site, and impacts from the landfill itself.

Life cycle inventory data used are representative of the situation in Switzerland in 2000 for a municipal sanitary landfill facility taking biogenic or untreated municipal waste. The landfill model includes a base seal, landfill gas and leachate collection systems and treatment of leachate in a municipal wastewater treatment plant.

The data account for:

- Waste-specific short-term emissions (over 100 year time horizon) to air via landfill gas incineration and landfill leachate. No energy recovery is assumed to result from the landfill gas.
- Burdens from treatment of short-term leachate (over 100 year time horizon) in a wastewater treatment plant (including WWTP sludge disposal in municipal incinerator).
- Long-term emissions from landfill to groundwater after base lining failure (up to 60,000 year time horizon).

The characteristics of the input material are taken from various literature sources as listed in the Ecoinvent reference documentation<sup>28</sup> and account for chemical elements in additives used to condition the plastics as well as the pure plastics themselves. Nitrogen containing additives explain the relatively high eutrophication potential for landfill as, over the long term, these result in the emission of ammonia, organically bound nitrogen compounds and other species that contribute to this impact category. Waste PET has particularly large quantities of nitrogen containing additives and contributes the majority of these impacts.

**Table 4.1.1** Scenario A impact assessment results for different feedstock compositions

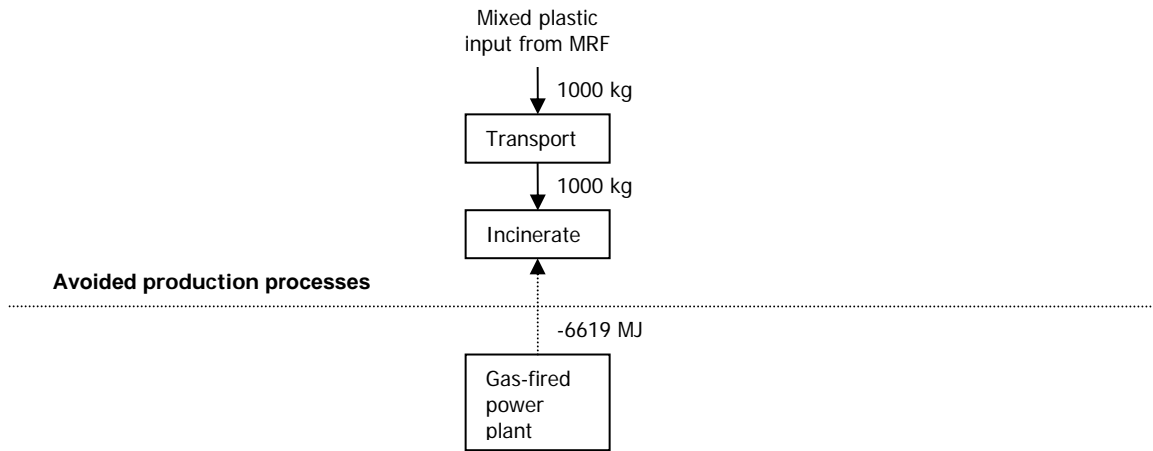
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	440	458	464
ADP	kg eq. Sb	0.179	0.187	0.189
AP	kg eq. SO <sub>2</sub>	0.263	0.240	0.231
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	1.487	1.053	0.792
HTP	kg eq. DCB	1134.31	1665.73	1931.83
OLDP	kg eq. R11	4.0E-06	4.1E-06	4.2E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.044	0.048	0.049
GWP	kg eq. CO <sub>2</sub>	147	159	166
Solid Waste	kg	1000	1000	1000

**Table 4.1.2** Scenario A impact assessment results showing contribution from different process stages (default feedstock)

<b>Impact Category</b>	<b>Unit</b>	<b>Landfill</b>	<b>Transport</b>	<b>Total</b>
Energy	MJ	381	77	458
ADP	kg eq. Sb	0.153	0.034	0.187
AP	kg eq. SO <sub>2</sub>	0.215	0.025	0.240
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	1.048	0.006	1.053
HTP	kg eq. DCB	1665.44	0.29	1665.73
OLDP	kg eq. R11	3.5E-06	6.6E-07	4.1E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.045	0.003	0.048
GWP	kg eq. CO <sub>2</sub>	154	5	159

## 4.2 Scenario B – Incineration with Energy Recovery

Figure 4.2 Process diagram for scenario B



For incineration with energy recovery the mixed plastic waste is not sorted but is assumed to be sent straight to the incineration plant after leaving the MRF. It is then burnt and the energy released used to produce electricity. To maximise the benefits from incineration the heat produced would be recovered in a CHP plant – however this is not the typical situation in the UK where incinerators tend to be located away from population centres where the heat could usefully be used. As such, heat recovery has not been modelled in this study.

It should be noted that the calorific value of the mixed plastic (and other materials) from the MRF is much higher than normal feedstock accepted for municipal incineration. It is possible that this may require incinerator operators to alter their process or to blend the mixed plastic waste with other material prior to being fed into the incinerator (although this is debated). This extra processing may affect whether this disposal option is economical compared to other options.

The study boundary is from the point at which the mixed plastic waste leaves the MRF to the point at which it is incinerated, so the results do not account for the energy and resources used to manufacture the materials in the waste stream. The benefits accrued from incineration are based on the avoided requirement to obtain electricity from other sources. The incinerator efficiency is assumed to be 23% (discussed in more detail in Section 6.2) and the energy that can be recovered from the waste stream is based on the following net calorific values sourced from the incineration datasets in Ecoinvent<sup>13</sup>:

- 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
- PLA 30.79 MJ/kg (based on Ecoinvent dataset for “mixed plastic” incineration – no specific data available on PLA)
- Paper 14.12 MJ/kg
- Aluminium, steel and other residuals are assumed to have no calorific value in the incineration process

Net calorific value rather than gross calorific value is used for this calculation as this represents the available energy derived from combustion that can be used to generate electricity (assumes that steam produced from water content in feedstock is lost to atmosphere so this energy is not recovered).

As well as being a disposal scenario in its own right incineration also plays a part in many of the other scenarios as a disposal option along with landfill for the material that is not recovered/recycled. The Ecoinvent life cycle inventories for waste incineration include emissions from both the incinerator and from the landfills for the non-combusted material and are based on average Swiss technology. It is expected that this would be comparable to incineration facilities in the UK. Further details can be found in the Ecoinvent reference documentation<sup>28</sup>. As with the landfill datasets, the incineration datasets accounts for the present of additives used to condition the plastics as well as the pure plastics themselves. The calculation of solid waste arising is based on residual materials remaining after incineration (e.g. boiler ash, precipitator ash, scrubber sludge and bottom-ash) and also includes solidifying cement used to stabilise these materials for landfill.

**Table 4.2.1** Scenario B impact assessment results for different feedstock compositions

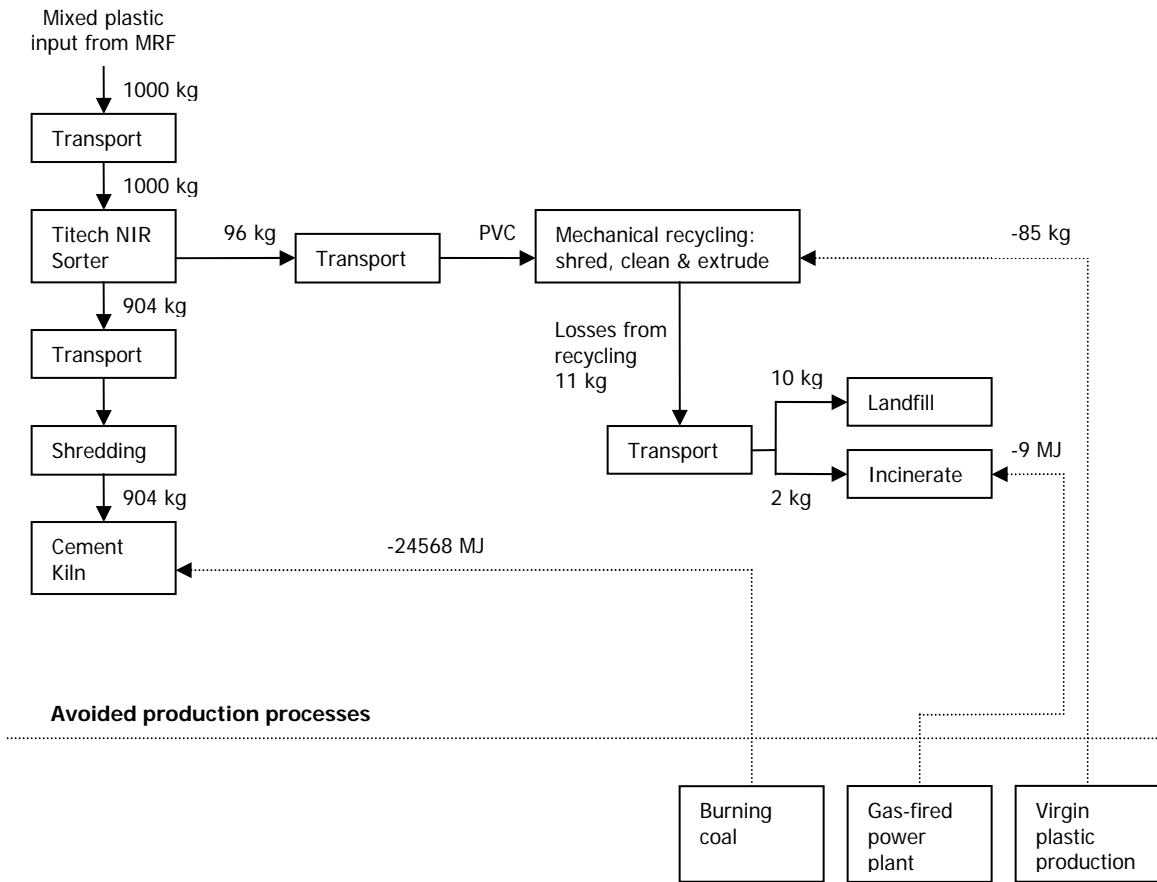
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-8443	-12083	-14142
ADP	kg eq. Sb	-4.228	-5.485	-6.240
AP	kg eq. SO <sub>2</sub>	0.548	0.055	-0.185
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.099	0.045	0.017
HTP	kg eq. DCB	1230.45	1350.05	1399.60
OLDP	kg eq. R11	-7.0E-05	-8.7E-05	-9.8E-05
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.012	-0.060	-0.087
GWP	kg eq. CO <sub>2</sub>	1629	1829	1919
Solid Waste	kg	53	49	48

**Table 4.2.2** Scenario B impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Incineration	Transport	Avoided Impacts	Total
Energy	MJ	1788	192	-14063	-12083
ADP	kg eq. Sb	0.509	0.085	-6.079	-5.485
AP	kg eq. SO <sub>2</sub>	0.681	0.062	-0.687	0.055
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.113	0.014	-0.083	0.045
HTP	kg eq. DCB	1357.19	0.73	-7.87	1350.05
OLDP	kg eq. R11	6.3E-06	1.6E-06	-9.5E-05	-8.7E-05
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.076	0.007	-0.143	-0.060
GWP	kg eq. CO <sub>2</sub>	2593	13	-777	1829

### 4.3 Scenario C – Solid recovered fuel (SRF) used in cement kiln

Figure 4.3 Process diagram for scenario C



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

A higher value energy recovery option (compared to burning in a municipal incinerator) is to convert the remaining mixed plastic waste into solid recovered fuel (SRF) – this could either then be burnt in a dedicated SRF power plant or used as fuel for a cement kiln.

As with the municipal incineration scenario, the composition of the mixed waste plastic stream in this study is unlike most normal SRF feedstock and in reality may have to be blended with other materials to give a suitable product. As such, this scenario should be viewed as a somewhat artificial construction developed for the purpose of comparing against the other technologies in this assessment.

Before conversion to SRF the PVC component of the waste stream must be reduced to below ~1%. This scenario assumes this is achieved using a NIR sorter – the separated PVC is assumed to be recycled.

In this scenario it is assumed that the SRF replaces use of primary fuel (as pulverised coal) in the cement kiln. In this case the energy that can be recovered from the waste stream is based on the following gross calorific values sourced from the incineration datasets in Ecoinvent<sup>13</sup>:

- PE 42.82 MJ/kg
- PP 36.16 MJ/kg

- PET 23.13 MJ/kg
- PS 38.88 MJ/kg
- PVC 21.67 MJ/kg (for residual PVC not removed during sorting)
- PLA 34.05 MJ/kg (based on Ecoinvent dataset for “mixed plastic” incineration – no specific data available on PLA)
- Paper 16.77 MJ/kg
- Aluminium, steel and other residuals are assumed to have no calorific value in the cement kiln.

Gross calorific values are used in this case as the plastic is being used directly as a fuel in the cement kiln process so all the energy in the material will be harnessed.

However it should be noted that cement kilns accept a wide range of different waste materials including tyres, liquid wastes and other forms of SRF, so mixed waste plastic would represent just one of a number of potential fuel options for this process. As such, it is possible in some cases that the mixed waste plastic would actually substitute for other secondary fuels – but this option has not been considered further in this study. It should also be recognised that the actual capacity for UK cement kilns to accept mixed plastic waste is finite. However this issue is outside the scope of the study, which focuses on relative environmental performance of different waste management options.

The study also attempted to assess the impacts of using SRF in CHP. However, as this is not commonplace, a number of hypothetical issues arose which reduced certainty in any results relating to e.g. the technologies applied, composition of SRF and the ratio of electricity to heat/steam generated. However, in a recent report <sup>29</sup>, Prognos – an independent German institute – used “cement kiln” as a reasonable approximation for SRF use in general. They found that the use of SRF in cement kilns reflected the performance of SRF in CHP plants which conformed to BAT requirements. The figures may be considered as an indicator of the potential impacts of SRF in CHP.

**Table 4.3.1** Scenario C impact assessment results for different feedstock compositions

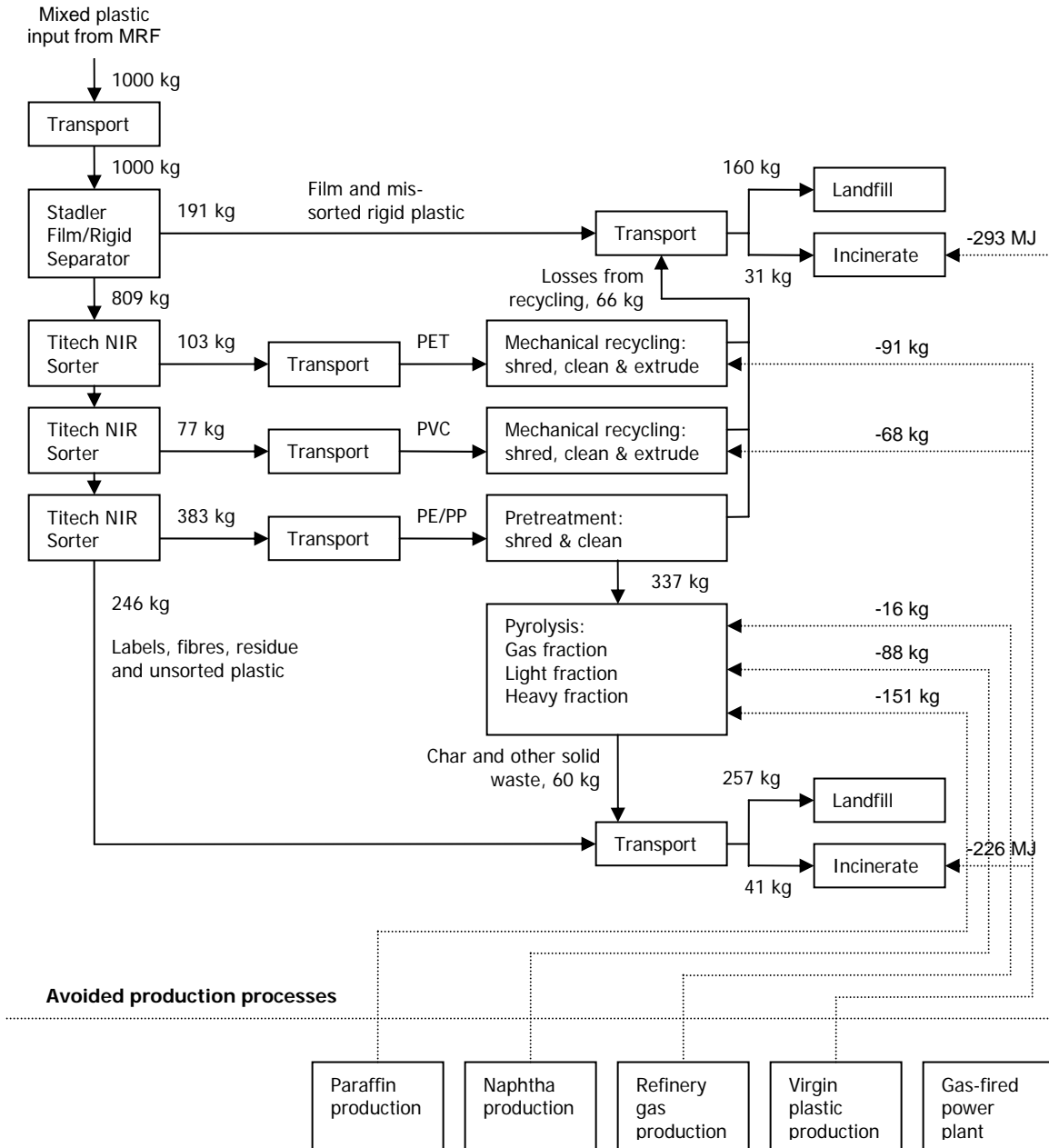
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-34685	-45323	-50581
ADP	kg eq. Sb	-16.1	-20.8	-23.1
AP	kg eq. SO <sub>2</sub>	-4.01	-4.33	-4.53
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.29	-0.32	-0.34
HTP	kg eq. DCB	915	1095	1168
OLDP	kg eq. R11	2.5E-06	-9.8E-07	-2.6E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.343	-0.341	-0.346
GWP	kg eq. CO <sub>2</sub>	-132	-299	-379
Solid Waste	kg	61	52	50

**Table 4.3.2** Scenario C impact assessment results showing contribution from different process stages (default feedstock)

<b>Impact Category</b>	<b>Unit</b>	<b>Mechanical Recycling</b>	<b>Incineration</b>	<b>Landfill</b>	<b>Transport</b>	<b>Avoided Impacts</b>	<b>Total</b>
Energy	MJ	866	482	3	561	-47234	-45323
ADP	kg eq. Sb	0.280	0.159	0.001	0.248	-21.510	-20.822
AP	kg eq. SO <sub>2</sub>	0.136	0.384	0.004	0.180	-5.030	-4.326
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.011	0.082	0.004	0.042	-0.461	-0.322
HTP	kg eq. DCB	3.78	1271.71	5.55	2.14	-188.36	1094.82
OLDP	kg eq. R11	8.5E-07	2.3E-06	3.0E-08	4.8E-06	-8.9E-06	-9.8E-07
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.009	0.050	0.000	0.020	-0.420	-0.341
GWP	kg eq. CO <sub>2</sub>	39	2384	1	38	-2760	-299

#### 4.4 Scenario D – Stadler, Titech & Pyrolysis (BP Polymer Cracking Process)

Figure 4.4 Process diagram for scenario D



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

Data on the BP polymer cracking process have been obtained from a previous LCA study<sup>30</sup>, based on published information on the process. It should be noted that the process has been further developed with significant efficiency gains since these data were made available<sup>31</sup> but is no longer current and will not be resurrected. As such, the results from the LCA model should be viewed with caution and not taken to represent the best performance available from modern pyrolysis plants.

The BP process produced three main products, a light fraction that can substitute for naphtha, a heavy waxy fraction that can substitute for paraffin, and a gaseous fraction that can substitute for refinery gas generated during conventional oil processing. In this scenario it is assumed that most of the gas produced (0.1 kg gas per kg polyolefin feedstock) is consumed as a fuel for heating the pyrolysis process itself.

This pyrolysis technology is only suited for processing polyolefins. As such, film separation and NIR sorting processes have been used to model the upstream material preparation stages based on data from the trials of Stadler and Titech equipment. However the material could equally be prepared using plant supplied by other technology providers included in this study, so this choice should not be viewed as specifically favouring these particular technology providers.

In this scenario it is assumed that the PET and PVC fractions, which are not suitable for use in the pyrolysis process, are mechanically recycled. This involves shredding the plastics, followed by mechanical cleaning (using Pla.to equipment) and extrusion to give a recycled pellet product. The PS fraction is not sorted and recycled as it is not present in sufficient quantities in the waste stream for this to be economical. Along with the other non-recycled fractions this is sent to landfill and incineration according to the average UK mix of these disposal options.

**Table 4.4.1** Scenario D impact assessment results for different feedstock compositions

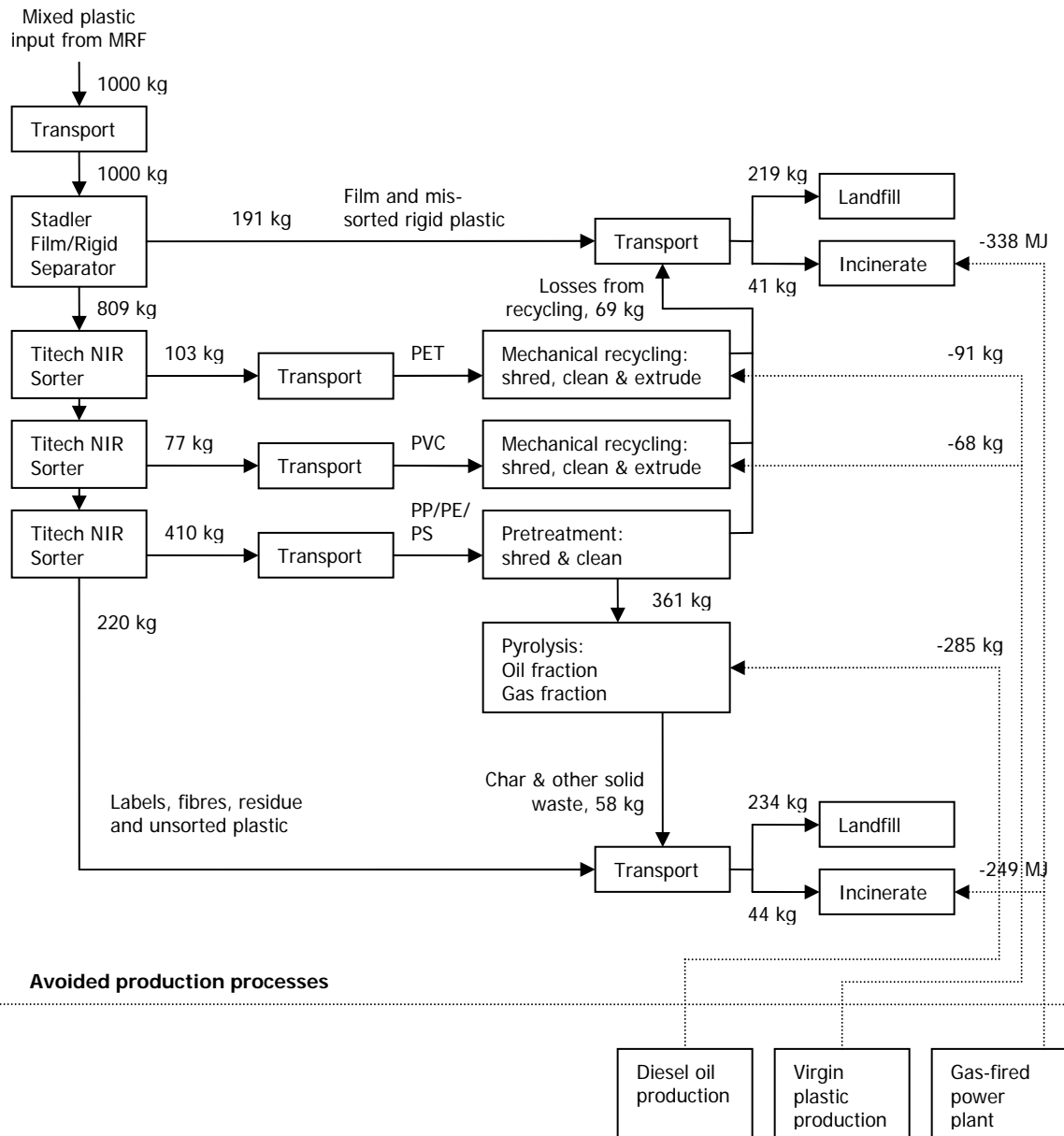
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-17182	-18374	-19752
ADP	kg eq. Sb	-11.021	-9.802	-9.547
AP	kg eq. SO <sub>2</sub>	-3.625	-1.680	-0.817
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.234	-0.067	-0.048
HTP	kg eq. DCB	332.90	573.09	656.86
OLDP	kg eq. R11	-3.8E-05	-6.3E-05	-7.8E-05
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.492	-0.300	-0.219
GWP	kg eq. CO <sub>2</sub>	-374	30	215
Solid Waste	kg	471	489	482

**Table 4.4.2** Scenario D impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Pyrolysis	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	1073	1722	116	163	547	-21995	-18374
ADP	kg eq. Sb	0.347	0.562	0.034	0.064	0.242	-11.050	-9.802
AP	kg eq. SO <sub>2</sub>	0.168	1.016	0.049	0.101	0.176	-3.189	-1.680
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.014	0.036	0.009	0.482	0.041	-0.649	-0.067
HTP	kg eq. DCB	4.69	7.53	96.07	595.21	2.09	-132.50	573.09
OLDP	kg eq. R11	1.1E-06	2.7E-06	4.2E-07	1.5E-06	4.7E-06	-7.4E-05	-6.3E-05
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.011	0.057	0.006	0.024	0.019	-0.417	-0.300
GWP	kg eq. CO <sub>2</sub>	48	204	198	89	37	-547	30

## 4.5 Scenario E – Stadler, Titech & Pyrolysis (Ozmotech)

Figure 4.5 Process diagram for scenario E



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

Compared to the BP polymer cracking process, the pyrolysis technology developed by Ozmotech operates on a smaller scale and is suitable for converting PE, PP and PS polymers into a liquid product that can substitute directly for diesel from conventional oil processing. Information on the Ozmotech process has been taken from published sources<sup>32-34</sup> but detailed information is not available so data gaps relating to power, water, nitrogen requirements, etc. have been filled based on discussions with Bowman Process Technologies<sup>34-36</sup> using reasonable assumptions based on these sources.

As well as diesel substitute, the process also produces a gas fraction and a solid char fraction. It is assumed that all the pyrolysis gas is fed back in to heat the process chamber. The char is disposed of to landfill and incineration and is assumed to have the same calorific value as hard coal.

It is assumed that upstream material processing to separate these from the other materials in the feedstock is carried out using film separation and NIR sorting processes. The separated PET and PVC fractions that cannot be used for pyrolysis are assumed to be mechanically recycled. The non-recycled fraction is sent to landfill and incineration according to the average UK mix of these disposal options.

**Table 4.5.1** Scenario E impact assessment results for different feedstock compositions

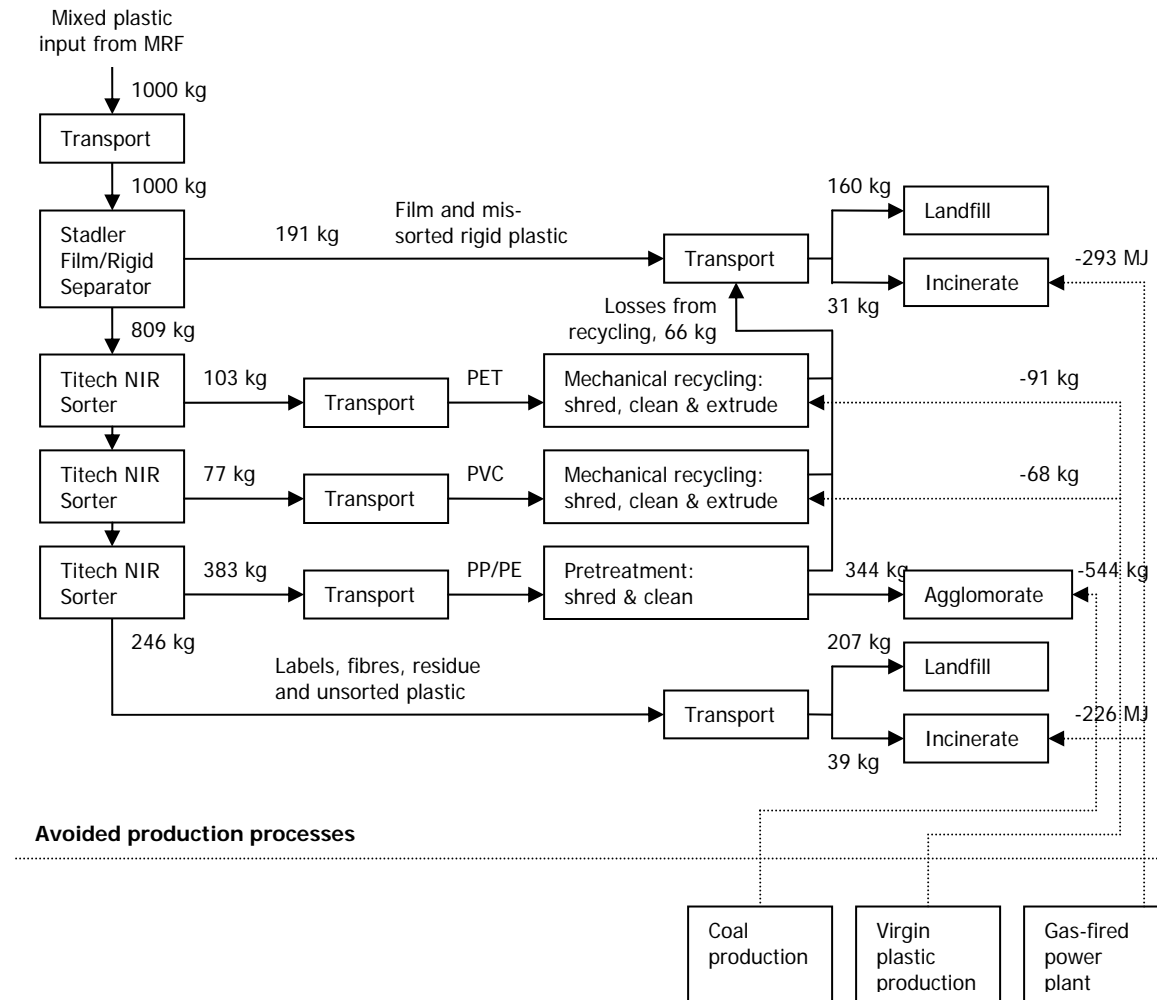
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-18857	-18999	-19918
ADP	kg eq. Sb	-11.818	-10.162	-9.720
AP	kg eq. SO <sub>2</sub>	-4.066	-2.577	-1.976
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.412	-0.359	-0.408
HTP	kg eq. DCB	307.90	577.54	675.23
OLDP	kg eq. R11	-7.6E-05	-1.4E-04	-1.8E-04
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.547	-0.391	-0.332
GWP	kg eq. CO <sub>2</sub>	-431	-61	104
Solid Waste	kg	408	501	522

**Table 4.5.2** Scenario E impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Pyrolysis	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	1169	2290	129	156	358	-23101	-18999
ADP	kg eq. Sb	0.378	0.739	0.039	0.061	0.158	-11.538	-10.162
AP	kg eq. SO <sub>2</sub>	0.183	0.359	0.055	0.097	0.115	-3.386	-2.577
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.015	0.030	0.009	0.465	0.027	-0.904	-0.359
HTP	kg eq. DCB	5.11	10.02	93.81	584.49	1.37	-117.25	577.54
OLDP	kg eq. R11	1.2E-06	2.3E-06	4.2E-07	1.4E-06	3.1E-06	-1.5E-04	-1.4E-04
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.012	0.023	0.006	0.023	0.013	-0.468	-0.391
GWP	kg eq. CO <sub>2</sub>	52	102	187	87	24	-514	-61

## 4.6 Scenario F – Redox Agent in Blast Furnace

Figure 4.6 Process diagram for scenario F



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

An alternative option for managing waste polyolefins is in steel production, by injecting them into blast furnaces to reduce iron ore. This is not current practice at Corus steelworks in the UK but is carried out successfully elsewhere and would be an option in future if sufficient quantity and quality of material supply could be assured. Based on discussions with Corus experts it is expected that polyolefins would displace the use of pulverised coal injected into the blast furnace <sup>24</sup>.

Blast furnace chemistry is very complicated and no account has been made in this assessment for changes that might occur in the emissions profile from the blast furnace caused by 'waste' contamination in the product, residual non-polyolefin contamination or chemical differences between polyolefin waste plastics and coal.

As with scenarios C and D it is assumed that upstream material processing to separate these from the other materials in the feedstock is carried out using film separation and NIR sorting processes. The polyolefin fraction is shredded, mechanically cleaned and then agglomerated to produce a suitably sized feedstock for

injection. The separated PET and PVC fractions that are not suitable redox agents are assumed to be mechanically recycled. The PS fraction is not recycled as it is not present in the feedstock stream in sufficient quantity for this to be economically viable. Along with the other non-recycled fractions this is sent to landfill and incineration according to the average UK mix of these disposal options.

It should also be recognised that the actual capacity for UK blast furnaces to accept mixed plastic waste is limited. However this issue is outside the scope of the study, which focuses on relative environmental performance of different waste management options.

**Table 4.6.1** Scenario F impact assessment results for different feedstock compositions

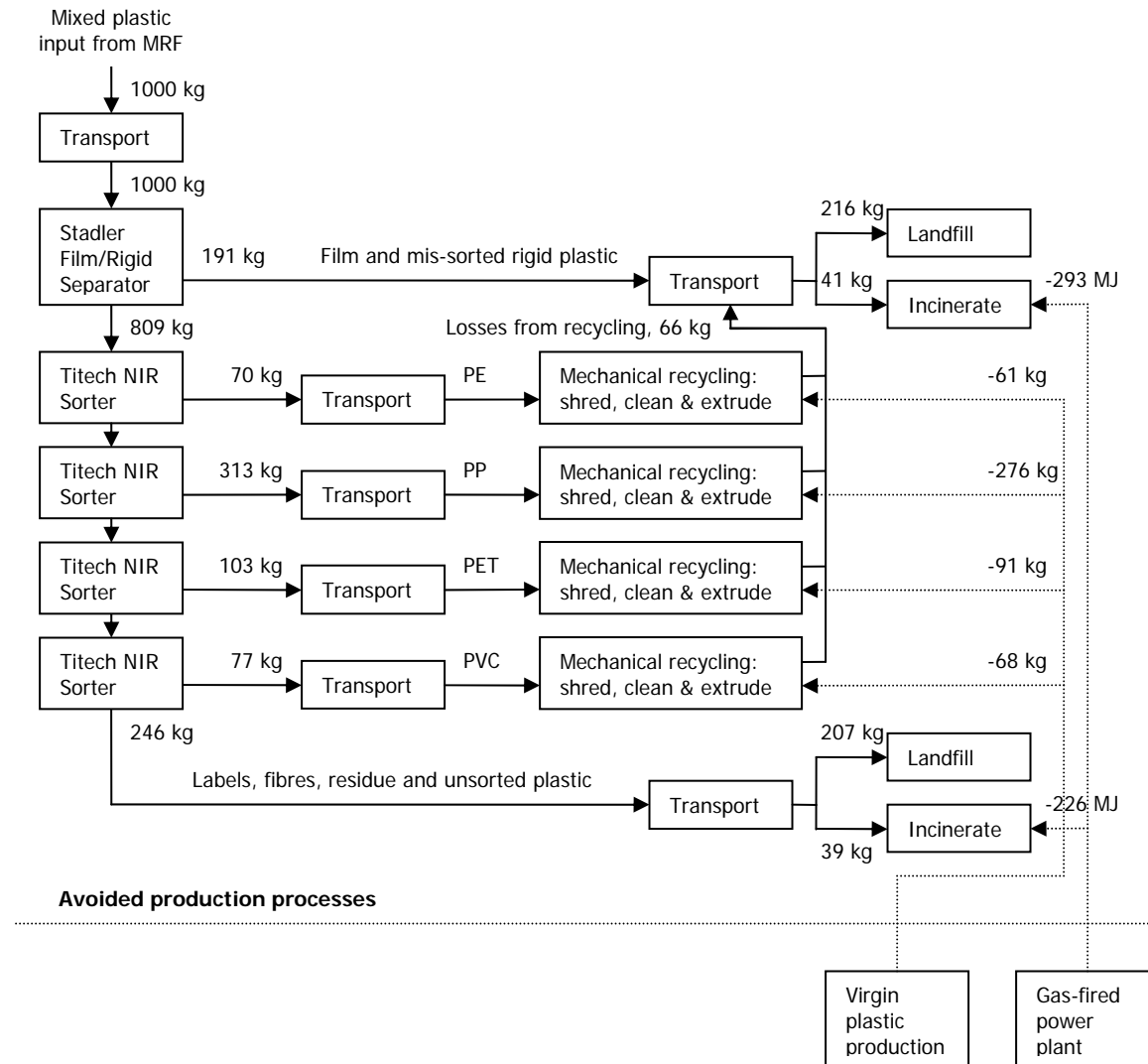
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-19840	-28286	-33643
ADP	kg eq. Sb	-12.275	-14.451	-16.058
AP	kg eq. SO <sub>2</sub>	-3.409	-1.243	-0.259
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.141	0.179	0.283
HTP	kg eq. DCB	343.44	605.24	700.87
OLDP	kg eq. R11	-1.9E-05	-6.8E-06	-4.2E-07
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.455	-0.208	-0.096
GWP	kg eq. CO <sub>2</sub>	-401	-124	-8
Solid Waste	kg	451	423	390

**Table 4.6.2** Scenario F impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Redox Agent	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	1073	964	116	161	931	-31529	-28286
ADP	kg eq. Sb	0.343	0.311	0.034	0.063	0.411	-15.617	-14.454
AP	kg eq. SO <sub>2</sub>	0.168	0.151	0.048	0.100	0.300	-2.010	-1.243
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.014	0.013	0.009	0.478	0.069	-0.404	0.179
HTP	kg eq. DCB	4.69	4.21	94.32	581.72	3.55	-83.26	605.24
OLDP	kg eq. R11	1.1E-06	9.5E-07	4.2E-07	1.4E-06	7.9E-06	-1.9E-05	-6.8E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.011	0.010	0.006	0.024	0.033	-0.291	-0.208
GWP	kg eq. CO <sub>2</sub>	48	43	195	89	63	-561	-124

## 4.7 Scenario G – Stadler & Titech

**Figure 4.7** Process diagram for scenario G



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

Titech use NIR sorting technology to separate out the different plastic fractions. This scenario assumes that there is an upstream film separation step using Stadler equipment leaving the Titech equipment to treat the remaining rigid fraction.

Each Titech machine can positively sort a single material type – so four are required to separate out the four major polymers (PE, PP, PET and PVC). Following the sorting stage it is assumed that each material stream is shredded, mechanically cleaned and extruded to form recycled pellets. The non-recycled fraction is sent to landfill and incineration according to the average UK mix of these disposal options.

**Table 4.7.1** Scenario G impact assessment results for different feedstock compositions

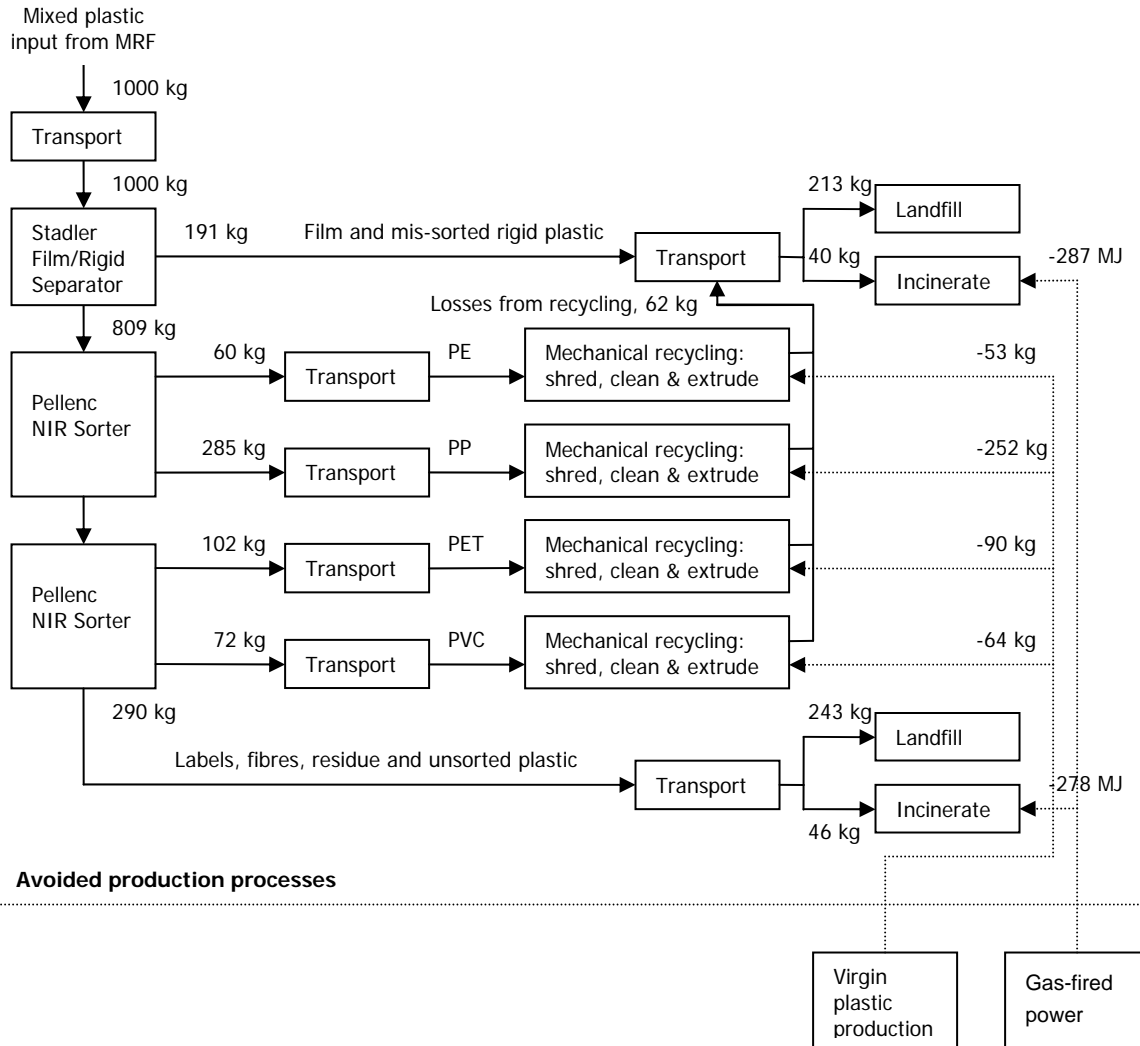
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-15646	-12897	-12147
ADP	kg eq. Sb	-12.508	-14.667	-16.291
AP	kg eq. SO <sub>2</sub>	-5.504	-7.875	-9.427
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.307	-0.281	-0.340
HTP	kg eq. DCB	342.78	608.17	705.03
OLDP	kg eq. R11	-2.4E-05	-1.0E-05	-3.6E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.677	-0.855	-1.038
GWP	kg eq. CO <sub>2</sub>	-571	-620	-678
Solid Waste	kg	453	429	398

**Table 4.7.2** Scenario G impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	2524	116	163	355	-16056	-12897
ADP	kg eq. Sb	0.816	0.034	0.064	0.157	-15.737	-14.667
AP	kg eq. SO <sub>2</sub>	0.396	0.049	0.101	0.114	-8.535	-7.875
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.033	0.009	0.482	0.026	-0.831	-0.281
HTP	kg eq. DCB	11.03	96.07	595.21	1.36	-95.50	608.17
OLDP	kg eq. R11	2.5E-06	4.2E-07	1.5E-06	3.0E-06	-1.8E-05	-1.0E-05
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.026	0.006	0.024	0.013	-0.923	-0.855
GWP	kg eq. CO <sub>2</sub>	113	198	89	24	-1044	-620

## 4.8 Scenario H – Stadler & Pellenc

**Figure 4.8** Process diagram for scenario H



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

Pellenc use near infrared (NIR) sorting technology to separate out the different plastic fractions. This scenario assumes that there is an upstream film separation step so the Pellenc equipment treats the remaining rigid fraction. Pellenc sorting machines can operate in binary (one positive sort) or ternary (two positive sorts) modes. To separate out the four major polymers (PE, PP, PET and PVC) two machines are required – both operating in ternary mode.

Following the sorting stage it is assumed that each material stream is shredded, mechanically cleaned and extruded form recycled pellets. The non-recycled fraction is sent to landfill and incineration according to the average UK mix of these disposal options.

**Table 4.8.1** Scenario H impact assessment results for different feedstock compositions

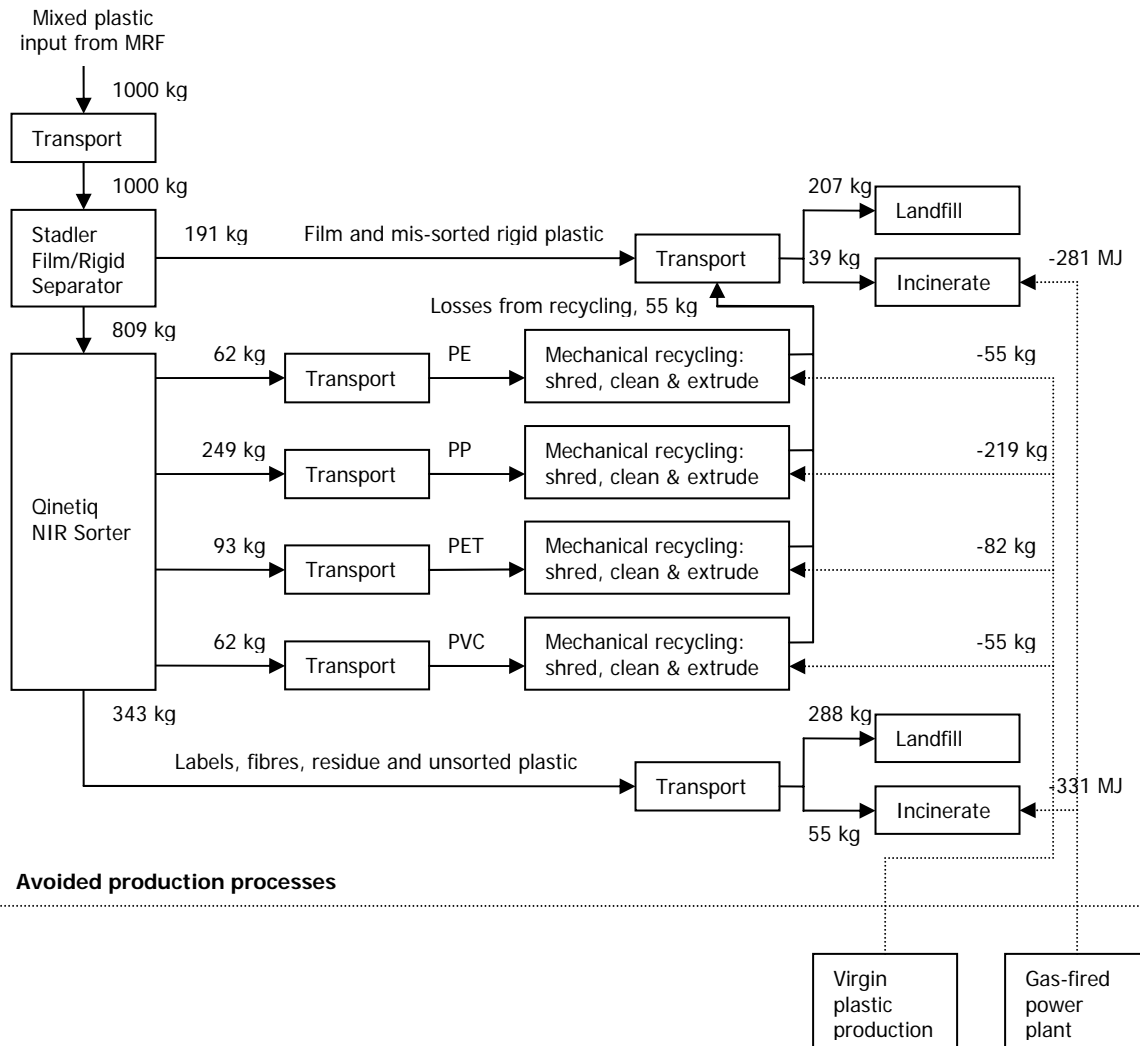
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-15449	-12441	-11553
ADP	kg eq. Sb	-12.120	-13.698	-14.921
AP	kg eq. SO <sub>2</sub>	-5.243	-7.243	-8.532
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.276	-0.221	-0.259
HTP	kg eq. DCB	374.11	685.12	813.13
OLDP	kg eq. R11	-2.4E-05	-1.2E-05	-5.0E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.645	-0.784	-0.931
GWP	kg eq. CO <sub>2</sub>	-549	-556	-586
Solid Waste	kg	471	461	439

**Table 4.8.2** Scenario H impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	1992	128	175	350	-15087	-12441
ADP	kg eq. Sb	0.644	0.037	0.069	0.155	-14.603	-13.698
AP	kg eq. SO <sub>2</sub>	0.312	0.053	0.107	0.113	-7.828	-7.243
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.026	0.009	0.500	0.026	-0.782	-0.221
HTP	kg eq. DCB	8.71	105.26	662.68	1.34	-92.86	685.12
OLDP	kg eq. R11	2.0E-06	4.7E-07	1.6E-06	3.0E-06	-1.9E-05	-1.2E-05
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.020	0.006	0.025	0.012	-0.848	-0.784
GWP	kg eq. CO <sub>2</sub>	89	216	92	24	-977	-556

## 4.9 Scenario I – Stadler & QinetiQ

Figure 4.9 Process diagram for scenario I



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

The Qinetiq system uses NIR sorting technology to separate out the different plastic fractions. It is assumed that the film fraction is first separated from the waste stream leaving the Qinetiq sorter to separate the remaining rigid fraction.

The Qinetiq sorter capable of sorting multiple materials from a mixed input stream in a single pass. It is assumed that the PE, PP, PVC and PET streams are sorted before being shredded, mechanically cleaned and extruded form recycled pellets. The non-recycled fraction is sent to landfill and incineration according to the average UK mix of these disposal options.

**Table 4.9.1** Scenario I impact assessment results for different feedstock compositions

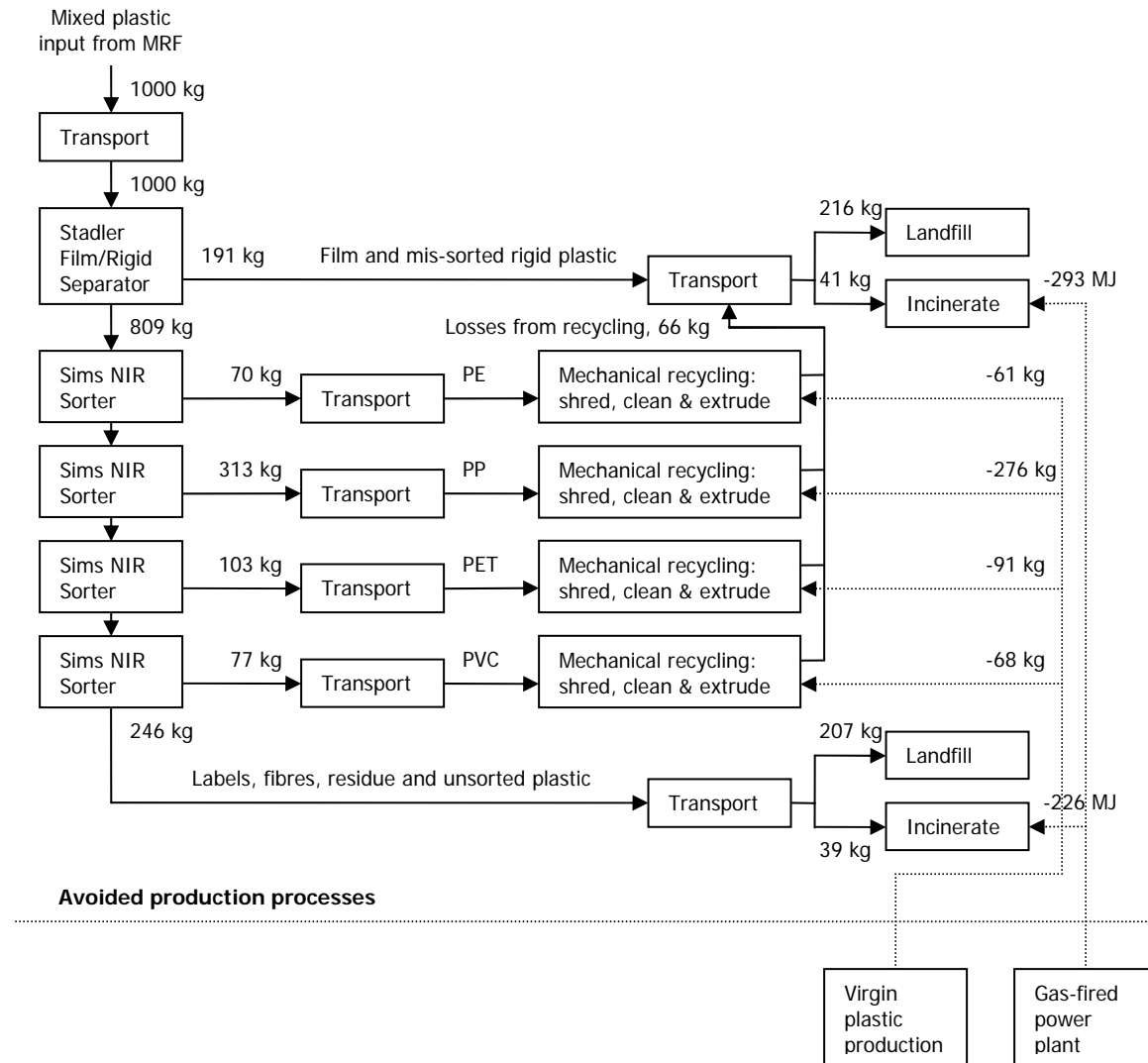
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-13977	-11403	-10740
ADP	kg eq. Sb	-11.008	-12.411	-13.694
AP	kg eq. SO <sub>2</sub>	-4.699	-6.499	-7.782
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.130	-0.111	-0.176
HTP	kg eq. DCB	446.63	777.13	903.37
OLDP	kg eq. R11	-2.3E-05	-1.1E-05	-5.5E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.583	-0.712	-0.864
GWP	kg eq. CO <sub>2</sub>	-459	-458	-495
Solid Waste	kg	510	501	477

**Table 4.9.2** Scenario I impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	1717	149	191	343	-13803	-11403
ADP	kg eq. Sb	0.555	0.043	0.075	0.152	-13.236	-12.411
AP	kg eq. SO <sub>2</sub>	0.269	0.060	0.115	0.111	-7.054	-6.499
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.023	0.010	0.537	0.026	-0.707	-0.111
HTP	kg eq. DCB	7.50	116.49	735.98	1.31	-84.15	777.13
OLDP	kg eq. R11	1.7E-06	5.4E-07	1.7E-06	2.9E-06	-1.8E-05	-1.1E-05
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.018	0.007	0.026	0.012	-0.774	-0.712
GWP	kg eq. CO <sub>2</sub>	77	236	96	23	-890	-458

## 4.10 Scenario J – Stadler & Sims

**Figure 4.10** Process diagram for scenario J



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

Sims use NIR sorting technology to separate out the different plastic fractions. This scenario assumes that there is an upstream film separation step using Stadler equipment leaving the Sims equipment to treat the remaining rigid fraction.

Each Sims machine can positively sort a single material type – so four are required to separate out the four major polymers (PE, PP, PET and PVC). Following the sorting stage it is assumed that each material stream is shredded, mechanically cleaned and extruded form recycled pellets. The non-recycled fraction is sent to landfill and incineration according to the average UK mix of these disposal options.

**Table 4.10.1** Scenario J impact assessment results for different feedstock compositions

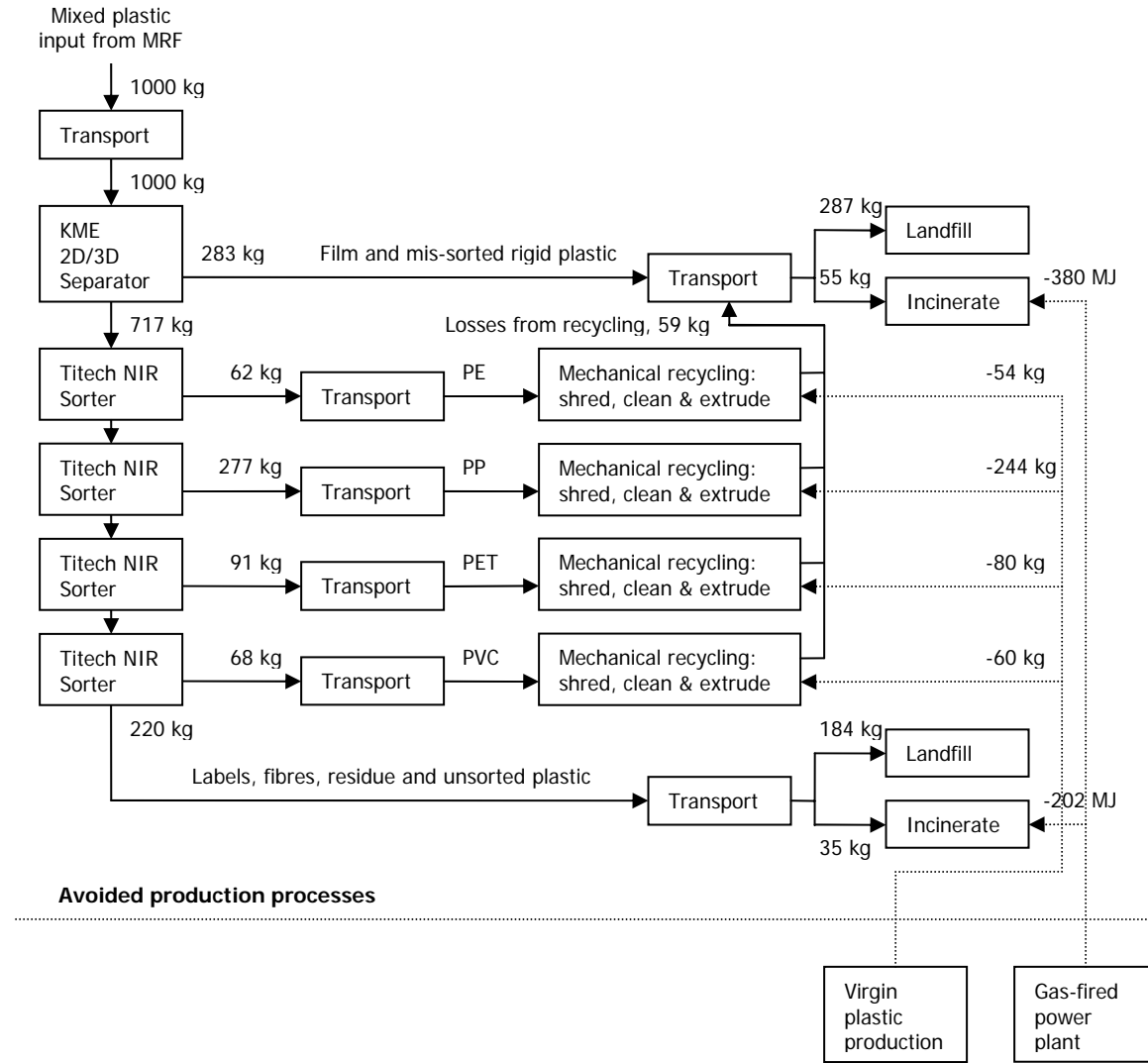
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-15646	-12897	-12147
ADP	kg eq. Sb	-12.508	-14.667	-16.291
AP	kg eq. SO <sub>2</sub>	-5.504	-7.875	-9.427
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.307	-0.281	-0.340
HTP	kg eq. DCB	342.78	608.17	705.03
OLDP	kg eq. R11	-2.4E-05	-1.0E-05	-3.6E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.677	-0.855	-1.038
GWP	kg eq. CO <sub>2</sub>	-571	-620	-678
Solid Waste	kg	453	429	398

**Table 4.10.2** Scenario J impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	2524	116	163	355	-16056	-12897
ADP	kg eq. Sb	0.816	0.034	0.064	0.157	-15.737	-14.667
AP	kg eq. SO <sub>2</sub>	0.396	0.049	0.101	0.114	-8.535	-7.875
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.033	0.009	0.482	0.026	-0.831	-0.281
HTP	kg eq. DCB	11.03	96.07	595.21	1.36	-95.50	608.17
OLDP	kg eq. R11	2.5E-06	4.2E-07	1.5E-06	3.0E-06	-1.8E-05	-1.0E-05
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.026	0.006	0.024	0.013	-0.923	-0.855
GWP	kg eq. CO <sub>2</sub>	113	198	89	24	-1044	-620

## 4.11 Scenario K - KME & Titech

**Figure 4.11** Process diagram for scenario K



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

This scenario is the same as scenario K but uses the KME process rather than Stadler equipment to remove the film fraction from the infeed material prior to processing in the NIR sorters.

**Table 4.11.1** Scenario K impact assessment results for different feedstock compositions

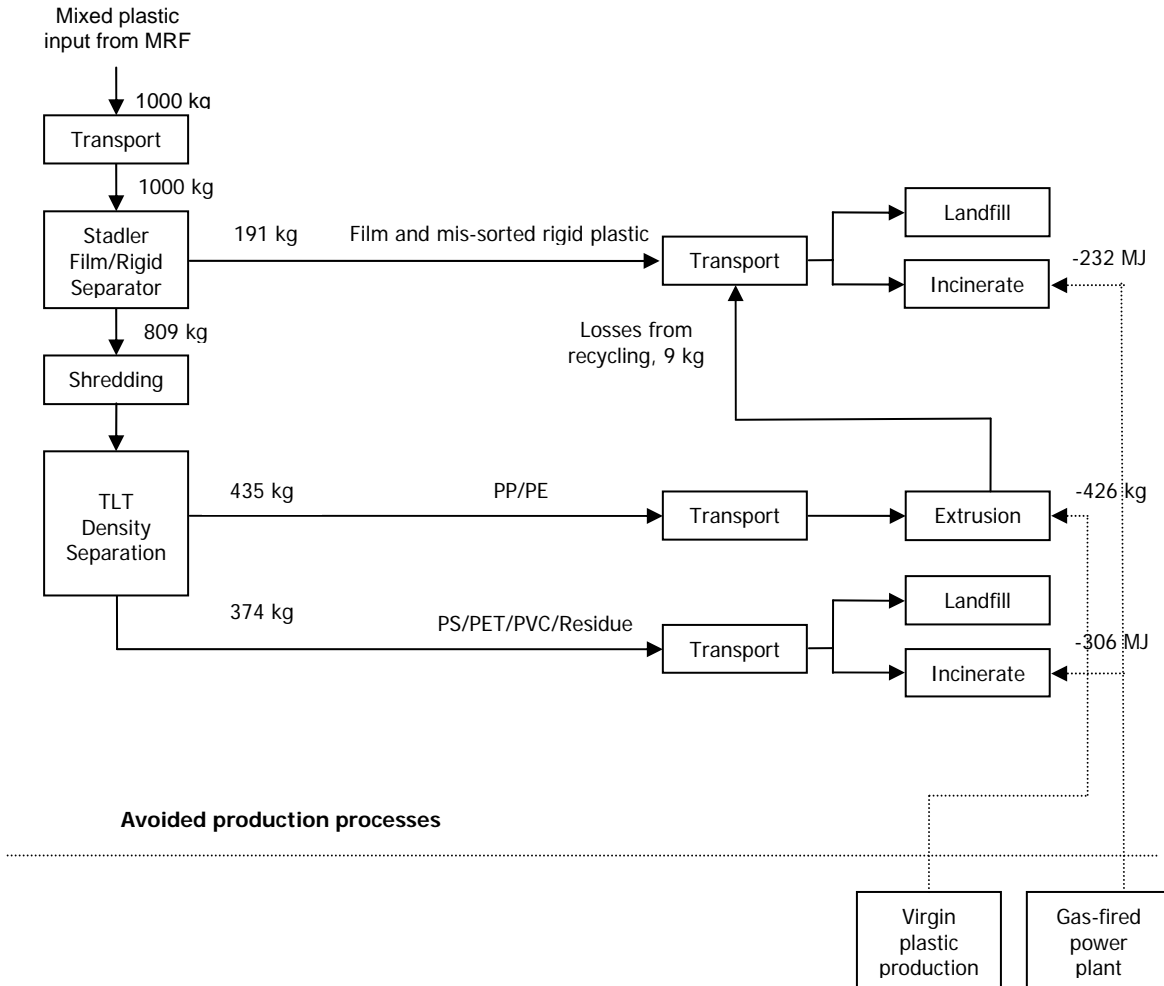
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-13820	-11472	-10799
ADP	kg eq. Sb	-11.076	-13.006	-14.456
AP	kg eq. SO <sub>2</sub>	-4.807	-6.914	-8.291
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.121	-0.142	-0.220
HTP	kg eq. DCB	436.90	725.51	837.97
OLDP	kg eq. R11	-2.2E-05	-1.0E-05	-4.3E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.593	-0.751	-0.912
GWP	kg eq. CO <sub>2</sub>	-455	-492	-541
Solid Waste	kg	498.62	477.32	450.41

**Table 4.11.2** Scenario K impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	2333	136	181	347	-14470	-11472
ADP	kg eq. Sb	0.754	0.039	0.072	0.153	-14.025	-13.006
AP	kg eq. SO <sub>2</sub>	0.366	0.056	0.110	0.112	-7.558	-6.914
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.031	0.010	0.528	0.026	-0.736	-0.142
HTP	kg eq. DCB	10.20	110.12	688.44	1.33	-84.57	725.51
OLDP	kg eq. R11	2.3E-06	4.9E-07	1.6E-06	3.0E-06	-1.8E-05	-1.0E-05
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.024	0.006	0.025	0.012	-0.819	-0.751
GWP	kg eq. CO <sub>2</sub>	104	223	94	24	-937	-492

## 4.12 Scenario L – Stadler & TLT

Figure 4.12 Process diagram for scenario L



\* For clarity, provision of utilities and material drying have been omitted from this diagram but are included in the assessment.

This scenario assumes that the film fraction is removed first, and the remaining rigid fraction is then shredded prior to processing. TLT's technology uses a float/sink density separation processes to separate out the various polymer streams. In principle a cascade of these processes could be used with float media of varying densities (which TLT have developed) to separate out all the polymer types. However in this scenario only a single separation step has been modelled to produce a float fraction comprised of mixed polyolefin (PE and PP) that is sent for mechanical recycling with no further attempt to separate these polymers.

The sink fraction is comprised of the non-polyolefin plastics and other residual materials and is assumed to be sent to landfill or incineration with energy recovery.

**Table 4.12.1** Scenario L impact assessment results for different feedstock compositions

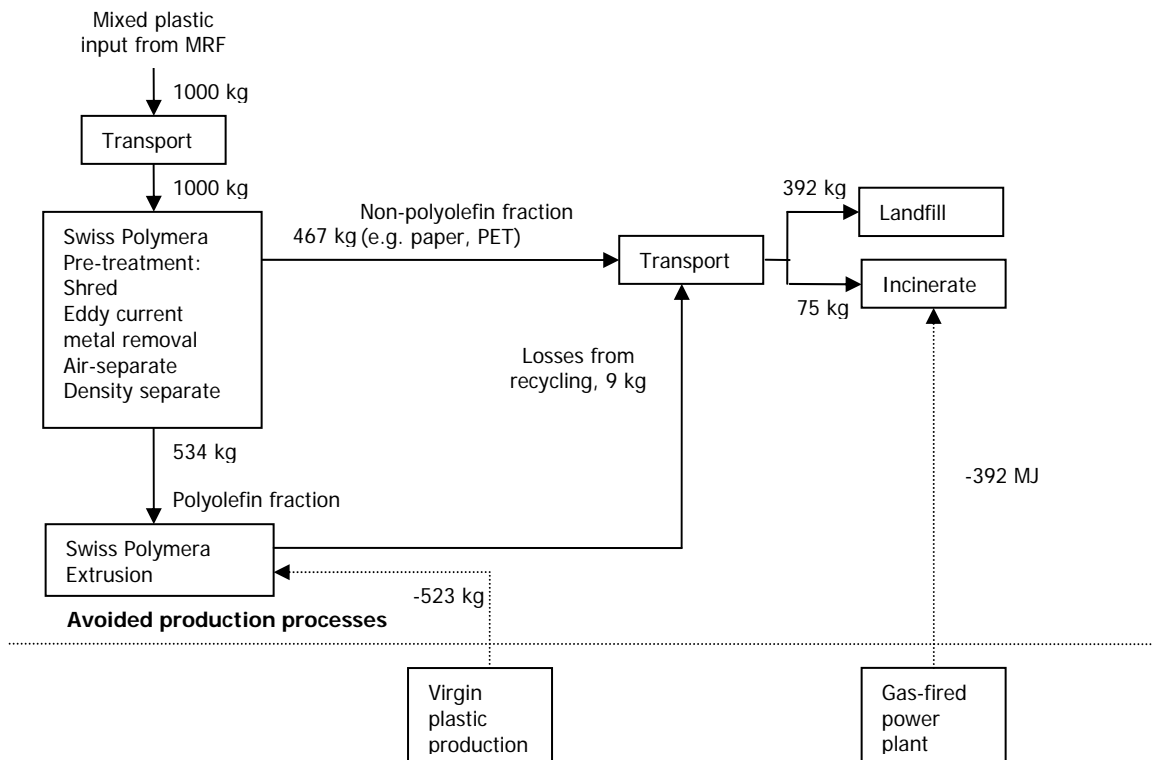
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-2984	-9753	-13505
ADP	kg eq. Sb	-4	-13.735	-19
AP	kg eq. SO <sub>2</sub>	-2	-8.271	-12
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	1	0.152	0
HTP	kg eq. DCB	863	652.02	497
OLDP	kg eq. R11	0	-6.1E-07	0
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0	-1.291	-2
GWP	kg eq. CO <sub>2</sub>	140	-464	-809
Solid Waste	kg	741	488	344

**Table 4.12.2** Scenario L impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	1886	271	180	332	-12421	-9753
ADP	kg eq. Sb	0.609	0.075	0.071	0.147	-14.637	-13.735
AP	kg eq. SO <sub>2</sub>	0.296	0.085	0.120	0.107	-8.879	-8.271
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.025	0.013	0.674	0.025	-0.584	0.152
HTP	kg eq. DCB	8.24	108.09	563.81	1.27	-29.39	652.02
OLDP	kg eq. R11	1.9E-06	9.0E-07	1.6E-06	2.8E-06	-7.8E-06	-6.1E-07
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.019	0.009	0.025	0.012	-1.356	-1.291
GWP	kg eq. CO <sub>2</sub>	84	208	90	22	-869	-464

## 4.13 Scenario M - Swiss Polymera

**Figure 4.13** Process diagram for scenario M



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

The Swiss Polymera pre-treatment process separates film and rigid plastics into polyolefin and non-polyolefin fractions using density separation so no additional upstream treatment processes are required. The pre-treatment comprise several steps as including:

- Shredding
- Eddy current metal removal (metals recovered are still assumed to be landfilled in this assessment, though in practise these may well be recycled. The low content of metals in the waste stream means that this assumption should not significantly affect the results)
- Zig-zag air separator to remove films
- Density separation for both film and rigid fractions
- Washing
- Densification of PO films prior to extrusion

The polyolefin fraction is extruded to form a mixed recycled granulate, which is assumed to replace virgin polyethylene production. The non-polyolefin fraction is sent to landfill and incineration according to the average UK mix of these disposal options.

**Table 4.13.1** Scenario M impact assessment results for different feedstock compositions

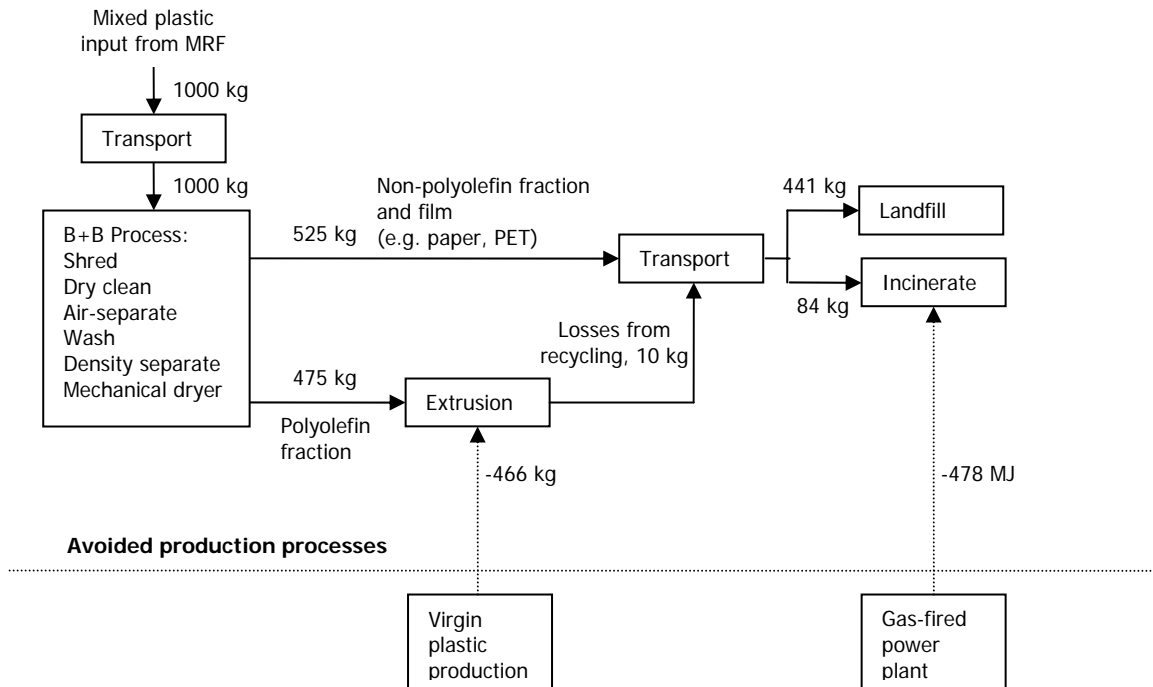
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-2607	-10758	-15039
ADP	kg eq. Sb	-4.514	-16.429	-22.679
AP	kg eq. SO <sub>2</sub>	-2.341	-10.087	-14.145
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	1.038	-0.013	-0.593
HTP	kg eq. DCB	832.56	438.57	218.86
OLDP	kg eq. R11	-2.6E-06	1.5E-06	3.8E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.392	-1.585	-2.211
GWP	kg eq. CO <sub>2</sub>	137	-631	-1034
Solid Waste	kg	728	407	238

**Table 4.13.2** Scenario M impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	3243	264	150	239	-14654	-10758
ADP	kg eq. Sb	1.047	0.073	0.059	0.106	-17.713	-16.429
AP	kg eq. SO <sub>2</sub>	0.510	0.079	0.107	0.077	-10.860	-10.087
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.043	0.012	0.627	0.018	-0.713	-0.013
HTP	kg eq. DCB	14.30	84.09	375.00	0.91	-35.73	438.57
OLDP	kg eq. R11	3.2E-06	8.6E-07	1.3E-06	2.0E-06	-5.9E-06	1.5E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.033	0.008	0.022	0.009	-1.657	-1.585
GWP	kg eq. CO <sub>2</sub>	145	163	82	16	-1036	-631

## 4.14 Scenario N – B+B

**Figure 4.14** Process diagram for scenario N



\* For clarity, provision of utilities have been omitted from this diagram but are included in the assessment.

The B+B recycling process consists of a number of steps as follows:

- Shredding incoming feedstock
- Mechanically “dry” cleaning
- Zig-zag air filter to remove film
- Pre-wash and hot wash
- Centrifuge
- Friction wash
- Density separation
- Mechanical Dryer

As with the other flake separation scenarios it is assumed that the rigid polyolefin fraction is mechanically recycled, while the remaining material (non-PO polymers, films and residue) is disposed of to landfill or incineration with energy recovery.

**Table 4.14.1** Scenario N impact assessment results for different feedstock compositions

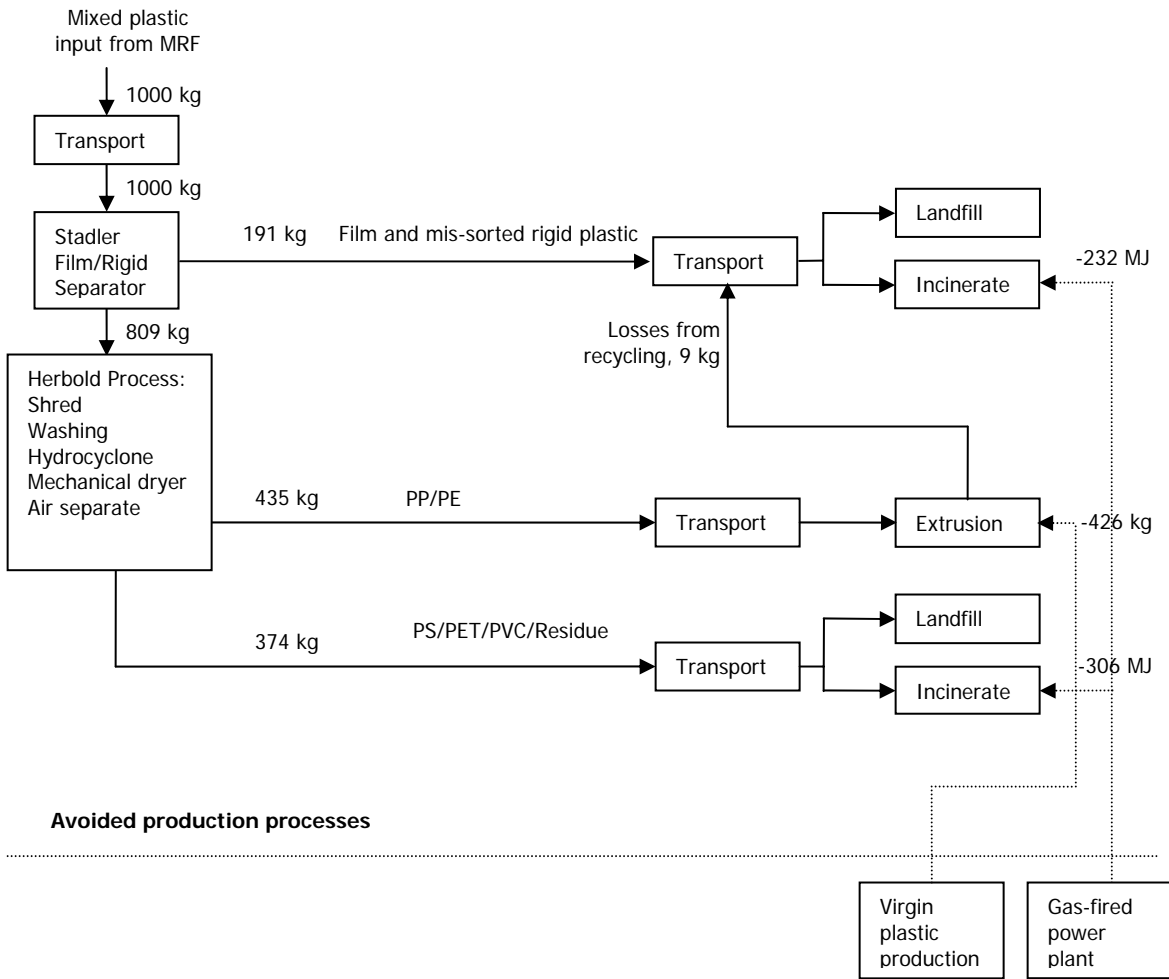
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-897	-7782	-11702
ADP	kg eq. Sb	-3.694	-13.460	-19.027
AP	kg eq. SO <sub>2</sub>	-1.888	-8.213	-11.816
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	1.078	0.156	-0.381
HTP	kg eq. DCB	863.81	627.51	457.27
OLDP	kg eq. R11	-1.2E-06	1.9E-06	3.9E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.344	-1.314	-1.867
GWP	kg eq. CO <sub>2</sub>	232	-397	-758
Solid Waste	kg	737	476	327

**Table 4.14.2** Scenario N impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	4170	279	175	333	-12739	-7782
ADP	kg eq. Sb	1.347	0.077	0.069	0.147	-15.101	-13.460
AP	kg eq. SO <sub>2</sub>	0.654	0.086	0.118	0.107	-9.178	-8.213
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.055	0.013	0.667	0.025	-0.603	0.156
HTP	kg eq. DCB	18.22	103.11	535.25	1.27	-30.34	627.51
OLDP	kg eq. R11	4.1E-06	9.2E-07	1.6E-06	2.8E-06	-7.5E-06	1.9E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.043	0.009	0.024	0.012	-1.401	-1.314
GWP	kg eq. CO <sub>2</sub>	186	199	89	23	-895	-397

## 4.15 Scenario O - Herbold

**Figure 4.15** Process diagram for scenario O



\* For clarity, provision of utilities and material drying have been omitted from this diagram but are included in the assessment.

In this scenario it is assumed that film is removed from the waste plastic feedstock prior to processing through Herbold's plant, which consists of a number of steps as follows:

- Shredding incoming feedstock
- Friction wash
- Turbo-wash
- Hydrocyclone density separation
- Centrifuge
- Mechanical dryer
- Zig-zag air filter to remove film

As with the other flake separation scenarios it is assumed that the rigid polyolefin fraction is mechanically recycled, while the remaining material (non-PO polymers, films and residue) is disposed of to landfill or incineration with energy recovery.

**Table 4.15.1** Scenario O impact assessment results for different feedstock compositions

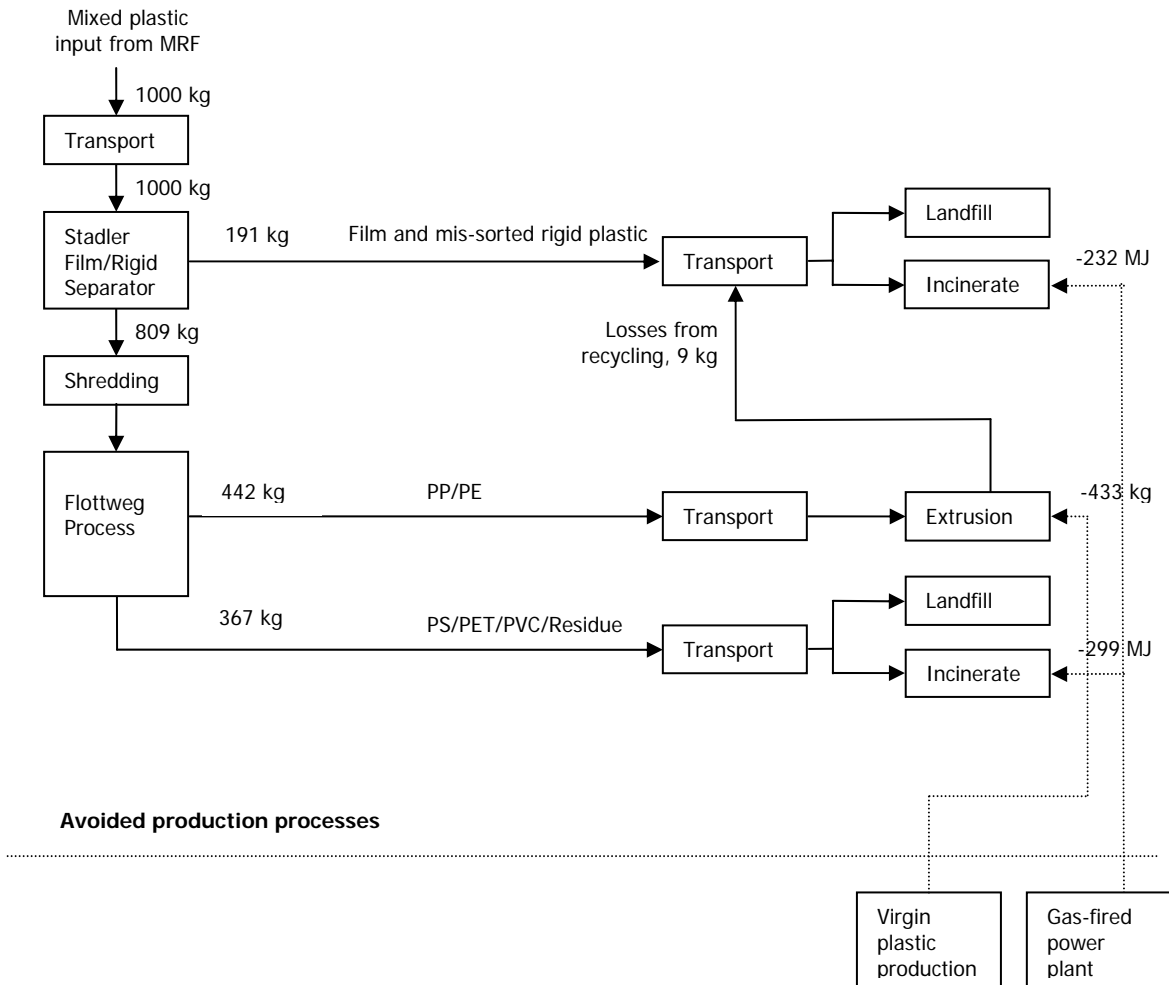
Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	812	-6076	-9709
ADP	kg eq. Sb	-3.042	-12.547	-17.894
AP	kg eq. SO <sub>2</sub>	-1.549	-7.694	-11.159
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	1.107	0.201	-0.325
HTP	kg eq. DCB	879.41	668.16	513.71
OLDP	kg eq. R11	4.0E-07	3.0E-06	5.0E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.314	-1.253	-1.787
GWP	kg eq. CO <sub>2</sub>	310	-300	-640
Solid Waste	kg	741	488	344

**Table 4.15.2** Scenario O impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	5562	271	180	332	-12421	-6076
ADP	kg eq. Sb	1.797	0.075	0.071	0.147	-14.637	-12.547
AP	kg eq. SO <sub>2</sub>	0.873	0.085	0.120	0.107	-8.879	-7.694
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.073	0.013	0.674	0.025	-0.584	0.201
HTP	kg eq. DCB	24.38	108.09	563.81	1.27	-29.39	668.16
OLDP	kg eq. R11	5.5E-06	9.0E-07	1.6E-06	2.8E-06	-7.8E-06	3.0E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.057	0.009	0.025	0.012	-1.356	-1.253
GWP	kg eq. CO <sub>2</sub>	248	208	90	22	-869	-300

## 4.16 Scenario P - Flottweg

**Figure 4.16** Process diagram for scenario P



\* For clarity, provision of utilities and material drying have been omitted from this diagram but are included in the assessment.

In this scenario it is assumed that film is removed from the waste plastic feedstock prior to processing through Flottweg's sorticanter equipment, which cleans, separates and mechanically dries the mixed plastic flakes in one step.

As with the other flake separation scenarios it is assumed that the rigid polyolefin fraction is mechanically recycled, while the remaining material (non-PO polymers, films and residue) is disposed of to landfill or incineration with energy recovery.

**Table 4.16.1** Scenario P impact assessment results for different feedstock compositions

Impact Category	Unit	Low Polyolefin	Default	High Polyolefin
Energy	MJ	-1996	-8897	-12663
ADP	kg eq. Sb	-3.999	-13.630	-19.091
AP	kg eq. SO <sub>2</sub>	-2.024	-8.254	-11.789
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	1.067	0.153	-0.378
HTP	kg eq. DCB	862.67	641.18	480.42
OLDP	kg eq. R11	-2.3E-06	5.0E-07	2.4E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.349	-1.302	-1.846
GWP	kg eq. CO <sub>2</sub>	182	-434	-783
Solid Waste	kg	739	482	336

**Table 4.16.2** Scenario P impact assessment results showing contribution from different process stages (default feedstock)

Impact Category	Unit	Mechanical Recycling	Incineration	Landfill	Transport	Avoided Impacts	Total
Energy	MJ	2914	268	178	332	-12588	-8897
ADP	kg eq. Sb	0.940	0.074	0.070	0.147	-14.861	-13.630
AP	kg eq. SO <sub>2</sub>	0.458	0.084	0.119	0.107	-9.022	-8.254
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.038	0.013	0.670	0.025	-0.593	0.153
HTP	kg eq. DCB	12.85	106.74	550.17	1.27	-29.85	641.18
OLDP	kg eq. R11	2.9E-06	8.9E-07	1.6E-06	2.8E-06	-7.7E-06	5.0E-07
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	0.030	0.009	0.025	0.012	-1.377	-1.302
GWP	kg eq. CO <sub>2</sub>	130	206	90	23	-882	-434

## 5.0 Scenario comparisons and discussion

### 5.1 Normalisation

To get an indication of the relative importance of each impact category a normalisation exercise has been conducted. Although WRAP has organisational goals that prioritise global warming and solid waste as key issues this LCA study also considers other impact categories and normalisation can be used to help understand their relative importance.

Due to the time and budget restraints on the project this normalisation exercise is somewhat crude and is based on data provided in the CML 2001 Normalisation Factors for Western Europe<sup>37</sup> (relevant UK data were not available for the range of impact categories assessed in this study). It is acknowledged that these data are in need of updating to properly reflect the current situation but it is felt that their use is valid in this instance to give a general impression of the relative scale of the different impact categories. It is also noted that several alternative approaches to normalisation are possible (such as basing the assessment on the distance to achieving a legislated target). Each of these has strengths and weaknesses but will not be considered further in this report.

Four scenarios representative of the range of different management options assessed in this study have been normalised against the reference of total annual contributions to each impact category from Western Europe. The impact categories have been ranked as shown in Table 5.1 – with the ranking ranging from 1 (most significant contribution) through to 7 (least significant contribution) relative to the reference data. Information for energy consumption and solid waste arising are not included in the CML 2001 Normalisation Factors and have been omitted from this exercise.

**Table 5.1** Relative ranking of the normalised impact categories for selected scenarios

Scenario	ADP	AP	EP	HTP	OLDP	POCP	GWP
A (Landfill)	4	5	2	1	7	6	3
C (SRF)	7	6	3	1	2	4	5
G (Stadler & Titech)	7	6	3	1	2	4	5
L (Stadler & TLT)	7	6	2	1	3	5	4
<b>Total "Score"</b>	<b>25</b>	<b>23</b>	<b>10</b>	<b>4</b>	<b>14</b>	<b>19</b>	<b>17</b>

It is clear that the ranking based on normalisation varies according to the particular impacts associated with each scenario. Nevertheless, some trends are evident with scenarios C, G and F broadly agreeing the relative ranking of the categories, while scenario A (the landfill option) differs significantly in places. To aggregate these differences a total "score" summing the results for all the scenarios is given at the bottom of the table, the lower the number, the higher the ranking and the greater the relative importance of the impact category.

This normalisation exercise gives the following ranking in order of importance:

- Human toxicity potential (HTP)
- Eutrophication potential (EP)
- Ozone layer depletion potential (OLDP)
- Global warming potential (GWP)
- Photochemical ozone creation potential (POCP)
- Acidification potential (AP)
- Abiotic depletion potential (ADP)

It is important to interpret these results carefully. For example it may be decided that even though OLDP ranks highly in normalised terms the emissions are still very small in absolute terms due to existing control measures and so this would not be considered a priority impact category for WRAP. Equally, the high ranking given to EP will be in part due to the use of Ecoinvent datasets for landfill which assume a worst-case scenario for leaching as described in Section 4.1.

Nevertheless, this quick top-level assessment indicates that impacts relating to human toxicity are important aspects associated with management processes for waste plastic, while impacts relating to acidification and abiotic depletion are of less concern.

## 5.2 Summary of results

The overall results are summarised in Table 5.2, which gives the relative ranking of each scenario for the impact categories assessed in this study. The results of the normalisation have been used to help rank the impact categories in order of importance (taking into account the broader issues discussed above for specific impact categories).

**Table 5.2** Summary of results showing relative ranking of the scenarios against each impact category (rank 1 = best, rank 16 = worst), green = top 25%, red = bottom 25%

Scenario	High priority ← → Low priority								
	GWP	Solid Waste	Energy	HTP	EP	POCP	AP	ADP	OLDP
A (Landfill)	15	16	16	16	16	16	16	16	16
B (Incineration)	16	1	8	15	10	15	15	15	2
C (SRF)	11	2	1	14	2	12	11	1	10
D (BP pyrolysis)	14	12	4	2	8	13	13	14	3
E (Ozmotech pyrolysis)	13	15	3	3	1	11	12	13	1
F (Redox agent)	12	4	2	4	13	14	14	5	9
G (Stadler & Titech)	1	5	5	5	3	6	4	3	6
H (Stadler & Pellenc)	4	7	7	11	5	8	8	7	4
I (Stadler & Qinetiq)	7	14	10	13	7	10	10	12	5
J (Stadler & Sims)	2	6	6	6	4	7	5	4	7
K (KME & Titech)	5	8	9	12	6	9	9	9	8
L (Stadler & TLT)	6	10	12	8	11	3	2	6	11
M (Swiss Polymera)	3	3	11	1	9	1	1	2	13
N (B+B)	9	13	14	10	14	5	6	10	14
O (Stadler & Herbold)	10	11	15	9	15	4	7	11	15
P (Stadler & Flottweg)	8	9	13	7	12	2	3	8	12

Each impact category is discussed in more detail below. To facilitate comparison and discussion of the various scenarios modelled in this study two sets of charts are presented for each impact category, based on the results provided in Section 4.

- The first chart gives the net impact (accounting for avoided impacts from recycling, etc.) of each scenario. The purple bars indicate scenarios incorporating recycling processes with data obtained from plant trials, the yellow bars indicate scenarios looking at alternative management options based on available published data.
- The second chart shows the contribution to the overall result from the various sub-processes in each scenario (e.g. transport, mechanical recycling, landfill, etc.).

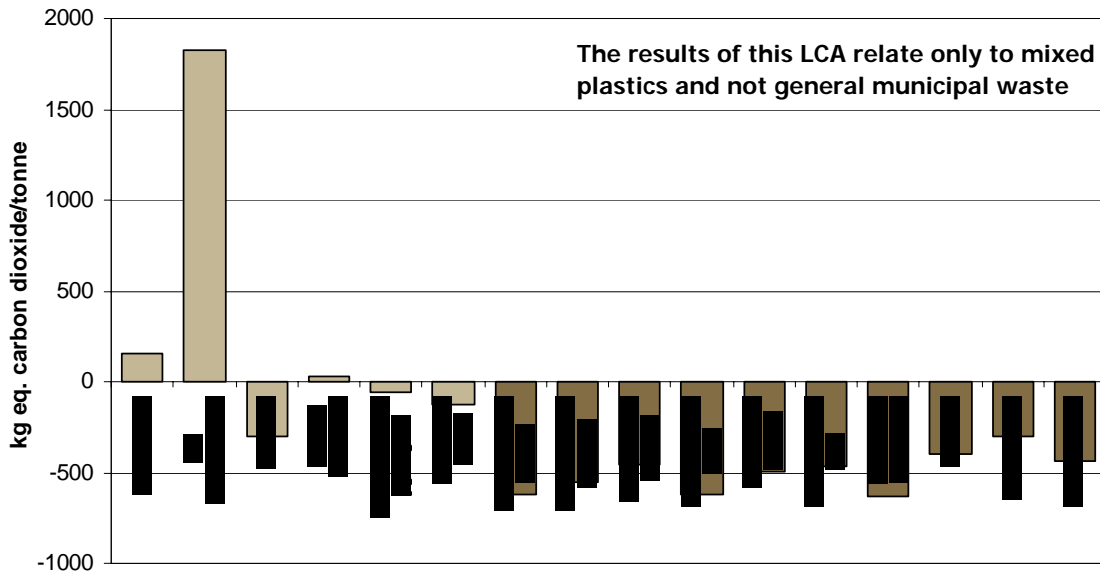
Results on both charts relate to the default feedstock composition and default assumptions. Sensitivity analyses around key assumptions are considered in Section 6.

When reading the charts, positive values signify negative environmental impacts arising from the recycling/reprocessing supply chain. Negative values signify an environmental benefit and are due to avoided processes (e.g. avoiding the need to produce primary plastic).

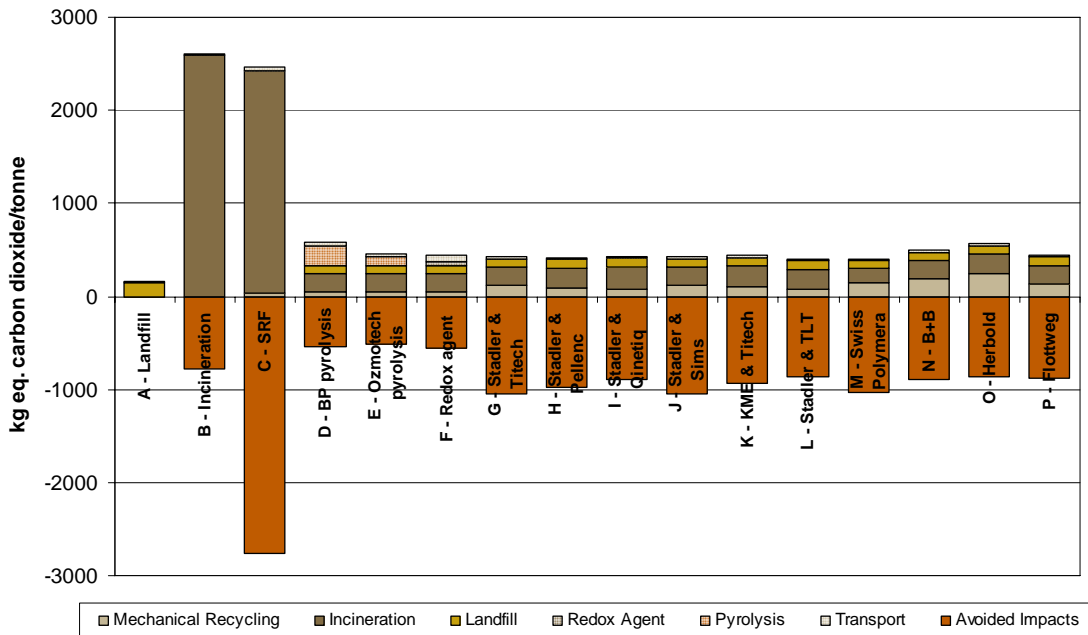
Some caution should be exercised when making direct comparisons between scenarios when the differences between them are small. As well as the uncertainties inherent in LCA studies further differences may arise due to the way the trials were organised. For example, data on the Titech process were collected with the sorter operating at a lower speed than for the Pellenc process and this may explain the slightly higher apparent recycling efficiency of the Titech equipment.

### 5.3 Global Warming Potential

**Chart 5.3.1** Net global warming potential



**Chart 5.3.2** Contribution to global warming potential by process stage



Emissions contributing to global warming have a global effect on the environment wherever they are released and continuing work by the Intergovernmental Panel on Climate Change (IPCC) means that the cause-effect relationship between emission of greenhouses gases and climate change are fairly well understood. A 100 year time horizon has been used for considering global warming impacts. In almost all cases carbon dioxide is by far the most important greenhouse gas, followed by methane, while contributions

to the impact category from other greenhouse gases are negligible. The exception is scenario A (landfill), where emissions of methane have the biggest contribution.

The overall picture for GWP tends to be dominated by the avoided emissions from substituted processes associated with each scenario although with some important exceptions. The two energy recovery scenarios (B & C) both produce large emissions of greenhouse gases as a result of the plastic being burnt. In scenario B (municipal incineration) this is not fully compensated for by the avoided production of electricity from natural gas, resulting in this scenario having the greatest net GWP of the scenarios assessed.

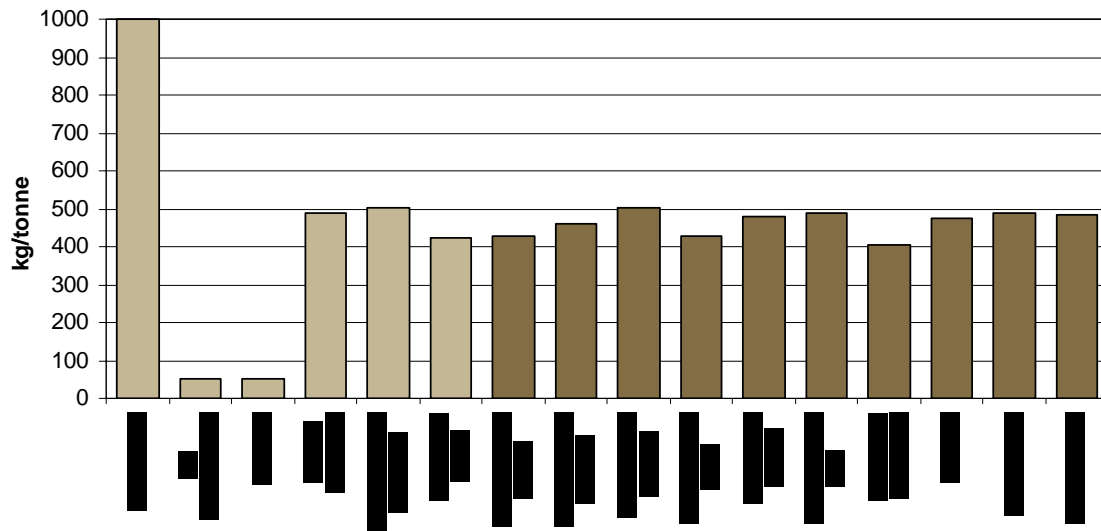
In contrast, the carbon dioxide emissions from burning plastic in scenario C (SRF to cement kilns) are largely cancelled out by the displaced carbon dioxide emissions from avoiding burning coal. Interestingly this means that the avoided methane emissions associated with coal production play an important role and are the biggest contributors to the resulting negative GWP in this scenario.

The pyrolysis and redox agent scenarios (D, E & F) all have near zero net GWP as the benefits of the avoided processes are largely balanced by greenhouse gas emissions from processing the material. Compared against the recycling scenarios (G – P) it can be seen that they all have similar process emissions, but that the recycling routes receive a greater credit for avoided processes – and so are preferred over pyrolysis and redox routes for this impact category.

Most of the recycling scenarios have similar net global warming potential and are all preferred over the alternative management options.

## 5.4 Solid waste

**Chart 5.4.1** Solid waste arising



This metric assesses the portion of landfilled material from the input feedstock (i.e. that fraction that is not recycled or recovered in each scenario), but does not include solid waste arising from other processes along the supply chain.

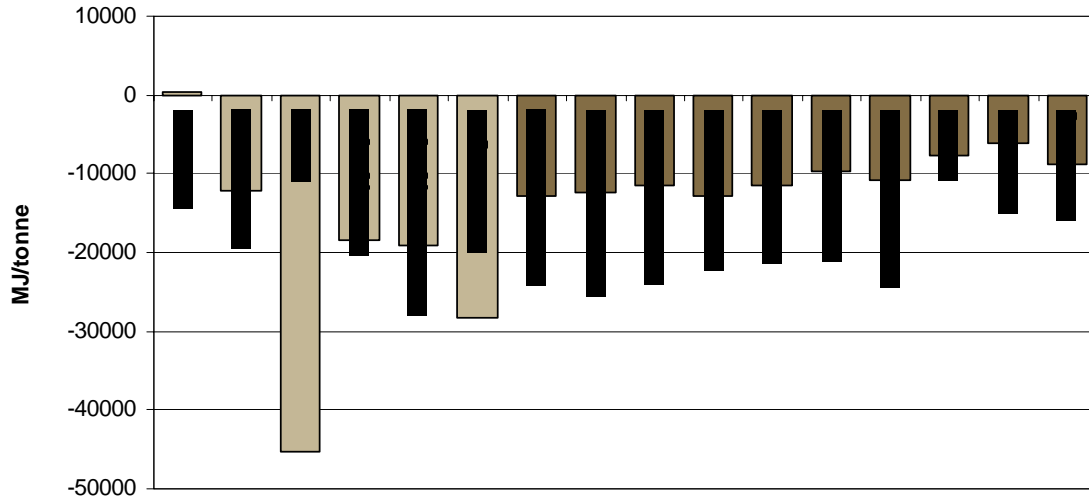
Scenario A (landfill), clearly, has the most adverse performance – with all the input material being landfilled. Scenario B (incineration) and scenario C (SRF) have the best performance as combustion residues from burning plastic are very small compared to the mass of input material.

Most of the remaining scenarios result in similar quantities of solid waste arising – between 400 – 500 kg/tonne, depending upon the process.

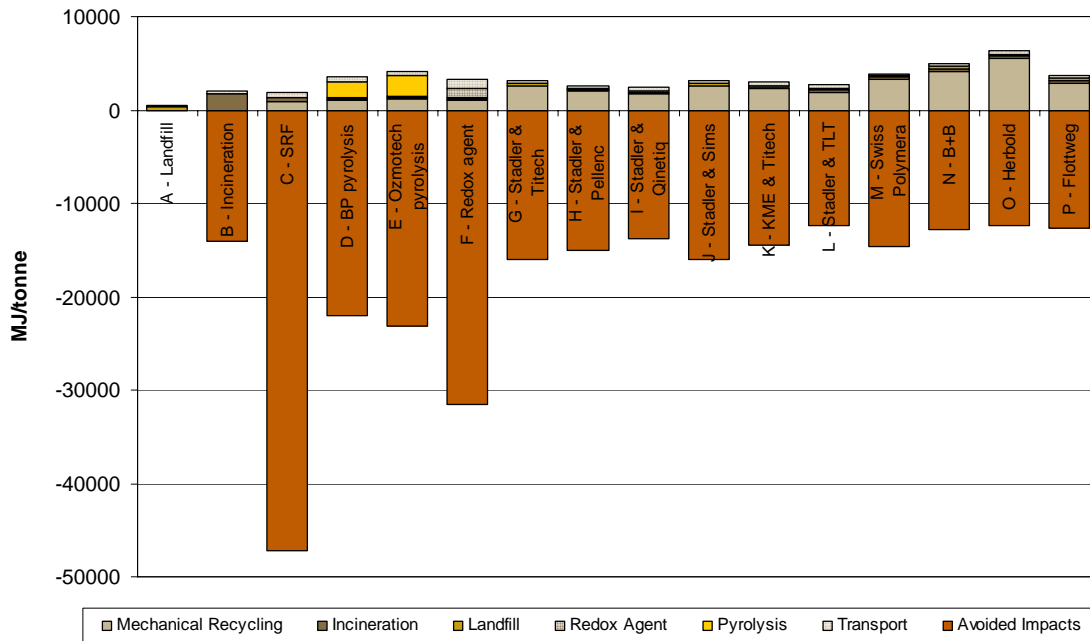
The current UK mix of disposal options for mixed waste plastic – landfill (84%) and incineration (16%) – results in around 838 kg solid waste/tonne. Therefore these results show that all the alternative recycling/recovery scenarios give clear benefits compared to the current situation.

## 5.5 Primary Energy

**Chart 5.5.1** Net primary energy requirement



**Chart 5.5.2** Contribution to primary energy requirement by process stage



There are large differences between the process energy demands of each scenario, but the overall picture is dominated by the avoided impacts associated with displacing production of virgin plastics, electricity, etc.

Scenario A (landfill) has the lowest process energy requirements but as it receives no credits for avoided impacts it has the greatest net energy demand among the scenarios assessed in this study.

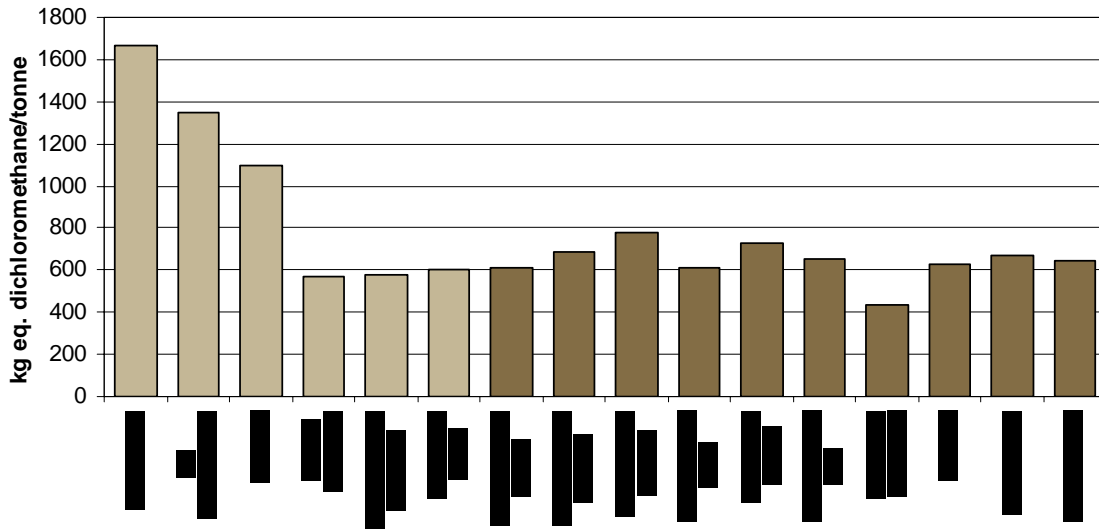
Scenario B (incineration) receives credit for avoiding power production from natural gas and so has a better performance than landfill. However, the thermal conversion efficiency of incinerators is relatively poor, as is highlighted through comparison with scenario C (SRF to cement kilns) a higher value energy recovery option. SRF substitutes directly for coal and this gives scenario C a very large primary energy credit – consequently, this scenario has clearly the best performance in this impact category.

Scenarios D and E, the two pyrolysis options have very similar performance better than landfill and incineration, and also better than the recycling scenarios but still worse than the SRF scenario. Scenario F – the redox agent substitute scenario gives the second best performance in this category.

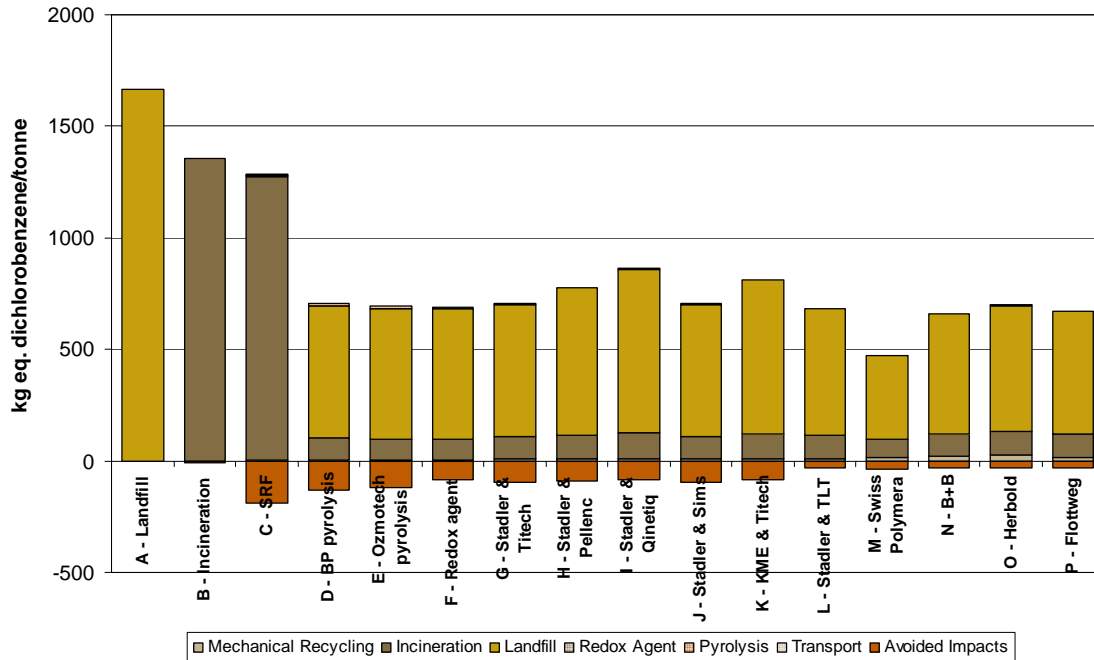
All the recycling scenarios (G – P) are clustered around a fairly small range of values and are broadly comparable to scenario C (incineration). These scenarios all receive credits from avoiding the energy required to process virgin plastic.

## 5.6 Human Toxicity Potential

**Chart 5.6.1** Net human toxicity potential



**Chart 5.6.2** Contribution to human toxicity potential by process stage



Calculating human toxicity potential in LCA is extremely difficult for several reasons:

- Different people respond to chemicals in different ways
- Cause and effect relationships can be very complicated and poorly understood
- Small quantities of some chemicals can be very toxic, but these may be omitted from life cycle inventories (e.g. if the cut-off point for data collection is based on mass)

- Impacts will be dependent upon the location of the release and lifetime of the chemical in the environment
- Lack of relevant toxicity data on many chemicals will mean that the impact category will be incomplete

As such, these results can be considered to be a guide to relative human toxicity potential between scenarios but the absolute values should not be relied upon.

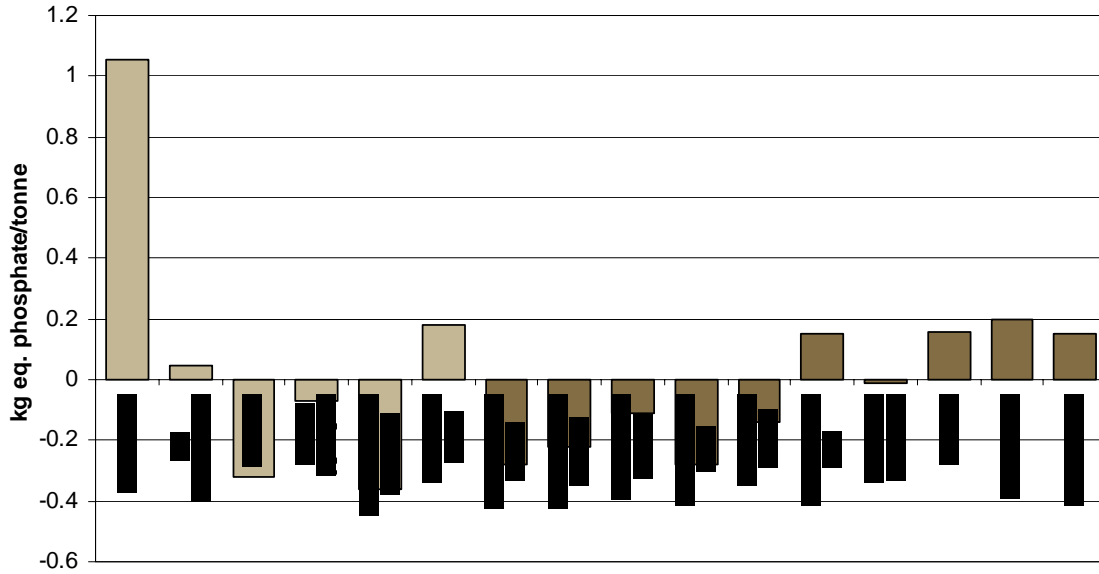
All the scenarios assessed result in a net adverse impact for the human toxicity potential category. This is due to the large contributions from both landfill and incineration, which easily outweigh any benefits deriving from recycling or reprocessing.

As for the EP impact category the majority of the emissions contributing to HTP are due to long-term leaching from landfill (over 60,000 years). Because of this, the results tend to vary according to the quantity of solid waste produced by each scenario (see Section 5.9). However, incineration processes also show large contributions to this impact category because it is assumed that the incineration residues are landfilled and so will eventually also leach into the environment. As such, it can be seen that scenario A (landfill) and scenario's B and C (incineration and SRF) have the most adverse performance in this impact category. It should be remembered that HTP is a measure of *potential* toxicity impacts, but that toxic emissions occurring over a period of 60,000 years may well have only minimal actual impact.

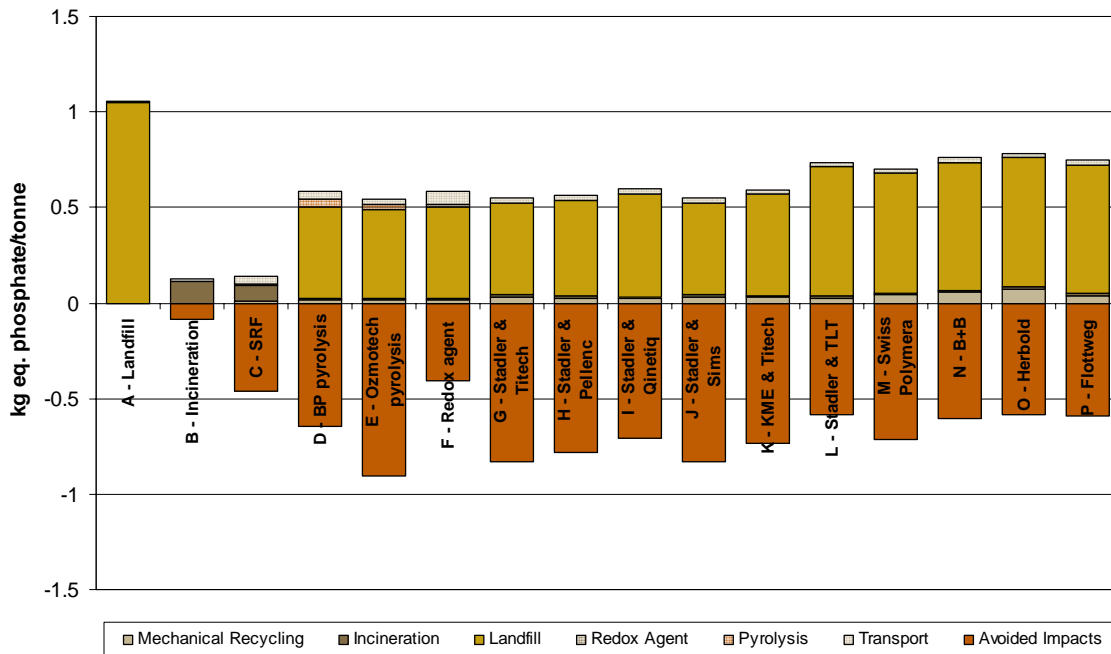
Vanadium is the key toxic component contributing to this impact category and vanadium compounds are often used to provide smoke redartant properties to plastics. Smaller contributions resulting from release of barium, thalium and selenium are also often seen.

## 5.7 Eutrophication Potential

**Chart 5.7.1** Net eutrophication potential



**Chart 5.7.2** Contribution to eutrophication potential by process stage



In spatial terms eutrophication is largely confined locally to the site of emission. It is primarily caused by waterborne emissions so there does not tend to be the same long range transport that can occur for atmospheric pollutants (although there is some contribution from gaseous emissions that are subsequently washed out in rain or through “dry deposition”). The CML impact assessment approach aggregates all

nitrifying emissions regardless of location so the results presented here represent worst-case potential impacts rather than the actual impacts that would occur at a given location.

What is most immediately noticeable about the results in this impact category is the very large contribution from landfill operations. This is largely a consequence of the approach taken by Ecoinvent to model the datasets for landfill processes. These take a worst-case position, considering total impacts over very long timescales (60,000 years), during which time it is assumed that the landfill lining would be breached. Nitrogen-containing additives are found in waste plastics and over these very long timescales these are assumed to degrade to result in emissions of ammonia, organically bound nitrogen compounds and other species that will leach into the wider environment and contribute to this impact category (the Ecoinvent data indicate that waste PET has particularly large quantities of nitrogen containing additives and contributes the majority of these emissions).

However, considering eutrophication impacts over shorter timescales, e.g. 100 years, it is likely that very little of the landfilled plastic will have degraded and the landfill lining would be expected to remain an effective barrier to leaching. As such, actual eutrophication from landfills over these timescales would be probably be very low.

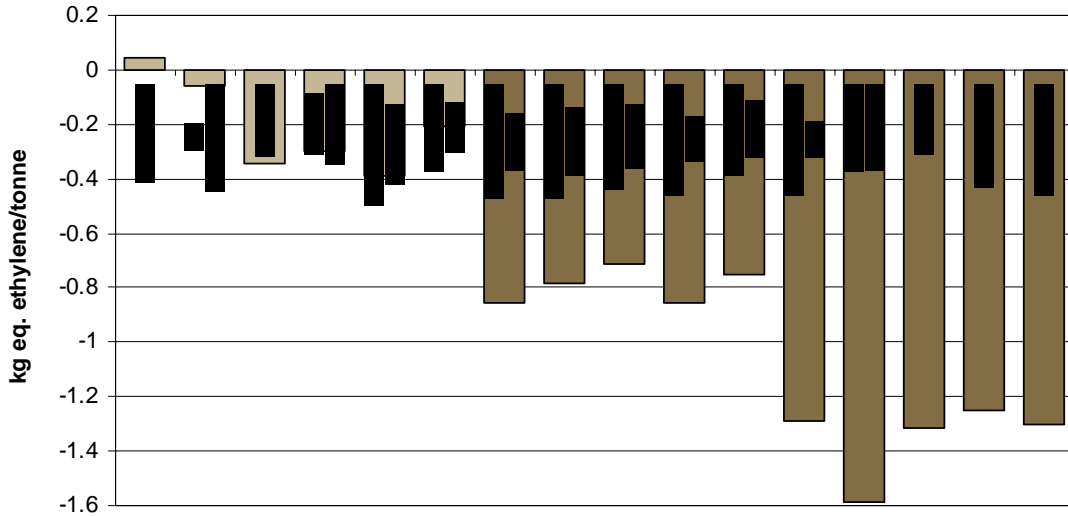
The pros and cons of taking different timescales into account are discussed in detail in the Ecoinvent database documentation<sup>26</sup>. A point to note here is that if only short timescale impacts are considered (e.g. over 100 years) then all the scenarios apart from B (incineration) and C (SRF) would show a considerable improvement in their net performance for this impact category.

Leaving aside this issue and accepting the Ecoinvent approach, it is clear that scenario A (landfill) has by far the most adverse performance of any scenario considered in this study. The two scenarios with the best performance are C (SRF) and E (Ozmotech pyrolysis) because the substituted products (coal and petrochemical diesel) both lead to large avoided emissions in this category.

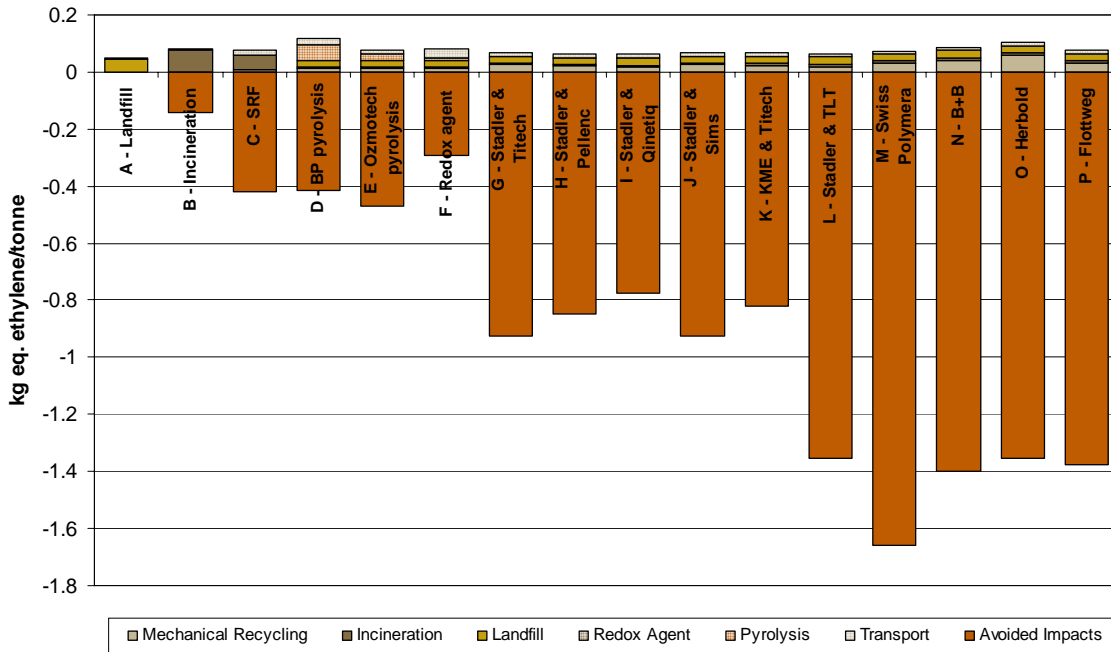
Again, there is a difference in performance between the NIR-based recycling scenarios (G – K) and the density separation-based recycling scenarios (L – P). In this case, however, the NIR-based scenarios have the better net performance. This is because these scenarios sort most of the PET from the feedstock whereas the density separation-based scenarios focus solely on recovering polyolefins, leaving the other polymers – including PET - to be disposed of to landfill and incineration.

## 5.8 Photochemical Ozone Creation Potential

**Chart 5.8.1** Net photochemical ozone creation potential



**Chart 5.8.2** Contribution to photochemical ozone creation potential by process stage



Photochemical ozone creation and the subsequent “photochemical smog” that often results relies on chemical reactions between volatile organic compounds (VOCs) and nitrogen oxides catalysed by ultraviolet light from the sun. As for eutrophication, POCP impacts are largely confined to the locality where the emissions occur. The actual degree of photochemical ozone creation that occurs depends on how all these factors interrelate – the amount of VOCs emitted, the background level of nitrogen oxides and the amount

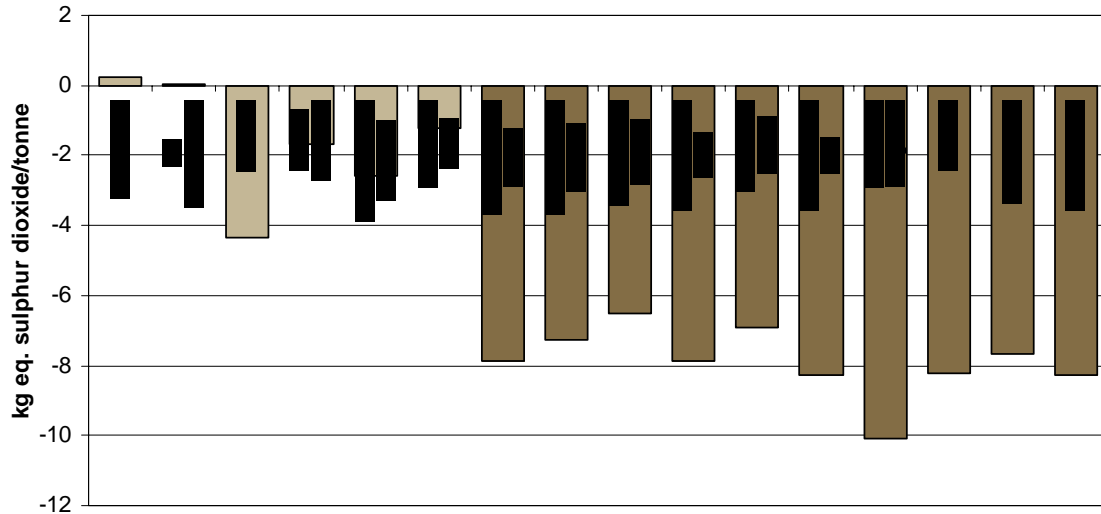
of sunshine received. Because of this complexity the results of this impact category may not necessarily be accurate in absolute terms, but the relative ranking of the scenarios can be considered to be more robust.

Overall the results for this impact category are somewhat similar to those for acidification potential, being dominated by credits from avoided emissions of substituted processes and with the recycling scenarios having a better environmental performance than the alternative waste management scenarios. To a large extent this similarity is explained because the same species - sulphur dioxide and nitrogen oxides – are significant contributors to both impact categories. For POCP there are also large contributions from emissions of non-methane VOCs such as produced during virgin plastic production. This provides additional benefits to the plastics recycling scenarios in this category.

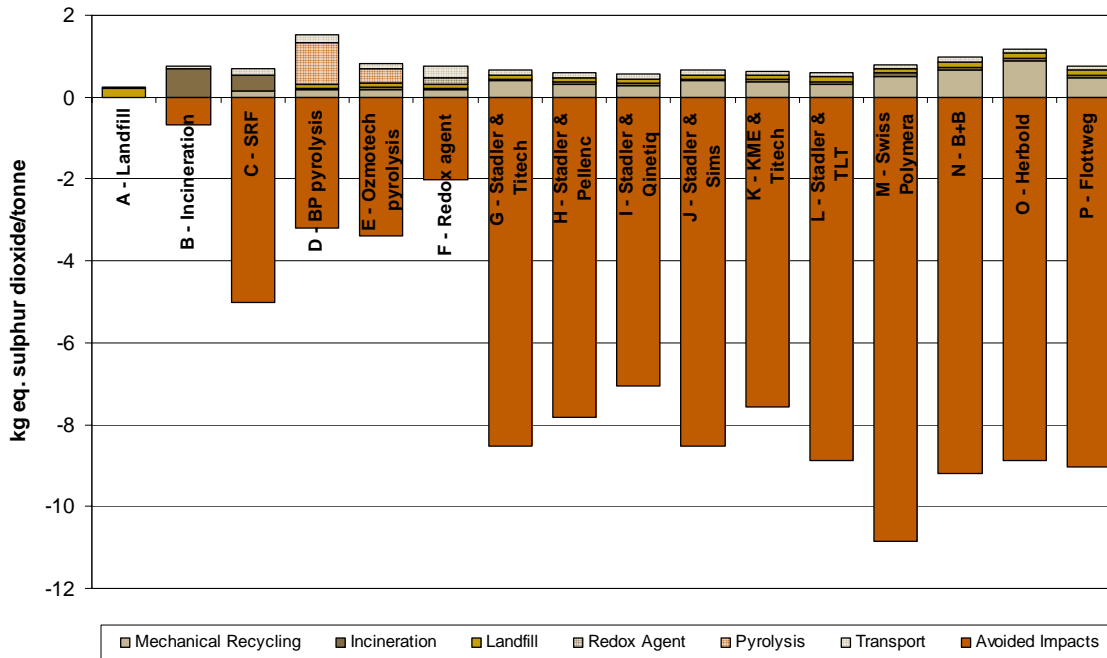
A noticeable further trend is that the density separation-based recycling scenarios (L – P) have a better environmental performance than the NIR-based recycling scenarios (G – K) in this category. This is mainly due to large avoided emissions of non-methane VOCs from virgin PE production. The density separation scenarios are focused on PE and PP recycling and tend to recycle a larger proportion of PE than the NIR-based scenarios and this leads to greater overall reductions in POCP.

## 5.9 Acidification Potential

**Chart 5.9.1** Net acidification potential



**Chart 5.9.2** Contribution to acidification potential by process stage



Acidification is an environmental problem that can affect quite a large region distant from the point of release of acidifying gases, but is not considered a global issue in the same way as global warming or ozone depletion. As such, acidifying emissions from the UK may affect forests in Norway but will not damage rainforests in the Amazon. Public awareness of acidification (as “acid rain”) grew in Europe during the 1970-80s in response to highly publicised damage occurring to European forests. Subsequent legislation such as the Convention on Long-Range Transboundary Air Pollution and the Sulphur Emissions Reduction Protocol

have led to mitigation measures such as requirements for power stations to fit flue-gas desulphurisation technology. These have meant that problems due to acidification are currently well managed in Europe (although problems may still exist elsewhere – particularly in rapidly developing countries such as China). Dealing with acidification in LCA is further complicated as acid damage only occurs after a threshold limit is exceeded – and this limit varies depending on location. The CML impact assessment approach aggregates all acidifying emissions regardless of location so the results presented here represent worst-case potential impacts rather than the actual impacts that would occur at a given location.

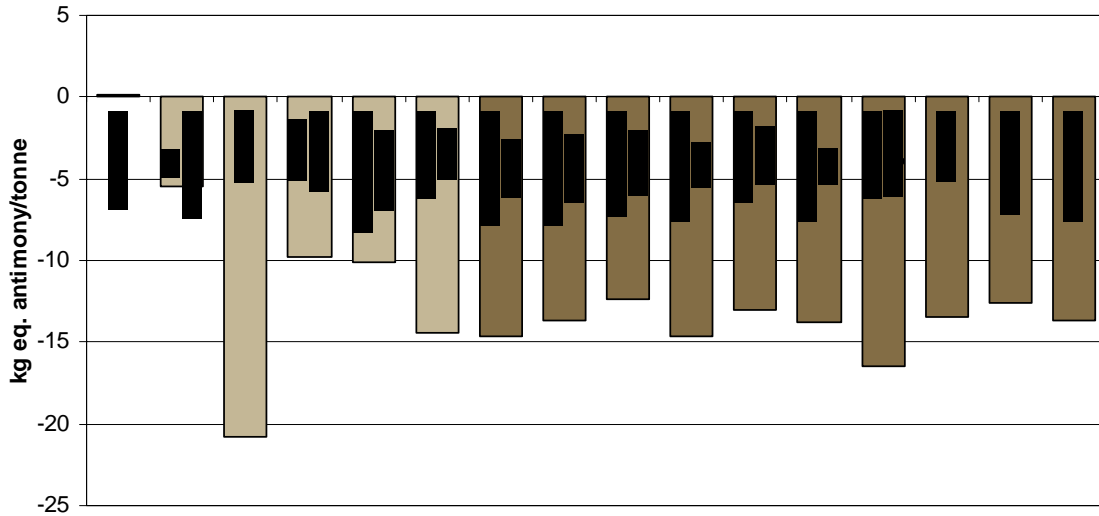
It is immediately apparent that there are large differences between the recycling scenarios and the alternative waste management options in this impact category. This is primarily because, although there is some variation in the process impacts, the results in this impact category are dominated by credits received from avoided emissions from substituted processes – to a similar extent as seen in the primary energy profiles. Because virgin plastic production results in larger emissions of acidifying gases than the other substituted processes the credits received in the recycling scenarios are also greater.

Scenarios A (landfill) and B (incineration) have the worst performance with net positive acidifying emissions. Scenarios D, E and F result in small net negative emissions. Scenario C (SRF) has an intermediate performance that is better than other alternative waste management scenarios but falls behind the recycling scenarios.

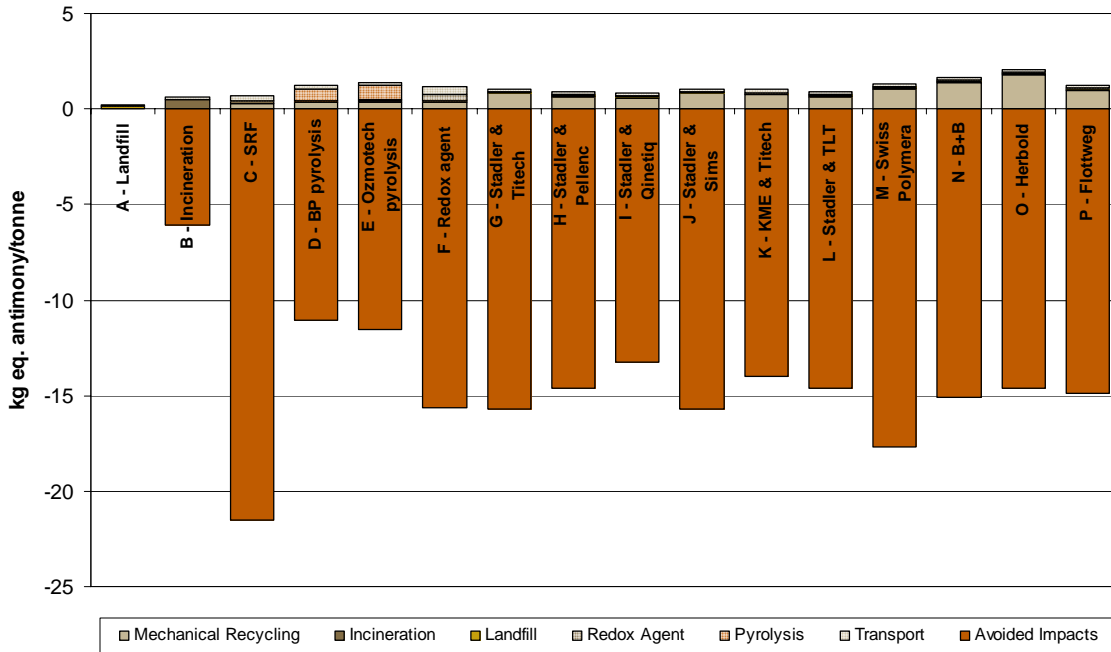
The most important contributors to the AP impact category are emissions of nitrogen oxides and sulphur dioxide, with smaller contributions from other species such as ammonia, hydrogen sulphide and hydrogen chloride. The category is dominated by the avoided emissions resulting from substituted processes. This is particularly true for the plastics recycling scenarios and explains why they outperform the alternative waste management options.

## 5.10 Abiotic depletion potential

**Chart 5.10.1** Net abiotic depletion potential



**Chart 5.10.2** Contribution to abiotic depletion potential by process stage



Abiotic depletion – the consumption of non-renewable resources – is a global issue (globalisation means that resources can easily be shipped around the world according to demand).

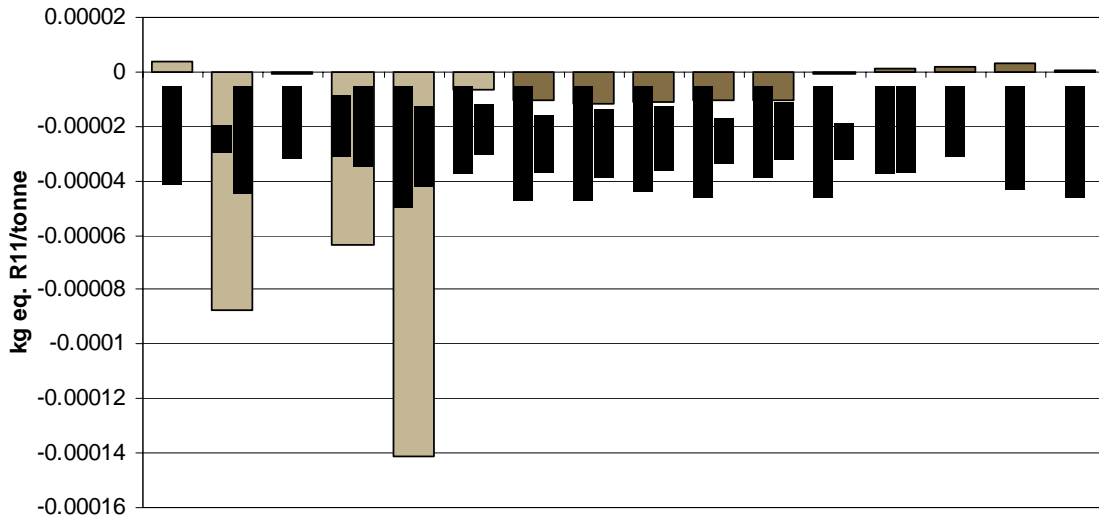
As with several other impact categories considered in this assessment, the results for ADP are dominated by credits received through avoiding emissions from substituted processes associated with each scenario.

The main contributors to this impact category are consumption of fossil fuels (hence the close similarities with the results for primary energy consumption) and as such, the total quantity of plastic recycled explains the variations between the recycling scenarios (G – M).

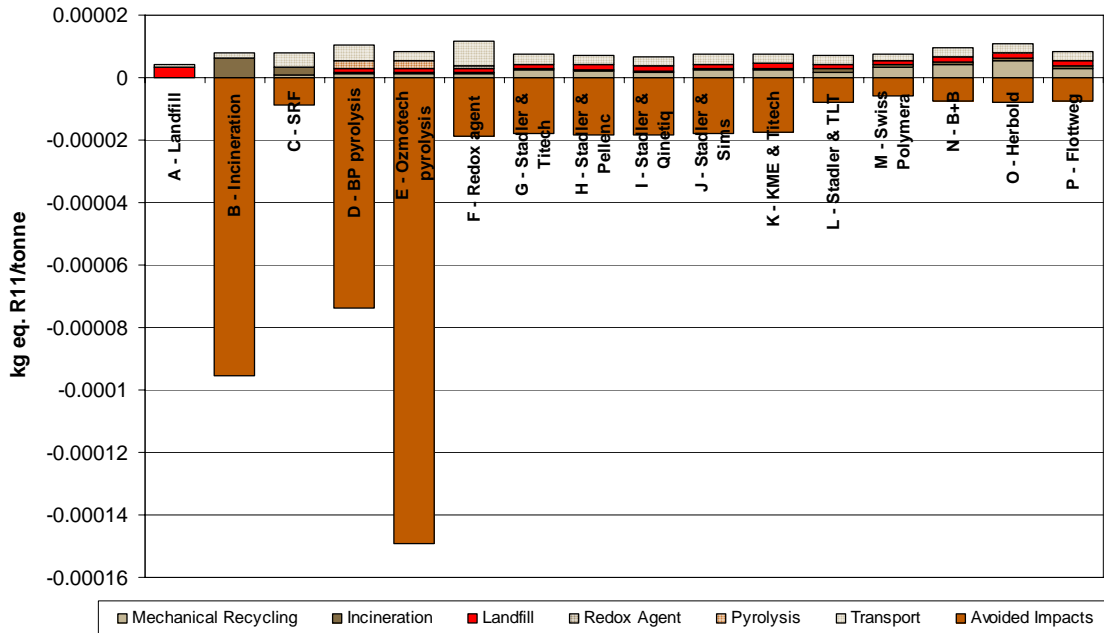
Scenario C (SRF to cement kilns) receives a large credit by avoiding the use of coal. The lesser credits assigned to scenario B (incineration) and scenarios D and E (pyrolysis) are due to the lower efficiency of these processes. Incineration has relatively low thermal conversion efficiency and the pyrolysis options require a significant proportion of their output to be fed back to the reactor fuel the process.

## 5.11 Ozone Layer Depletion Potential

**Chart 5.11.1** Net ozone layer depletion potential



**Chart 5.11.2** Contribution to ozone layer depletion potential by process stage



Ozone layer depletion is a global environmental issue in the same manner as global warming. Due to extremely long lifetimes in the atmosphere, an emission of CFC (or other ozone depleting chemicals) anywhere in the world will contribute to ozone depletion globally.

In relative terms there is significant variation in performance among the various scenarios for this impact category. Scenarios B (incineration), D (BP pyrolysis) and E (Oxmotech pyrolysis) stand out as having much greater net negative contributions than the other scenarios.

The main contributors to this impact category are emissions from energy production processes – in particular of Halon 1211 (bromochlorodifluoromethane) from production of natural gas and Halon 1301 (bromotrifluoromethane) from production of diesel and naphtha. These explain the large avoided impacts seen in these scenarios.

However, it is important when discussing the ODP impact category to note that none of the options assessed has a significant contribution, either positive or negative, in absolute terms. It may be concluded that this impact category is not an issue of concern for any of the scenarios assessed in this study as production and emissions of ozone depleting chemicals are restricted through existing legislation such as the Montreal Protocol.

## 6.0 Sensitivity analyses

The results of sensitivity analyses relating to variations in feedstock composition are presented with the main results for each scenario in Section 4, above, but are discussed in more detail here.

Further sensitivity analyses are presented here looking at:

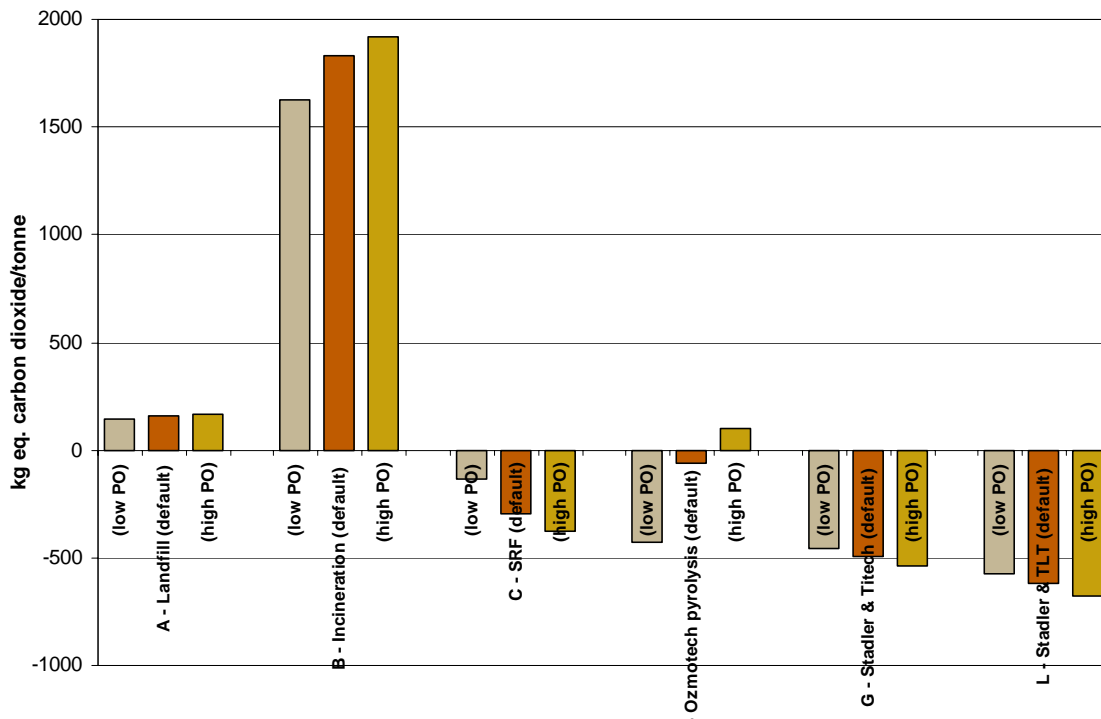
- Incinerator efficiency
- The basis for substitution of plastic recyclate
- Using UK grid electricity production as the substituted power source for electricity generated from municipal incinerators

In each case the effect of the sensitivity analysis on the global warming potential impact category is shown, as this is the priority issue for WRAP. A selection of representative scenarios for various technologies is included in each comparison (where scenarios are very similar e.g. there are several scenarios modelling NIR sorting technology only one has been included in these comparisons. This choice should not be considered to favour one technology over another but is solely to aid clarity in interpreting the sensitivity analyses by reducing the options to a manageable number). The scenarios modelled are as follows:

- Scenario A – Landfill
- Scenario B – Incineration with energy recovery
- Scenario C – SRF used in cement kilns
- Scenario E – Pyrolysis (plastic to diesel)
- Scenario G – Mechanical recycling based on NIR sorting technology
- Scenario L – Mechanical recycling based on density separation technology

### 6.1 Feedstock composition

**Figure 6.1** Sensitivity of feedstock composition on GWP



Composition of the input material to the recycling/reprocessing routes can vary considerably as discussed in Section 3.6.2. Analysis has been carried out to examine the sensitivity of the results to different input materials by considering a low polyolefin mix and a high polyolefin mix as well as the default mix. The compositions of these different input feedstocks are provided in Table 3.6.2. Results for the full range of impact categories are provided with the scenario descriptions in Section 4. It should be noted that the three scenarios for feedstock composition do not represent “extremes” but are all quite likely to occur given the variation from the MRF.

Figure 6.1 shows the effects of varying feedstock composition on the global warming potential impact category. In general it can be seen that although variation in the polyolefin content of the feedstock does affect the GWP results, this is not usually to an extent where the relative rankings of the scenarios change. The exception is scenario E (plastic-to-diesel pyrolysis) where the trend is for greater adverse impacts as polyolefin content increases – to the extent that for the high polyolefin composition there is a net increase in GWP. High polyolefin content means more material from the waste stream is sent to pyrolysis rather than recycling so these results indicate that the pyrolysis option is generally less favourable than mechanical recycling in terms of GWP.

## 6.2 Incinerator efficiency

The efficiency with which the incinerator converts energy in the mixed plastic waste into electricity is an important factor affecting the results of this study as it determines to what degree the impacts of the incineration process are offset by avoided the need to produce electricity from primary fuels. Published studies give a wide range of values for the efficiency of power generation from municipal waste incinerators. This variation arises due to a number of factors including:

- Type and nature of the waste feedstock
- Output options – potential to use electricity, water, steam produced
- Technology applied
- Whether internal energy consumption of the process is accounted for
- Whether gross calorific values (GCV) or net calorific values (NCV) are used in the calculations (in some reports it is not clear which is used).

Examples of values quoted in recent studies are given below:

- A 2006 study by the USEPA <sup>38</sup> gives an efficiency of 17.8% for electricity generated from mass burn incineration (not clear whether these figures are based on NCV or GCV).
- A 2001 report for the European Commission <sup>39</sup> indicates that efficiencies for power generation range from 15–22% in thermal treatment plants based on NCV.
- The 2006 BAT standard for incineration <sup>40</sup> quotes efficiencies ranging from 15-30% for thermal plants producing electricity only (not clear whether these figures are based on NCV or GCV).
- A 2003 Biffaward study carried out by C-Tech Innovation <sup>41</sup> reports a figure of 25.4% based on NCV.
- Fichtner, in a 2004 report <sup>42</sup> for ESTET, state that “For a modern plant based combustion technology, the net electrical efficiency is in the range 19 to 27%” based on NCV.
- A 2003 good-practice guide produced by CIWM <sup>43</sup> reports efficiency of generation of 22%-25% (not clear whether these figures are based on NCV or GCV).

Given this wide range, two different conversion efficiency scenarios have been considered for incineration with energy recovery:

- A baseline scenario with a conversion efficiency (NCV) of 23%, which is midway between the extremes reported in the literature and thus expected to be typical for modern incinerators

- A high efficiency scenario with a conversion efficiency (NCV) of 30%, at the top end of the efficiencies reported in the literature

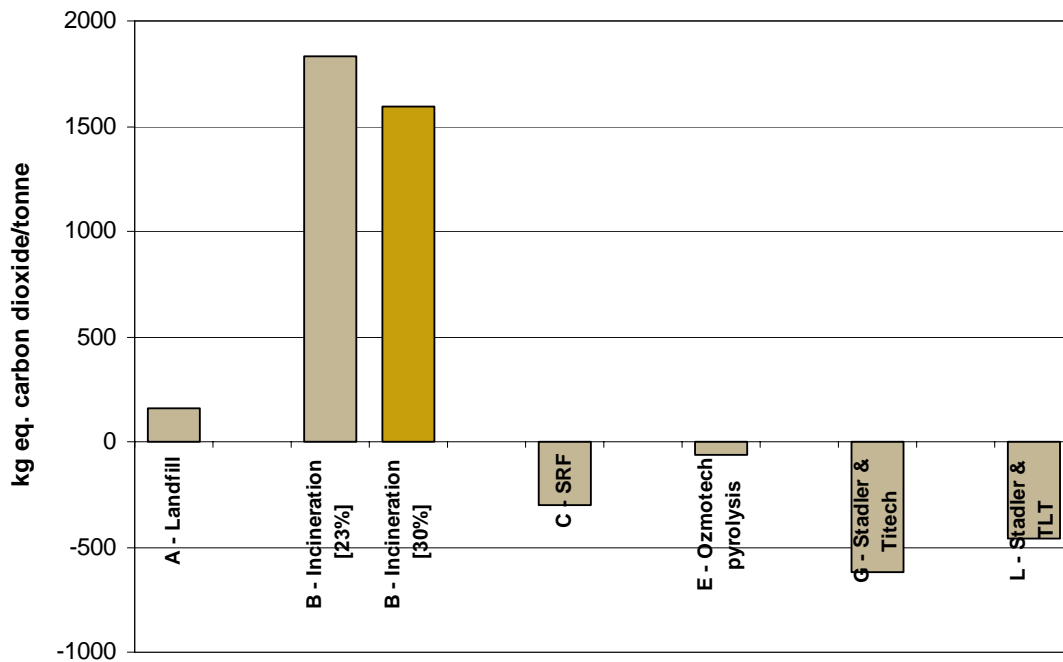
Benefits from producing heat from waste - as hot water or steam - as well as power has not been included in this assessment as heat energy is not typically recovered by UK incinerators.

The impact assessment results are given in Table 6.2 and the effects of differing incinerator efficiencies on the GWP impact category are shown in Figure 6.2.

**Table 6.2** Scenario B impact assessment results showing the effect of different thermal conversion efficiencies (based on net calorific values and using default feedstock)

Impact Category	Unit	23% Efficiency	30% Efficiency
Energy	MJ	-12083	-16363
ADP	kg eq. Sb	-5.485	-7.335
AP	kg eq. SO <sub>2</sub>	0.055	-0.154
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	0.045	0.019
HTP	kg eq. DCB	1350.05	1347.66
OLDP	kg eq. R11	-8.7E-05	-1.2E-04
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.060	-0.104
GWP	kg eq. CO <sub>2</sub>	1829	1592
Solid Waste	kg	49	49

**Figure 6.2** Sensitivity of municipal incinerator thermal conversion efficiency on GWP



The results show that although the efficiency of the municipal incinerator does have a considerable impact on the absolute GWP from incineration it is not sufficient to alter its ranking relative to the other scenarios. Variation in this factor is not expected to significantly affect the conclusions of this study.

### 6.3 Substituted power from municipal incineration

The results presented in Section 4 assume that power generation from combustion of wastes at a municipal incinerator substitutes for that generated by a combined-cycle gas power plant (in line with UK Government recommendations for this type of analysis).

However there are numerous other potential sources of power generation (nuclear, coal, oil, wind, hydro, etc.) that power produced at municipal incinerators could substitute for.

It is clearly impractical to assess all of these options in this study and there are large uncertainties in how the UK power supply market will develop due to unresolved issues relating to climate change, energy security, planning restrictions and development of new technologies. In this sensitivity analysis only two alternative scenarios are considered.

The first option assumes that power generated in municipal incinerator facilities substitutes for power from the UK grid (i.e. from the range of UK power suppliers including gas, oil, coal, nuclear, hydro, wind, etc.). Data on the UK electricity mix were taken from the Ecoinvent database based on the supply situation in 2004, which is as follows:

- Coal – 32.6%
- Oil – 1.1 %
- Natural gas – 39.9%
- Industrial gas – 1.0%
- Hydropower – 2.0%
- Nuclear – 19.1%
- Wind – 0.5%
- Biomass – 1.0%
- Import from France – 2.5%

The second option considers that power generated at municipal incinerators substitutes for that supplied by coal-fired power stations.

The impact assessment results are given in Tables 6.3.1 and 6.3.2 and the effects of these alternatives on the GWP impact category are shown in Figure 6.3.

These results show that for global warming potential the study is not particularly sensitive to a switch of substitution from gas to UK average grid mix. Considering the make up of the UK electricity mix this is perhaps not surprising as fuels such as coal that emit higher levels of carbon dioxide than natural gas are largely offset by power production from nuclear sources which have near zero emissions of greenhouse gases.

For scenario B (incineration) larger improvements can be seen in other impact categories such as primary energy, acidification potential and eutrophication potential, but these are still not sufficient for it to change the overall ranking compared to the recycling technologies.

As a further comparison results are also presented for the scenario where power generation substitutes for electricity produced from a coal-fired power plant, as shown in Table 6.3.2. Burning coal results in greater emissions of carbon dioxide (contributing to global warming) and of SO<sub>x</sub> and NO<sub>x</sub> gases (leading to higher acidification) than burning natural gas and this leads to some significant differences between these scenarios. As a consequence, substituting for power from coal leads to improvements in environmental performance and this is particularly noticeable for scenario B (incineration) as is illustrated in Figure 6.3.

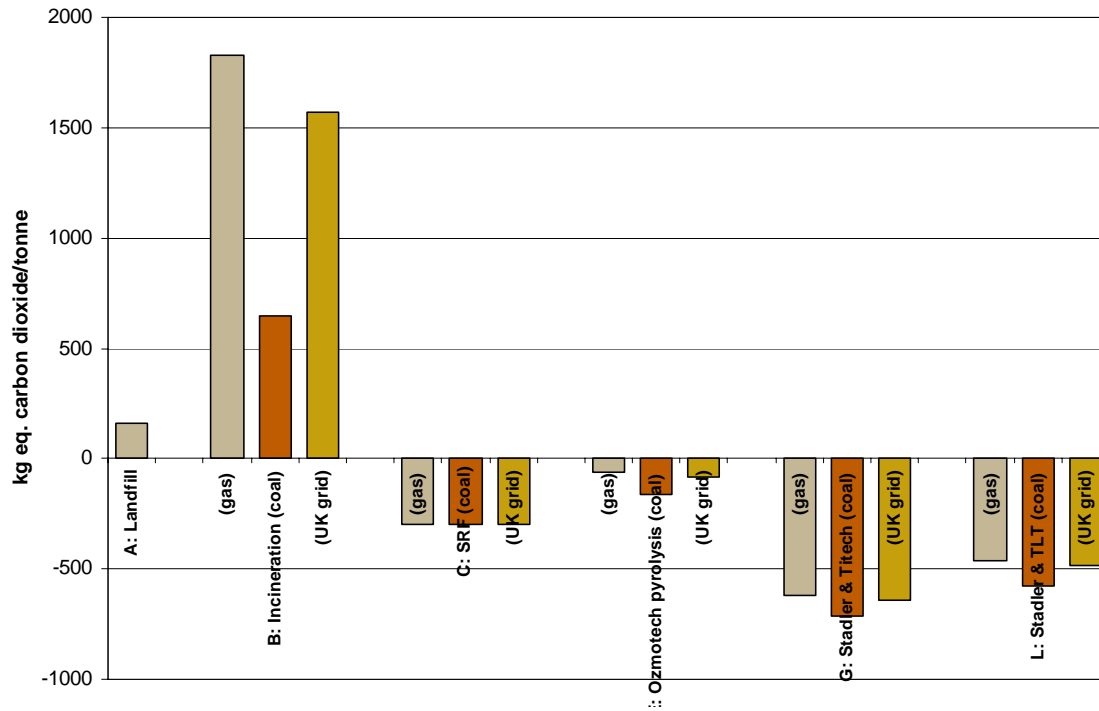
**Table 6.3.1** Impact assessment results for when power production from municipal incineration substitutes for average production from the UK grid

Impact Category	Unit	Scenario B (Incineration)	Scenario C (SRF)	Scenario E (Ozmotech Pyrolysis)	Scenario G (Stadler & Titech)	Scenario L (Stadler & TLT)
Energy	MJ	-21144	-47312	-19748	-23561	-10489
ADP	kg eq. Sb	-6.878	-20.824	-10.277	-14.776	-13.848
AP	kg eq. SO <sub>2</sub>	-2.882	-4.330	-2.820	-8.106	-8.510
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.177	-0.322	-0.377	-0.298	0.134
HTP	kg eq. DCB	1256.86	1094.70	569.83	600.85	644.45
OLDP	kg eq. R11	-1.5E-05	-8.8E-07	-1.3E-04	-4.8E-06	5.3E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.154	-0.342	-0.399	-0.863	-1.299
GWP	kg eq. CO <sub>2</sub>	1573	-300	-82	-640	-485
Solid Waste	kg	49	52	501	429	488

**Table 6.3.2** Impact assessment results for when power production from municipal incineration substitutes for production from a coal-fired power plant

Impact Category	Unit	Scenario B (Incineration)	Scenario C (SRF)	Scenario E (Ozmotech Pyrolysis)	Scenario G (Stadler & Titech)	Scenario L (Stadler & TLT)
Energy	MJ	-29900	-47323	-20472	-24248	-11484
ADP	kg eq. Sb	-13.877	-20.834	-10.856	-15.326	-14.545
AP	kg eq. SO <sub>2</sub>	-8.364	-4.337	-3.273	-8.536	-9.017
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.472	-0.322	-0.401	-0.321	0.105
HTP	kg eq. DCB	1118.90	1094.51	558.42	590.02	631.51
OLDP	kg eq. R11	-2.1E-06	-8.6E-07	-1.3E-04	-3.8E-06	5.9E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.445	-0.342	-0.423	-0.886	-1.326
GWP	kg eq. CO <sub>2</sub>	646	-301	-159	-712	-578
Solid Waste	kg	49	52	501	429	260

**Figure 6.3** Sensitivity of substitution options for power generation from municipal incinerators on global warming potential



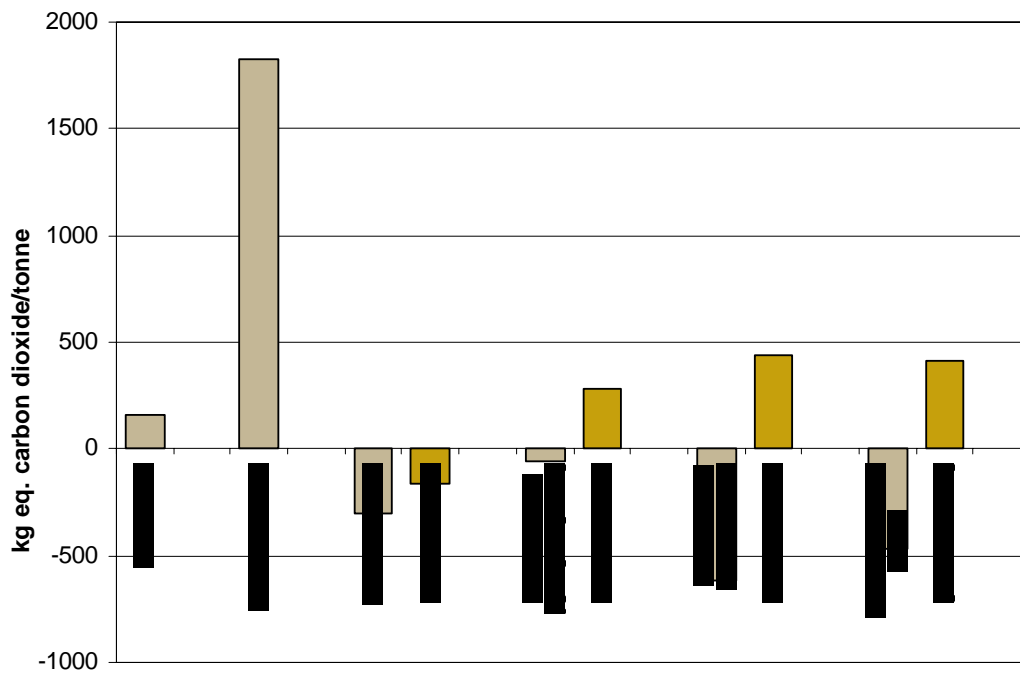
#### 6.4 Substituted material from recycling plastic

The default assumption in this study is that recycled plastic obtained from the recycling processes is of high quality and substitutes directly for virgin plastic on a 1:1 basis. This sensitivity analysis considers the effect on the results if the quality of the recyclate is not consistent and that only 20% of the recyclate replaces virgin plastic, the remainder is assumed to go into lower value applications that substitute for wood (40%) and concrete (40%). The impact assessment results are given in Table 6.3 and the effects of this change on the global warming potential impact category are shown in Figure 6.3.1.

**Table 6.4** Impact assessment results for when recycled plastic substitutes for 20% virgin plastic, 40% concrete and 40% wood

Impact Category	Unit	Scenario C (SRF)	Scenario E (Diesel Pyrolysis)	Scenario G (Stadler & Titech)	Scenario L (Stadler & TLT)
Energy	MJ	-43714	-14901	-7363	-1457
ADP	kg eq. Sb	-19.617	-6.797	-2.547	-2.496
AP	kg eq. SO <sub>2</sub>	-3.640	-1.177	-1.177	-1.287
EP	kg eq. PO <sub>4</sub> <sup>+</sup>	-0.259	-0.059	0.363	0.601
HTP	kg eq. DCB	1104.49	638.04	680.99	672.37
OLDP	kg eq. R11	-1.2E-06	-1.3E-04	-3.5E-06	-1.7E-06
POCP	kg eq. C <sub>2</sub> H <sub>4</sub>	-0.275	-0.221	-0.147	-0.234
GWP	kg eq. CO <sub>2</sub>	-163	278	439	415
Solid Waste	kg	52	501	429	488

**Figure 6.4.1** Sensitivity of substitution options for recycled plastic on global warming potential (100% displaced virgin plastic vs. 20% displaced virgin plastic, 40% concrete, 40% wood)



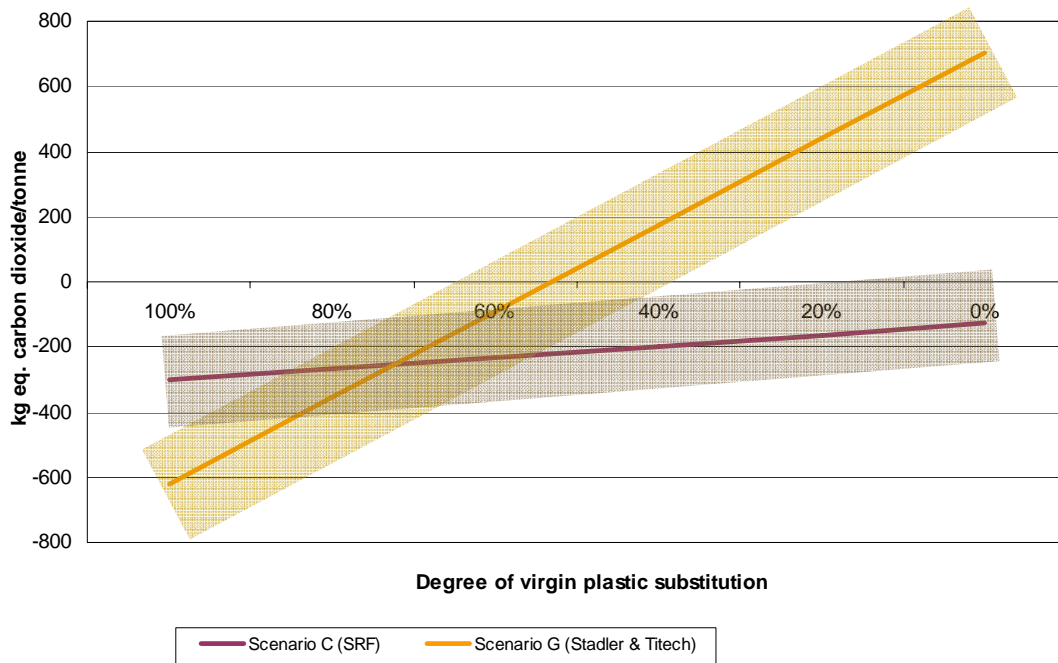
The effect on the results of changing the basis of substitution of recycled plastic from 100% virgin to a mix of virgin, concrete and wood is dramatic. This can be seen for the global warming potential impact category where the recycling processes switch from causing a net reduction in global warming to contributing to a net increase as emissions from the displaced materials fail to offset the impacts of the recycling processes.

Figure 6.4.2 shows the cross-over point for scenarios C (SRF to cement kilns) and G (Stadler & Titech) as the degree of virgin plastic displaced by recycled plastic is reduced from 100% to 0% (the remainder being evenly split between substituting for concrete and wood). These two scenarios have been selected as scenario G represents a typical recycling option while scenario C represents the best performing alternative technology. It should be noted that the results would change if different scenarios were compared. For global warming potential, scenario C becomes favoured over scenario G once the degree of virgin plastic substitution drops below about 70%.

A cross-over in the preferred scenario also occurs for acidification potential (once the degree of virgin plastic substitution drops to below about 55%) and photochemical ozone creation potential impact categories (once the degree of virgin plastic substitution drops to below about 45%). Scenario G also shows large negative changes all in other impact categories other than human toxicity potential (which is more or less unchanged).

Due to the inherent uncertainties in LCA the “absolute” values presented here should be treated with some caution and there is likely to be considerable variation around the 70% figure due to the specific assumptions and datasets in this study. Nevertheless, despite this uncertainty the general principle holds that the quality of the recyclates is a very important aspect affecting the environmental performance of the recycling scenarios and that the best environmental performance is achieved when high quality recycle is generated. If only lower quality recyclates are obtained then alternative disposal options may offer a better environmental solution.

**Figure 6.4.2** Sensitivity of substitution options for recycled plastic on global warming potential (comparison of scenarios C and G for varying degrees of substitution). Bands placed around each line to emphasise uncertainties in the data although these have not been quantified



This clearly is a critical issue for understanding the environmental performance of the recycling technologies – if a large proportion of the input material cannot be recycled to sufficient purity to replace virgin plastic then the contribution to total global warming potential of the recycling process is likely to become greater than that of alternative reprocessing/disposal options.

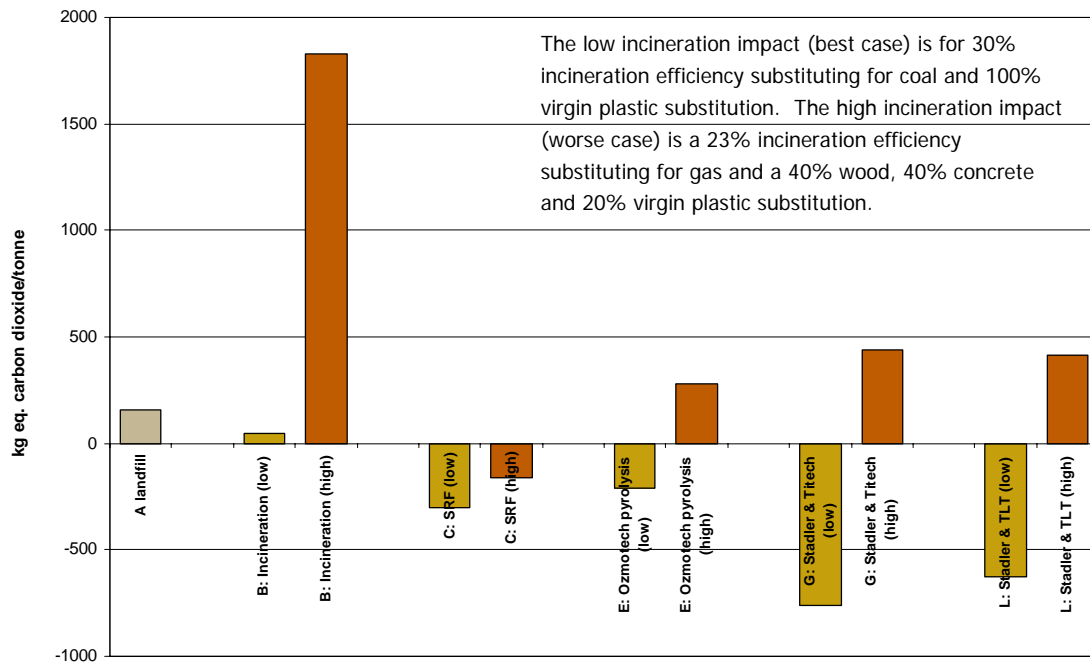
These results have clear implications for the development of plastics recycling processes in the UK and shows that no single scenario is likely to provide a complete solution. Rather, waste plastics recycling plants should be designed to produce high quality recycled material. Lower quality recycled applications should not be considered – instead it is likely to be preferable for lower quality fractions to be sent for alternative reprocessing options such as SRF or use as a redox agent in blast furnaces.

It should be emphasised that the goal of this project is not to specify a particular technology as superior to others but to understand the trade-offs that arise depending on the circumstances. Understanding these issues better is an area that would benefit from further work.

### 6.5 Effects of combining uncertainties

Figure 6.5 shows the results of combining uncertainties associated with incinerator efficiency and for substitution options for plastic recycle and incinerator power generation as discussed in Sections 6.2 – 6.4 above. The effects of the different feedstock scenarios (high and low polyolefin content) have not been included in this assessment as they do not represent extremes but simply different material compositions (all of which are fairly likely and could represent typical output from the MRF). Given the number of components in the feedstock it is difficult to decide which “extreme” scenario (e.g. 100% PET output from the MRF) should be used and would end up modelling scenarios that are extremely unlikely to ever occur in practise.

**Figure 6.5** Range of results for global warming potential when combining uncertainties associated with incinerator efficiency and for substitution options for power generation and recycling plastic (light orange = lowest impact; dark orange = highest impact).



The majority of the variation for scenarios E, G and L is due to substitution options for plastic recycling (ranging from 100% virgin plastic substitution through to 20% virgin plastic: 40% wood: 40% concrete). While for scenario B the key factor relates to substitution options for power generation at municipal incinerators (natural gas power vs. coal power). Scenario C (SRF) is largely insensitive to the aspects being considered in this assessment.

The results show that there are possible scenarios where incineration becomes preferable to recycling – when incineration substitutes for coal power and recycling does not produce high quality plastic recycle. However if it can be ensured that recycled plastic is of high quality then the recycling scenarios always have superior environmental performance to incineration regarding global warming potential.

## 7.0 Summary & conclusions

This life cycle assessment relates only to waste management options for mixed plastics. An assessment of the potential effect of managing mixed plastics as part of a mixed municipal waste stream was outside of the scope of this study. The results only refer to the specific case where mixed plastic waste is sourced as output from a MRF and collection processes for the mixed waste plastic are not included within the study boundaries.

For most of the impact categories studied, landfill is less favourable than incineration of mixed plastics. However for global warming potential this study has found that incineration (with or without energy recovery) is the least favourable waste management option of those studied for domestic mixed plastics. On the basis of these results we can conclude that it is environmentally beneficial to remove mixed plastic from the waste stream prior to either landfilling or incineration. The diverted mixed plastics stream should be managed through a combination of mechanical recycling and SRF type processes.

Overall, the results of this LCA indicate that recycling scenarios are generally the environmentally preferable options for all impact categories considered in this study and with the assumptions made. However if one attempts to prioritise these impact categories and give more weight to the particular issues driving WRAP – global warming potential and solid waste – the results become more nuanced. The recycling options are favoured when considering global warming, but the Energy from Waste options (incineration and SRF) produce the least amount of solid waste.

This disparity is emphasised further by the high sensitivity of the results to the quality of the recycled plastic produced. The environmental performance of the recycling scenarios rapidly deteriorates as quality declines. Once the proportion of high quality recyclate (that can substitute directly for virgin plastic) falls below a certain level it is likely that alternative waste management technologies will become the more favourable option. This assessment estimates the crossover point for global warming potential to occur once recycled plastic can only substitute for about 70% virgin plastic or less, but there is a large degree of uncertainty around this exact figure and the results differ for different impact categories.

The best environmental option will be to focus on developing facilities capable of delivering high quality recycled plastics that can substitute for virgin plastics. Where this quality cannot be achieved the material should be sent for use in alternative processing options such as SRF or for use as a redox agent in blast furnaces.

Another notable outcome of this assessment is that there is generally little to choose between the two main classes of recycling technologies – NIR sorting and density separation. NIR technologies can sort a wider variety of plastics, but density separation processes, while less flexible, tend to recover a higher proportion of their selected plastics from the waste stream. Which technology is actually preferable from an environmental point of view may come down to whether markets can be found for the products from these recycling processes (this study assumes that such markets exist in all cases). Further discussion on the relative merits of the NIR sorting vs. density separation can be found in the main report, which includes assessment of the economic aspects of the various technologies.

The results relating to solid waste arisings are also interesting because they show that, for the individual recycling scenarios modelled, it is not possible to divert more than 60% of the material stream away from landfill. The same is true for the alternative reprocessing technologies, the exceptions being incineration and SRF to cement kilns (although the capacity of this latter option is limited in the UK). However it should be noted that by combining recycling technologies to give a full process a higher proportion can be recycled. This can be seen in the results for Process Design B (described in the main report) where a 67% recycling rate is achieved.

This happens for several reasons, a key one being the prevalence of landfill as the “default” disposal option for wastes that are difficult to recycle. For plastics-rich waste streams an increase in the use of incineration

would help to reduce the quantities going to landfill. However a better approach would be to consider how to increase the amounts of recyclable wastes in the material stream. Understanding the strengths and weaknesses of the different recycling technologies can lead to the development of more sustainably designed plastic products.

For example, NIR-sorting technologies have difficulty sorting black plastics and can also get confused when packaging and their labels are made from different plastics (the sensor may “see” the label and so miss-sort the pack – a particular problem for shrink wrap labels that cover the whole bottle). Fairly simple design changes can overcome these problems.

For density separation technologies the main problems occur when the density ranges of different polymers overlap resulting in some inevitable mixing of polymer types in the overlapping region. This diversity in range is largely due to the use of additives and fillers to modify the properties of the polymers.

## 7.1 Landfill

Landfill is currently the most common option for managing mixed waste plastic in the UK. In terms of process impacts it performs well compared to other options as energy inputs associated with managing a landfill are low.

However, the landfill option does not benefit from avoiding the requirement for other processes. This means that overall it is usually less favoured than other management options. Landfill gas is assumed to be burnt but without energy recovery – combustible gaseous emissions from plastic waste would be very low in any case.

## 7.2 Incineration

Incineration is another currently available option for managing mixed plastic waste. As energy is recovered from this process (albeit with relatively low efficiency) it generally has better environmental performance than landfill.

When considering WRAP's priority issues of global warming potential and solid waste, the incineration option has contrasting outcomes. It has the most adverse global warming impact of any scenario considered, but, in contrast, it also results in the lowest solid waste.

It should be noted that this report only considers a particular high plastic content waste stream and does not make any general statements about the relative merits of using incineration as waste management option for other waste streams.

## 7.3 SRF to cement kilns

Municipal incinerators are not a very efficient way of recovering energy from mixed plastic waste. A higher value energy recovery option is to convert the waste plastic to SRF and use this in a dedicated SRF power plant or as a fuel for cement kilns. The cement kiln option has been modelled in this assessment and generally has a much improved environmental performance compared to municipal incineration.

For impact categories including primary energy consumption, ozone layer depletion potential, abiotic resource depletion potential and solid waste it also outperforms many of the recycling scenarios considered in this study.

## 7.4 Pyrolysis

Pyrolysis covers a wide variety of different processes. Because of this, and due to the relatively poor data available on pyrolysis processes in the literature, this study does not claim to draw general conclusions about this whole class of processes. However, the two pyrolysis scenarios that were assessed in this study had broadly similar environmental performance in most impact categories and generally performed better than landfill and incineration but worse than the recycling options.

## 7.5 Redox agent

The use of the polyolefin fraction of the mixed waste to substitute for other reducing agents in blast furnaces is not current practise in the UK but regularly occurs elsewhere in Europe and Japan. The results show that this option is often quite favourable and compares well against the recycling options. Depending on the exact quality requirements for this process, it could be a useful route for disposing of lower quality polyolefin fractions not suitable for substituting for virgin polymers.

## 7.6 Near infra-red sorting

It is difficult to directly compare the different NIR processes due to variations in results during trials (e.g. data on the Titech sorter was collected using a lower operating speed than for the Pellenc process which will affect the relative performance of these machines). There are some fairly large differences in equipment design and power requirements but the environmental performance is usually dominated by the recycling efficiency (the quantity of plastic in the feedstock that is correctly identified and sorted) and this is broadly similar in all cases. As such, the NIR technologies all have broadly similar environmental performances and compare well against alternative waste management options.

## 7.7 Density separation

Various density separation processes have been included in this study ranging from simple tanks of water, through to more sophisticated tanks (such as used by TLT) and onto processes including hydrocyclones and sorticanter. The strength of sorting processes based on density separation is that they can often achieve a higher sorting efficiency (i.e. remove more of a target material from the waste stream) than NIR sorting. However they also tend to be a less flexible option and sometimes have high energy requirements. The scenarios modelled in this assessment only separated the polyolefin fraction from the feedstock and assumed that markets exist for the resulting mixed flake material. If this assumption is accepted, the results of this study indicate that the density separation technologies usually have similar performance to the NIR sorters for the waste streams considered in this assessment.

## 7.8 Film/rigid separation

In the scenarios modelled in this study the Stadler equipment has better environmental performance than the KME equipment. This difference is primarily due to the different design objectives of each process. The Stadler ballistic separator is designed to separate out films from rigid objects, whereas the KME process is primarily designed to separate 2-dimensional objects from 3-dimensional objects.

The feedstock used in the trials included a reasonable number of rigid plastic objects, such as crushed food trays, that the KME equipment identified – correctly – as 2-dimensional and removed with the film fraction, meaning that less rigid material was available for mechanical recycling. So for this feedstock the Stadler equipment gave the best environmental performance.

## 8.0 Further considerations

No account is taken here of possible future changes in waste arisings (aside from noting in general terms the likely short-term trends in use of polymer types and consumption in Section 3.10), UK energy markets, technological advances and so on. To do so would require the development of a series of future scenarios subject to their own uncertainties. Purely in the interests of transparency, therefore, the analysis is based around current conditions. However, it is still informative to consider how things may change in the future, as it reflects on the long-term robustness of the results. To illustrate:

### ■ Waste arisings:

- The amount of plastic entering the waste stream will change
- The variety of plastics in the waste stream may reduce in response to the desire for recyclability

- Sorting speed and efficiency of technologies is likely to improve as they are utilised more widely
- The costs of these technologies will fall, again as experience with them increases
- Energy technologies:
  - The marginal technology for power generation (currently gas-fired CCGT) may change, possibly to less carbon intensive fuel cycles such as nuclear or renewables
  - The efficiency of generation may improve
  - In the medium to long term the fossil fuel cycles as developed in the UK may adopt carbon capture and storage, significantly reducing their greenhouse gas burdens
- Incineration:
  - There may be an increase in the efficiency of incineration processes, particularly if the utilisation of waste heat becomes more widespread
  - The demand for plastic materials in incinerator feedstock may change in response to changes in the residual waste stream due to higher levels of recycling
- Availability of alternative processes for handling plastic wastes:
  - Cement kilns and blast furnaces may not have the capacity to take a significant fraction of plastic waste. WRAP could consider undertaking further work to assess which wastes are best disposed of through cement kilns and blast furnaces
- Environmental technologies:
  - Revision of the Large Combustion Plant and IPPC Directives may cause a reduction in emissions from various of the technologies considered in this report

More issues could be added, but the length of the list demonstrates that it is not possible to develop a clear idea of changes into the future. It is therefore recommended that WRAP keep the conclusions of this study (and others like it) under review as the waste management and other relevant sectors develop in the years to come.

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# Appendix 1 Primary Data

## Stadler

Description	Unit	Value	Comment
Throughput	t/h	3.77	Based on run #2
Power consumption (per unit)	kW	4.55	Based on 9.1 kW max rating operating at 50% loading
<b>Separation efficiency</b>			
Film removal	%	98.7	Calculated as removal from the "rigids" stream
Mis-sorted rigids	%	11.2	Assuming that 4 kg of the total 5.4 kg in bottom deck mixed fraction is rigids and that this would not be sent for mechanical recycling due to being intermixed with film.

## KME

Description	Unit	Value	Comment
Throughput	t/h	2.54	Based on run #3
Power consumption (per unit)	kW	26	Based on 2 machines at 13 kW each
<b>Separation efficiency</b>			
Film removal	%	97	Based on runs #1 and #2
Mis-sorted rigids	%	21.5	"Flat-rigids" in the film fraction are calculated as mis-sort

## Pla.To

Description	Unit	Value	Comment
Throughput (rigids)	t/h	4	
Throughput (films)	t/h	1	
Max power rating	kW	100	Range = 90 - 110 kW
Loading during use	%	75	Range = 70 - 80%
Material loss (as plastic in the residue fraction)	%	10	Based on 8% loss in 2 mm screen and 2% loss in separator

### Titech (four positive sorts)

Description	Unit	Value	Comment
Throughput	t/h	0.861	Based on run 1
Power consumption (per unit) - 1000 mm	kW	1.6	Suggested set-up uses 2 x 1000 mm sorters and 2 x 700 mm sorters - maximum capacity for this set-up is 2 t/h
Power consumption (per unit) - 700 mm	kW	1.3	Suggested set-up uses 2 x 1000 mm sorters and 2 x 700 mm sorters - maximum capacity for this set-up is 2 t/h
Acceleration belt	kW	2.2	Requires 1 per sort unit
Conveyor	kW	1.5	Requires 2 per sort unit (one infeed and one outfeed conveyor)
Compressed air	kW	15	Centralised compressor serving all sorters
<b>Separation efficiency</b>			
PP	%	88.1	
PE	%	78.5	
PET	%	77.1	
PS	%	60.7	Not sorted in modelled scenario
PVC	%	87.2	

### Pellenc (four positive sorts)

Description	Unit	Value	Comment
Throughput	t/h	3	Pellenc trial report for 3rd and 4th Big Bag
Power consumption (per unit)	kW	6	Pellenc trial report for 3rd and 4th Big Bag – includes conveyors
Compressed air (binary mode - 1 sort)	kW	5	
Compressed air (ternary mode - 2 sorts)	kW	11	Four positive sorts requires 2 Pellenc machines operating in ternary mode
<b>Separation Efficiency</b>			
PP	%	80.3	
PE	%	67.4	
PET	%	76.9	
PS	%	64.7	Not sorted in modelled scenario
PVC	%	81.2	

### Qinetiq (four positive sorts)

Description	Unit	Value	Comment
Throughput	t/h	5	
Power consumption (per unit)	kW	15.5	Includes compressed air
<b>Separation Efficiency</b>			
PP	%	70.0	Based on results from trial on mixed waste form Milton Keynes
PE	%	70.0	Based on results from trial on mixed waste form Milton Keynes
PET	%	70.0	Based on results from trial on mixed waste form Milton Keynes
PS	%	70.0	Not sorted in modelled scenario. Based on results from trial on mixed waste form Milton Keynes
PVC	%	70.0	Based on results from trial on mixed waste form Milton Keynes

### Swiss Polymera

Description	Unit	Value	Comment
<b>Pretreatment</b>			
Throughput	t/h	2	
Max power rating	kW	630	
Loading during use	%	70	
Pre-treatment water consumption	litres/h	5500	Based on expected performance of planned process
<b>Extrusion</b>			
Throughput	t/h	0.25	
Max power rating	kW	120	Range = 115 - 120 kW
Loading during use	%	100	
Pre-treatment water consumption	litres/h	0.1	
Material Loss	%	2	Due to losses on filters, start up and blockages

### TLT

Description	Unit	Value	Comment
Throughput	t/h	4	
Power consumption (per unit)	kW	28	2 x pumps @ 3 kW and 2 x vibration sieves @ 11 kW
Drying (per unit)	kW	32.5	Based on 4 t/h throughput with drying requiring 85 KW/t plus 15 kW per additional tonne
Float media loss (w/w of plastic)	%	3	
Polyolefin separation efficiency	%	98	

## B+B

Description	Unit	Value	Comment
Throughput	t/h	0.17	Carried out on test rig – so very slow throughput of material
Power consumption (per unit)	kW	35	Test rig – no info available on how this would scale up to full size plant
Float media loss (w/w of plastic)	%	3	Used to assess water consumption – majority of water is recirculated.
Polyolefin separation efficiency	%	95	

## Herbold

Description	Unit	Value	Comment
Throughput	t/h	1.25	
Power consumption (per unit)	kW	488	
Water consumption	m <sup>3</sup> /h	2	
Separation Efficiency	%	98	

## Flottweg

Description	Unit	Value	Comment
Throughput	t/h	1.25	
Power consumption (per unit)	kW	140	
Water consumption	m <sup>3</sup> /h	4	
Separation Efficiency	%	99.6	

## Appendix 2 Secondary Data

### Landfill

Process/product	Source	Geographic Coverage	Year	Comment
Polypropylene, 15.9% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Expected that landfill in Switzerland are managed similarly to landfill in UK
Polyethylene terephthalate, 0.2% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Expected that landfill in Switzerland are managed similarly to landfill in UK
Polystyrene, 0.2% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Expected that landfill in Switzerland are managed similarly to landfill in UK
Polyvinylchloride, 0.2% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Expected that landfill in Switzerland are managed similarly to landfill in UK
Polyethylene, 0.4% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Expected that landfill in Switzerland are managed similarly to landfill in UK
Plastics, mixture, 15.3% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Used to model PLA in landfill. Expected that landfill in Switzerland are managed similarly to landfill in UK
Aluminium, 0% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Expected that landfill in Switzerland are managed similarly to landfill in UK
Tin sheet, 0% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Expected that landfill in Switzerland are managed similarly to landfill in UK
Packaging paper, 13.7% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Used to model paper and card. Expected that landfill in Switzerland are managed similarly to landfill in UK
Inert material, 0% water, to sanitary landfill	Ecoinvent v1.3	Switzerland	2000	Used to model PLA in landfill. Expected that landfill in Switzerland are managed similarly to landfill in UK

### Incineration

Process/product	Source	Geographic Coverage	Year	Comment
Polypropylene, 15.9% water, to municipal incineration	Ecoinvent v1.3	Switzerland	2000	Expected that incineration facilities in Switzerland are managed similarly to landfill in UK
Polyethylene terephthalate, 0.2% water, to municipal incineration	Ecoinvent v1.3	Switzerland	2000	Expected that incineration facilities in Switzerland are managed similarly to landfill in UK
Polystyrene, 0.2% water, to municipal incineration	Ecoinvent v1.3	Switzerland	2000	Expected that incineration facilities in Switzerland are managed similarly to landfill in UK
Polyvinylchloride, 0.2% water, to municipal	Ecoinvent v1.3	Switzerland	2000	Expected that incineration facilities in Switzerland are managed

incineration				similarly to landfill in UK
Polyethylene, 0.4% water, to municipal incineration	Ecoinvent v1.3	Switzerland	2000	Expected that incineration facilities in Switzerland are managed similarly to landfill in UK
Plastics, mixture, 15.3% water, to municipal incineration	Ecoinvent v1.3	Switzerland	2000	Used to model PLA in landfill. Expected that incineration facilities in Switzerland are managed similarly to landfill in UK
Aluminium, 0% water, to municipal incineration	Ecoinvent v1.3	Switzerland	2000	Expected that incineration facilities in Switzerland are managed similarly to landfill in UK
Tin sheet, 0% water, to municipal incineration	Ecoinvent v1.3	Switzerland	2000	Expected that incineration facilities in Switzerland are managed similarly to landfill in UK
Packaging cardboard, 19.6% water, to municipal incineration	Ecoinvent v1.3	Switzerland	2000	Used to model paper and card. Expected that incineration facilities in Switzerland are managed similarly to landfill in UK

### Electricity production

Process/product	Source	Geographic Coverage	Year	Comment
Wood chip burned in Cogen ORC 1400kWth	Ecoinvent v1.3	Switzerland	2001	Allocation based on exergy
Oil power plant	Ecoinvent v1.3	UK	2000	
Hard coal power plant	Ecoinvent v1.3	UCTE	2000	UCTE (Union for the coordination of transmission of electricity) links the majority of mainland European electricity grids
Industrial gas power plant	Ecoinvent v1.3	UCTE	2000	UCTE (Union for the coordination of transmission of electricity) links the majority of mainland European electricity grids
Nuclear power plant	Ecoinvent v1.3	UCTE	1999	UCTE (Union for the coordination of transmission of electricity) links the majority of mainland European electricity grids
Natural gas power plant	Ecoinvent v1.3	UK	2000	
Hydropower at power plant	Ecoinvent v1.3	UK	2000	
Hydropower at pumped storage power plant	Ecoinvent v1.3	UK	1970	Based on Swiss data modified for UK situation
Wind power plant	Ecoinvent v1.3	European Average	2002	
France electricity production mix	Ecoinvent v1.3	France	2000	

## Primary material production

Process/product	Source	Geographic Coverage	Year	Comment
High Density Polyethylene granulate (HDPE)	Ecoinvent v1.3	European Average	1993	Data are from the Eco-profiles of the European plastics industry (APME)
Polyethylene Terephthalate (PET) granulate (amorphous)	Ecoinvent v1.3	European Average	2000	Data are from the Eco-profiles of the European plastics industry (APME)
Polyvinylchloride resin (B-PVC); Bulk Polymerisation	Ecoinvent v1.3	European Average	1998	Data are from the Eco-profiles of the European plastics industry (APME)
Polystyrene (General Purpose) granulate (GPPS)	Ecoinvent v1.3	European Average	1994	Data are from the Eco-profiles of the European plastics industry (APME)
Polypropylene granulate (PP)	Ecoinvent v1.3	European Average	1993	Data are from the Eco-profiles of the European plastics industry (APME)
Concrete	Ecoinvent v1.3	Switzerland	2001	Expected that concrete production in Switzerland would perform similarly to that in UK
Softwood logs	Ecoinvent v1.3	European Average	1996	

## Transport

Process/product	Source	Geographic Coverage	Year	Comment
28-32t Capacity Lorry (22 t maximum payload) Euro IV	PE-International	European Average	2005	

## Other

Process/product	Source	Geographic Coverage	Year	Comment
Coal burned in power plant	Ecoinvent v1.3	Germany	2000	Assumed that coal power plant emissions in Germany are similar to those from coal burned in cement kiln in UK
Natural gas in combined cycle plant	Ecoinvent v1.3	European Average	2002	Used as substituted process to account for savings from electricity from incineration

# Appendix 3 Life Cycle Inventories

## Material emissions, output to atmosphere, kg/tonne waste

	A - Landfill	B - Incineration	C - SRF	D - BP pyrolysis	E - Oznotech pyrolysis	F - Redox agent	G - Stadler & Titech	H - Stadler & Pellenc	I - Stadler & Qinetiq	J - Stadler & Sims	K - KME & Titech	L - Stadler & TLT	M - Swiss Polymera	N - B+B	O - Herbold	P - Flottweg
<b>Heavy Metals</b>																
Antimony	1.3E-07	8.0E-07	-3.1E-06	-3.5E-06	-2.2E-06	-2.4E-06	-2.0E-06	-2.1E-06	-1.9E-06	-2.0E-06	-1.8E-06	4.1E-07	5.5E-07	6.4E-07	7.8E-07	5.2E-07
Arsenic	9.1E-07	6.2E-06	-4.3E-05	-3.7E-05	-2.5E-05	-2.2E-05	-1.9E-05	-2.0E-05	-1.8E-05	-1.9E-05	-1.6E-05	4.2E-06	6.0E-06	7.3E-06	9.1E-06	5.6E-06
Cadmium	9.6E-07	3.5E-06	-3.1E-06	-2.7E-05	-2.3E-05	-1.1E-05	-1.1E-05	-1.1E-05	-9.7E-06	-1.1E-05	-9.3E-06	1.7E-06	1.9E-06	2.3E-06	2.6E-06	1.9E-06
Chromium (unspecified)	1.8E-05	7.3E-05	-3.4E-05	-4.5E-04	-2.8E-04	-2.7E-04	-2.6E-04	-2.6E-04	-2.4E-04	-2.6E-04	-2.3E-04	3.0E-05	3.5E-05	4.0E-05	4.5E-05	3.4E-05
Chromium +VI	4.4E-07	1.9E-06	-2.6E-06	-1.1E-05	-6.8E-06	-7.0E-06	-6.6E-06	-6.6E-06	-5.9E-06	-6.6E-06	-5.7E-06	8.2E-07	9.9E-07	1.2E-06	1.4E-06	9.7E-07
Cobalt	5.4E-07	4.6E-06	-1.1E-05	-2.6E-05	-2.2E-05	-1.1E-05	-9.3E-06	-1.0E-05	-9.1E-06	-9.3E-06	-7.9E-06	4.1E-06	6.0E-06	7.6E-06	9.7E-06	5.7E-06
Copper	7.6E-06	3.1E-05	-8.3E-05	-1.7E-04	-1.3E-04	-1.0E-04	-9.8E-05	-9.9E-05	-8.9E-05	-9.8E-05	-8.5E-05	1.4E-05	1.7E-05	2.0E-05	2.3E-05	1.7E-05
Iron	2.5E-05	9.3E-05	-5.2E-04	-6.3E-04	-3.9E-04	-6.8E-04	-3.5E-04	-3.5E-04	-3.1E-04	-3.5E-04	-3.0E-04	4.4E-05	5.1E-05	5.9E-05	6.9E-05	5.1E-05
Lead	5.8E-06	2.4E-05	-1.7E-04	-1.8E-04	-1.4E-04	-1.2E-04	-1.0E-04	-1.1E-04	-9.6E-05	-1.0E-04	-9.1E-05	1.5E-05	2.1E-05	2.6E-05	3.2E-05	2.0E-05
Manganese	1.1E-06	5.1E-06	-3.6E-05	-1.0E-05	-1.5E-06	-7.4E-06	-2.2E-06	-4.5E-06	-4.4E-06	-2.2E-06	-1.2E-06	1.0E-05	1.7E-05	2.1E-05	2.8E-05	1.5E-05
Mercury	7.9E-07	3.1E-05	-1.1E-04	-4.4E-05	-4.5E-05	-4.2E-05	-1.7E-04	-1.6E-04	-1.4E-04	-1.7E-04	-1.5E-04	-1.4E-04	-1.7E-04	-1.4E-04	-1.3E-04	-1.4E-04
Molybdenum	1.2E-07	1.5E-06	-9.7E-06	-1.0E-05	-9.1E-06	-3.8E-06	-3.2E-06	-3.4E-06	-3.1E-06	-3.2E-06	-2.7E-06	1.2E-06	1.7E-06	2.1E-06	2.7E-06	1.6E-06
Nickel	5.9E-06	4.2E-05	-2.5E-04	-4.3E-04	-3.4E-04	-1.7E-04	-1.6E-04	-1.6E-04	-1.5E-04	-1.6E-04	-1.3E-04	3.3E-05	4.7E-05	5.9E-05	7.4E-05	4.5E-05
Platinum	6.4E-13	1.1E-12	-6.5E-13	-1.7E-12	-1.4E-12	-1.3E-12	-1.0E-12	-1.0E-12	-8.5E-13	-1.0E-12	-8.3E-13	5.3E-13	5.2E-13	5.7E-13	6.0E-13	5.6E-13
Selenium	2.5E-07	3.8E-06	-1.4E-04	-9.5E-06	-7.2E-06	-4.8E-06	-2.3E-06	-3.4E-06	-3.2E-06	-2.3E-06	-1.7E-06	4.9E-06	7.7E-06	9.7E-06	1.3E-05	7.0E-06
Silver	1.7E-12	3.8E-11	-2.7E-09	-2.2E-09	-2.1E-09	-2.2E-09	-2.1E-09	-2.0E-09	-1.7E-09	-2.1E-09	-1.9E-09	1.5E-11	2.8E-11	4.4E-11	6.2E-11	2.8E-11
Thallium	8.1E-09	4.9E-07	1.9E-07	-1.7E-07	-8.7E-08	-2.2E-07	-9.4E-08	-9.1E-08	-7.5E-08	-9.4E-08	-7.3E-08	4.6E-08	4.1E-08	5.1E-08	5.7E-08	5.0E-08
Tin	3.5E-07	9.0E-05	3.9E-05	1.4E-06	3.8E-06	4.1E-06	4.3E-06	4.7E-06	5.9E-06	4.3E-06	5.5E-06	1.4E-05	1.4E-05	1.5E-05	1.5E-05	1.4E-05
Titanium	8.0E-07	9.1E-04	7.7E-04	2.2E-05	4.0E-05	1.0E-05	4.0E-05	4.6E-05	5.6E-05	4.0E-05	5.3E-05	8.2E-05	6.7E-05	8.0E-05	8.3E-05	8.1E-05
Vanadium	8.0E-06	2.5E-04	3.1E-05	-1.4E-03	-8.3E-04	-5.5E-04	-5.1E-04	-5.2E-04	-4.7E-04	-5.1E-04	-4.5E-04	7.0E-05	9.0E-05	1.1E-04	1.4E-04	8.9E-05
Zinc	1.6E-05	6.9E-05	-1.5E-04	-3.2E-04	-2.2E-04	-1.9E-04	-1.7E-04	-1.8E-04	-1.6E-04	-1.7E-04	-1.5E-04	4.5E-05	6.3E-05	7.6E-05	9.5E-05	6.0E-05

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
<b>Inorganic Emissions</b>																
Ammonia	5.5E-04	1.3E-02	-4.9E-02	-4.4E-04	4.5E-04	-4.0E-03	1.1E-03	7.0E-04	8.0E-04	1.1E-03	1.4E-03	3.7E-03	4.8E-03	6.0E-03	7.4E-03	4.7E-03
Barium	4.6E-06	1.9E-04	1.1E-05	8.5E-06	1.8E-05	1.2E-06	1.5E-05	1.4E-05	1.5E-05	1.5E-05	1.8E-05	2.7E-05	3.0E-05	3.8E-05	4.7E-05	3.2E-05
Beryllium	3.8E-09	5.3E-07	2.9E-07	-1.3E-07	-5.8E-08	-1.6E-07	-6.3E-08	-6.1E-08	-4.7E-08	-6.3E-08	-4.5E-08	5.6E-08	5.2E-08	6.2E-08	6.7E-08	5.9E-08
Boron	4.0E-05	8.3E-05	2.1E-05	-1.2E-05	1.5E-05	-2.5E-05	1.0E-05	1.0E-05	1.3E-05	1.0E-05	1.4E-05	4.6E-05	4.6E-05	4.8E-05	4.8E-05	4.7E-05
Boron compounds																
(unspecified)	1.1E-05	5.4E-04	-3.3E-03	-4.9E-04	-4.8E-04	-5.2E-04	-3.4E-04	-3.8E-04	-3.4E-04	-3.4E-04	-2.8E-04	2.4E-04	3.5E-04	4.3E-04	5.3E-04	3.3E-04
Bromine	2.9E-05	2.8E-04	-1.3E-03	1.0E-04	1.1E-04	8.1E-05	1.1E-04	9.0E-05	8.5E-05	1.1E-04	1.1E-04	1.3E-04	1.8E-04	2.2E-04	2.7E-04	1.7E-04
Carbon dioxide	5.0E+01	1.9E+03	-1.4E+01	-1.1E+01	-9.7E+01	7.3E-01	-6.2E+02	-5.6E+02	-4.7E+02	-6.2E+02	-5.0E+02	-4.8E+02	-6.3E+02	-4.1E+02	-3.2E+02	-4.5E+02
Carbon disulphide	2.8E-05	1.6E-04	-2.7E-04	-9.4E-04	-6.0E-04	-5.7E-04	-5.3E-04	-5.3E-04	-4.7E-04	-5.3E-04	-4.6E-04	5.6E-05	6.5E-05	7.2E-05	8.1E-05	6.4E-05
Carbon monoxide	4.3E-02	2.0E-01	-2.1E-01	-1.9E-01	-3.2E-01	-1.4E-01	-4.0E-01	-3.7E-01	-3.3E-01	-4.0E-01	-3.4E-01	-2.7E-01	-3.4E-01	-2.5E-01	-2.2E-01	-2.6E-01
Chlorine	3.8E-06	8.4E-04	-7.7E-05	-2.1E-04	-2.4E-04	-1.6E-04	-2.7E-04	-2.5E-04	-2.0E-04	-2.7E-04	-2.3E-04	-5.7E-05	-1.0E-04	-4.9E-05	-4.1E-05	-5.7E-05
Cyanide (unspecified)	5.2E-06	2.2E-03	2.1E-03	1.6E-04	1.6E-04	1.6E-04	1.6E-04	1.7E-04	1.9E-04	1.6E-04	1.8E-04	2.7E-04	2.5E-04	2.8E-04	2.7E-04	2.7E-04
Fluorine	3.7E-07	1.2E-06	-2.0E-06	-3.1E-05	-2.8E-05	-2.9E-05	-6.6E-05	-6.2E-05	-5.9E-05	-6.6E-05	-5.8E-05	-2.1E-04	-2.6E-04	-2.2E-04	-2.1E-04	-2.2E-04
Helium	4.4E-05	3.0E-05	3.3E-07	-2.6E-04	-7.4E-04	3.6E-05	1.2E-05	1.2E-05	1.6E-05	1.2E-05	1.7E-05	4.3E-05	3.9E-05	4.9E-05	5.4E-05	4.6E-05
Hydrogen	5.6E-05	1.4E-02	-3.2E-02	-3.1E-02	-3.1E-02	-3.1E-02	-5.8E-02	-5.4E-02	-4.7E-02	-5.8E-02	-5.1E-02	-4.0E-02	-5.0E-02	-4.2E-02	-4.0E-02	-4.1E-02
Hydrogen chloride	2.2E-02	3.5E-03	-6.1E-02	-2.3E-03	9.2E-04	-3.6E-03	-1.1E-02	-9.7E-03	-6.6E-03	-1.1E-02	-7.5E-03	1.6E-03	-9.1E-04	4.5E-03	7.4E-03	2.9E-03
Hydrogen fluoride	1.5E-04	6.3E-04	-3.2E-02	2.9E-04	7.6E-04	-6.2E-06	-2.0E-05	-2.5E-04	-2.5E-04	-2.0E-05	6.8E-05	3.1E-04	8.5E-04	1.6E-03	2.4E-03	8.8E-04
Hydrogen sulphide	1.3E-05	-8.5E-03	-2.6E-04	-1.8E-03	-1.5E-03	-1.4E-03	-1.9E-03	-1.9E-03	-1.9E-03	-1.9E-03	-1.9E-03	-1.5E-03	-1.5E-03	-1.5E-03	-1.5E-03	-1.5E-03
Iodine	3.9E-07	1.8E-05	-5.8E-04	1.7E-05	2.7E-05	6.6E-06	2.0E-05	1.2E-05	9.6E-06	2.0E-05	1.9E-05	3.2E-05	5.3E-05	6.7E-05	8.9E-05	4.8E-05
Nitrate	7.0E-09	8.1E-08	-4.4E-06	5.7E-08	1.4E-07	-4.8E-07	9.4E-08	4.8E-08	3.7E-08	9.4E-08	9.5E-08	1.8E-07	3.0E-07	3.9E-07	5.1E-07	2.7E-07
Nitrogen oxides																
Nitrous oxide	1.4E-01	9.0E-02	-2.3E+00	-1.1E+00	-1.1E+00	-5.9E-01	-3.9E+00	-3.6E+00	-3.2E+00	-3.9E+00	-3.4E+00	-3.9E+00	-4.8E+00	-3.9E+00	-3.6E+00	-3.9E+00
Nitrogen dioxide	8.8E-04	-5.1E-05	-9.1E-02	-1.0E-03	-5.4E-04	-2.6E-04	7.5E-04	1.5E-04	1.1E-04	7.5E-04	8.8E-04	3.2E-03	4.7E-03	5.8E-03	7.3E-03	4.3E-03
Ozone	2.5E-05	4.7E-04	-3.1E-04	-5.9E-04	-6.3E-04	-5.9E-04	-4.6E-04	-4.6E-04	-4.0E-04	-4.6E-04	-3.9E-04	1.1E-04	1.5E-04	1.4E-04	1.6E-04	1.4E-04
Phosphorus	1.7E-07	7.0E-06	-9.0E-07	1.7E-06	1.0E-05	-2.1E-06	4.8E-06	2.2E-06	1.7E-06	4.8E-06	4.9E-06	9.4E-06	1.6E-05	2.1E-05	2.8E-05	1.5E-05
Scandium	1.1E-09	8.8E-09	-1.6E-07	-1.5E-07	-8.4E-08	-1.9E-07	-9.2E-08	-9.3E-08	-8.4E-08	-9.2E-08	-8.1E-08	4.3E-09	6.1E-09	7.7E-09	9.8E-09	5.8E-09
Silicium tetrafluoride	5.4E-10	1.5E-08	3.0E-09	-2.4E-08	-3.3E-08	-6.8E-09	-7.4E-09	-7.4E-09	-6.4E-09	-7.4E-09	-6.1E-09	4.2E-09	4.5E-09	5.0E-09	5.3E-09	4.5E-09
Steam	2.4E-04	2.8E-03	-1.5E-01	1.9E-03	4.7E-03	-1.6E-02	3.2E-03	1.7E-03	1.3E-03	3.2E-03	3.3E-03	6.2E-03	1.0E-02	1.3E-02	1.7E-02	9.4E-03
Strontium	2.4E-07	1.5E-05	-3.2E-05	-1.3E-05	5.4E-07	-2.3E-05	-4.2E-06	-7.1E-06	-6.7E-06	-4.2E-06	-2.8E-06	1.3E-05	2.0E-05	2.6E-05	3.4E-05	1.9E-05
Sulphur dioxide	3.3E-02	-2.4E-02	-2.6E+00	-9.7E-01	-1.9E+00	-8.6E-01	-5.2E+00	-4.8E+00	-4.3E+00	-5.2E+00	-4.6E+00	-5.6E+00	-6.8E+00	-5.6E+00	-5.2E+00	-5.6E+00
Sulphur hexafluoride	3.0E-07	7.8E-06	-1.9E-06	-1.0E-05	-1.1E-05	-8.2E-06	-7.7E-06	-7.7E-06	-6.8E-06	-7.7E-06	-6.6E-06	1.6E-06	1.8E-06	1.8E-06	1.9E-06	1.8E-06

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
<b>Organic Emissions</b>																
Polycyclic aromatic hydrocarbons (PAH)	5.7E-06	-8.8E-05	-4.6E-05	-2.0E-05	-1.5E-05	-1.2E-05	-8.3E-06	-1.1E-05	-1.1E-05	-8.3E-06	-8.0E-06	3.8E-06	1.1E-05	1.3E-05	1.9E-05	8.1E-06
Halogenated organic emissions to air	1.1E-05	-5.5E-05	-2.2E-02	-1.8E-02	-1.8E-02	-1.8E-02	-1.8E-02	-1.6E-02	-1.4E-02	-1.8E-02	-1.5E-02	-3.0E-05	-3.5E-05	-2.7E-05	-2.3E-05	-2.9E-05
Acentaphthene	2.3E-12	-9.0E-09	1.0E-10	-2.9E-10	-1.8E-10	-4.1E-10	-2.9E-10	-4.7E-10	-5.8E-10	-2.9E-10	-4.0E-10	-3.2E-10	1.5E-10	2.0E-10	4.6E-10	-9.3E-11
Acetaldehyde	5.6E-07	9.4E-06	-9.4E-06	-1.3E-04	-8.4E-05	-8.4E-05	-7.6E-05	-7.8E-05	-7.2E-05	-7.6E-05	-6.6E-05	1.4E-05	2.2E-05	2.7E-05	3.5E-05	2.0E-05
Acetic acid	8.7E-06	-1.3E-03	2.2E-05	-2.0E-02	-2.0E-02	-2.0E-02	-2.0E-02	-2.0E-02	-1.8E-02	-2.0E-02	-1.8E-02	1.0E-05	1.1E-04	1.3E-04	2.0E-04	6.5E-05
Acetone	8.1E-07	2.5E-05	-1.1E-05	-8.2E-05	-3.9E-05	-4.1E-05	-3.1E-05	-3.5E-05	-3.2E-05	-3.1E-05	-2.6E-05	2.0E-05	3.2E-05	4.0E-05	5.1E-05	2.9E-05
Acrolein	3.1E-08	1.1E-08	-1.4E-08	6.5E-09	-3.5E-09	1.1E-08	1.6E-08	1.4E-08	1.5E-08	1.6E-08	1.8E-08	2.7E-08	3.1E-08	3.8E-08	4.6E-08	3.2E-08
Aldehyde (unspecified)	9.9E-08	8.5E-07	1.3E-07	-2.8E-05	-2.8E-05	-2.7E-05	-2.8E-05	-2.8E-05	-2.5E-05	-2.8E-05	-2.5E-05	-7.0E-07	-5.7E-07	9.0E-08	6.5E-07	-3.5E-07
Alkane (unspecified)	6.2E-05	-3.2E-03	-5.8E-03	-1.6E-03	-1.5E-03	-9.1E-04	-8.1E-04	-8.7E-04	-8.4E-04	-8.1E-04	-7.6E-04	-6.3E-05	1.2E-04	1.8E-04	3.1E-04	4.6E-05
Alkene (unspecified)	2.8E-06	9.2E-05	-5.3E-03	9.3E-05	2.1E-04	2.4E-05	1.4E-04	8.0E-05	6.5E-05	1.4E-04	1.3E-04	2.2E-04	3.7E-04	4.7E-04	6.2E-04	3.3E-04
Aromatic hydrocarbons (unspecified)	5.0E-05	6.9E-06	-4.8E-04	-3.3E-02	-3.3E-02	-3.3E-02	-4.2E-02	-4.1E-02	-3.8E-02	-4.2E-02	-3.7E-02	-6.1E-02	-7.5E-02	-6.3E-02	-6.1E-02	-6.2E-02
Benzaldehyde	1.6E-08	1.3E-09	-6.7E-09	2.5E-09	-4.1E-09	6.3E-09	6.5E-09	6.8E-09	7.5E-09	6.5E-09	7.3E-09	8.6E-09	7.6E-09	8.9E-09	9.4E-09	8.7E-09
Benzene	1.6E-04	9.8E-04	-5.2E-03	-1.0E-03	-1.8E-03	1.7E-04	6.4E-05	-2.6E-05	-2.6E-06	6.4E-05	1.2E-04	7.0E-04	8.8E-04	1.1E-03	1.4E-03	8.9E-04
Butadiene	1.0E-12	1.6E-12	-2.3E-13	-4.4E-10	-6.9E-11	2.2E-12	4.2E-14	-8.3E-14	8.3E-14	4.2E-14	2.9E-13	2.4E-12	2.3E-12	3.0E-12	3.4E-12	2.7E-12
Butane	4.6E-04	-1.3E-02	-3.7E-04	-8.3E-03	-1.9E-02	-5.0E-04	-9.2E-04	-1.2E-03	-1.2E-03	-9.2E-04	-9.5E-04	1.9E-04	7.9E-04	1.0E-03	1.5E-03	5.6E-04
Butene	1.0E-05	1.2E-05	-1.4E-06	-1.6E-04	-4.2E-04	1.4E-05	6.4E-07	3.2E-07	1.7E-06	6.4E-07	2.5E-06	1.6E-05	1.4E-05	1.8E-05	2.0E-05	1.7E-05
Cumene	2.3E-06	1.9E-05	1.2E-05	-4.6E-05	-5.0E-05	-2.0E-05	-2.1E-05	-2.1E-05	-1.8E-05	-2.1E-05	-1.8E-05	4.0E-06	3.8E-06	4.6E-06	5.1E-06	4.3E-06
Cycloalkanes (unspec.)	1.9E-08	5.3E-08	1.1E-09	-2.6E-05	-2.6E-05	-2.6E-05	-2.6E-05	-2.6E-05	-2.4E-05	-2.6E-05	-2.3E-05	2.6E-08	3.4E-08	3.8E-08	4.7E-08	3.3E-08
Ethane	1.7E-04	-7.2E-02	-9.1E-04	-1.2E-02	-1.3E-02	-7.4E-03	-6.9E-03	-7.9E-03	-8.3E-03	-6.9E-03	-7.3E-03	-3.7E-03	-8.2E-04	-1.1E-03	8.3E-05	-2.5E-03
Ethanol	1.0E-06	3.7E-05	-2.1E-05	-1.7E-04	-8.5E-05	-8.2E-05	-6.7E-05	-7.1E-05	-6.5E-05	-6.7E-05	-5.7E-05	2.5E-05	3.7E-05	4.6E-05	5.9E-05	3.4E-05
Ethene	2.9E-05	4.7E-05	-4.0E-04	-5.9E-03	-6.3E-03	-5.7E-03	-5.5E-03	-5.5E-03	-5.0E-03	-5.5E-03	-4.8E-03	4.3E-05	7.2E-05	5.9E-05	8.4E-05	7.5E-05
Ethine	4.6E-07	3.6E-06	-6.2E-05	-6.0E-05	-3.3E-05	-7.5E-05	-3.7E-05	-3.7E-05	-3.4E-05	-3.7E-05	-3.2E-05	1.8E-06	2.5E-06	3.1E-06	4.0E-06	2.4E-06
Ethyl benzene	1.0E-05	1.2E-05	-1.2E-06	-1.6E-04	-4.2E-04	1.5E-05	1.6E-06	1.0E-06	2.3E-06	1.6E-06	3.4E-06	1.7E-05	1.6E-05	2.0E-05	2.2E-05	1.8E-05
Ethylene oxide	2.2E-08	1.2E-07	1.5E-07	-4.4E-04	-4.4E-04	-4.4E-04	-4.4E-04	-4.4E-04	-4.0E-04	-4.4E-04	-3.9E-04	2.7E-08	2.4E-08	3.3E-08	3.8E-08	3.0E-08
Ethylenediamine	2.0E-11	4.0E-11	-4.6E-10	-1.1E-10	-4.2E-11	-1.1E-10	-4.5E-11	-4.9E-11	-4.3E-11	-4.5E-11	-3.6E-11	3.4E-11	4.6E-11	5.7E-11	7.1E-11	4.4E-11
Formaldehyde	4.3E-06	-2.5E-04	-1.5E-03	-5.9E-04	-3.2E-04	-3.5E-04	-3.0E-04	-3.2E-04	-3.0E-04	-3.0E-04	-2.7E-04	6.9E-05	1.3E-04	1.6E-04	2.2E-04	1.1E-04
Heptane (isomers)	1.0E-04	1.2E-04	-1.3E-05	-1.6E-03	-4.2E-03	1.4E-04	6.4E-06	3.2E-06	1.7E-05	6.4E-06	2.5E-05	1.6E-04	1.4E-04	1.8E-04	2.0E-04	1.7E-04
Hexane (isomers)	2.2E-04	-8.8E-03	6.4E-05	-3.6E-03	-9.1E-03	-1.2E-04	-2.7E-04	-4.6E-04	-5.4E-04	-2.7E-04	-3.5E-04	3.4E-05	4.7E-04	6.2E-04	9.3E-04	2.9E-04
Hydrocarbons, aromatic	1.4E-05	-1.8E-03	-9.1E-05	-4.3E-04	-4.0E-04	-3.0E-04	-2.8E-04	-2.9E-04	-2.9E-04	-2.8E-04	-2.8E-04	-1.3E-04	-8.4E-05	-1.1E-04	-1.1E-04	-1.2E-04
Methanol	5.3E-06	1.1E-04	-6.7E-05	-1.1E-02	-1.1E-02	-1.1E-02	-1.1E-02	-1.1E-02	-1.0E-02	-1.1E-02	-9.9E-03	3.8E-05	5.1E-05	6.3E-05	7.9E-05	4.9E-05

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Methyl tert-butylether	1.6E-08	5.3E-08	-3.3E-07	-2.3E-07	-1.3E-07	-3.3E-07	-1.3E-07	-1.3E-07	-1.2E-07	-1.3E-07	-1.1E-07	2.3E-08	3.0E-08	3.9E-08	4.9E-08	3.0E-08
Monoethanolamine	5.3E-08	1.1E-06	-1.7E-07	-6.2E-06	-3.7E-06	-3.7E-06	-3.6E-06	-3.6E-06	-3.3E-06	-3.6E-06	-3.2E-06	3.3E-07	4.2E-07	4.9E-07	5.7E-07	4.0E-07
NMVOG (unspecified)	3.2E-02	-8.3E-02	-1.2E-01	-5.6E-01	-6.3E-01	-2.8E-01	-1.3E+00	-1.2E+00	-1.1E+00	-1.3E+00	-1.2E+00	-2.5E+00	-3.1E+00	-2.6E+00	-2.5E+00	-2.5E+00
Pentane	5.8E-04	-1.2E-02	-3.5E-03	-1.0E-02	-2.3E-02	-4.9E-04	-1.0E-03	-1.3E-03	-1.3E-03	-1.0E-03	-9.8E-04	4.9E-04	1.1E-03	1.5E-03	2.0E-03	9.1E-04
Phenol	9.2E-07	1.3E-05	-1.0E-06	-7.1E-05	-4.2E-05	-4.2E-05	-4.2E-05	-4.2E-05	-3.8E-05	-4.2E-05	-3.7E-05	2.8E-06	2.9E-06	3.1E-06	3.2E-06	2.9E-06
Propane	4.6E-04	-2.4E-02	-9.2E-04	-1.0E-02	-2.1E-02	-2.0E-03	-2.3E-03	-2.7E-03	-2.8E-03	-2.3E-03	-2.4E-03	-6.5E-04	2.4E-04	3.2E-04	7.9E-04	-2.3E-04
Propene	2.3E-05	3.9E-05	-4.5E-04	-3.9E-04	-8.8E-04	-5.3E-05	-3.9E-05	-4.2E-05	-3.5E-05	-3.9E-05	-2.9E-05	4.3E-05	4.6E-05	5.9E-05	6.8E-05	5.0E-05
Propionaldehyde	1.6E-08	1.3E-09	-6.7E-09	2.5E-09	-4.1E-09	6.3E-09	6.5E-09	6.8E-09	7.5E-09	6.5E-09	7.3E-09	8.6E-09	7.6E-09	8.9E-09	9.4E-09	8.7E-09
Propionic acid	1.1E-07	-1.8E-04	2.5E-06	-2.4E-05	-1.3E-05	-1.8E-05	-1.5E-05	-1.9E-05	-2.0E-05	-1.5E-05	-1.7E-05	-6.2E-06	3.2E-06	4.3E-06	9.7E-06	-1.6E-06
Propylene oxide	4.3E-07	4.3E-07	5.9E-08	-4.3E-06	-9.4E-07	-2.2E-07	-2.1E-07	-2.0E-07	-1.4E-07	-2.1E-07	-1.4E-07	2.8E-07	2.5E-07	2.9E-07	3.1E-07	2.9E-07
Styrene	1.9E-10	7.2E-09	-1.1E-09	1.4E-09	3.7E-09	-1.0E-09	2.8E-09	7.9E-10	4.9E-10	2.8E-09	3.0E-09	8.7E-09	1.4E-08	1.8E-08	2.3E-08	1.3E-08
Toluene	1.0E-04	1.1E-03	-2.0E-03	-1.1E-03	-2.6E-03	1.1E-04	1.8E-05	3.2E-06	2.8E-05	1.8E-05	5.6E-05	3.0E-04	3.2E-04	4.0E-04	4.7E-04	3.5E-04
Xylene	9.4E-05	4.0E-04	-2.3E-02	-3.6E-04	-1.2E-03	3.4E-04	3.6E-04	2.4E-04	2.1E-04	3.6E-04	3.7E-04	6.5E-04	9.3E-04	1.2E-03	1.5E-03	8.9E-04
meta-Xylene	2.2E-08	8.4E-07	1.3E-06	4.1E-06	5.8E-06	3.0E-06	4.1E-06	3.1E-06	2.6E-06	4.1E-06	3.9E-06	4.0E-06	6.7E-06	8.6E-06	1.1E-05	6.0E-06
Methane	4.7E+00	-1.7E+00	-1.1E+01	1.8E+00	1.6E+00	-5.4E+00	7.3E-02	3.3E-01	6.7E-01	7.3E-02	5.0E-01	4.5E-01	-2.1E-01	5.3E-01	7.7E-01	4.8E-01

<b>Particulate Emissions</b>																
Aluminum	6.0E-04	2.8E-03	-9.8E-02	4.9E-04	2.9E-03	-1.2E-02	1.8E-03	7.9E-04	6.2E-04	1.8E-03	1.9E-03	4.6E-03	7.2E-03	9.2E-03	1.2E-02	6.6E-03
Dust (> PM10)	5.8E-03	5.8E-02	-2.6E+00	-6.0E-02	-2.6E-02	-6.6E-01	-2.1E-01	-2.1E-01	-1.9E-01	-2.1E-01	-1.8E-01	-3.2E-01	-3.7E-01	-2.6E-01	-2.0E-01	-2.9E-01
Dust (PM2.5 - PM10)	2.8E-03	1.0E-02	-1.2E-01	-1.1E-01	-9.7E-02	-9.2E-02	-3.4E-01	-3.1E-01	-2.8E-01	-3.4E-01	-3.0E-01	-5.2E-01	-6.4E-01	-5.4E-01	-5.2E-01	-5.3E-01
Dust (PM2.5)	1.0E-02	1.2E-02	-1.7E-01	-9.0E-02	-8.5E-02	-5.4E-02	-1.9E-01	-1.8E-01	-1.6E-01	-1.9E-01	-1.7E-01	-2.9E-01	-3.5E-01	-2.8E-01	-2.6E-01	-2.8E-01

## Material emissions, discharged to waste effluent, kg/tonne waste

	A - Landfill	B - Incineration	C - SRF	D - BP pyrolysis	E - Ozmotech pyrolysis	F - Redox agent	G - Stadler & Titech	H - Stadler & Pellenc	I - Stadler & Qinetiq	J - Stadler & Sims	K - KME & Titech	L - Stadler & TLT	M - Swiss Polymera	N - B+B	O - Herbold	P - Flottweg
<b>Heavy Metals</b>																
Antimony	3.2E-05	1.4E-02	1.2E-02	4.4E-04	4.1E-04	4.6E-04	-1.2E-04	5.3E-06	2.4E-04	-1.2E-04	1.7E-04	1.1E-03	8.4E-04	1.2E-03	1.1E-03	3.4E-05
Arsenic	1.2E-05	8.8E-04	3.4E-04	-6.8E-05	-7.0E-05	-5.9E-05	-7.3E-05	-6.6E-05	-4.5E-05	-7.3E-05	-4.6E-05	4.2E-05	2.7E-05	6.1E-05	8.0E-05	9.7E-07
Cadmium	4.0E-05	8.6E-06	-8.9E-06	2.2E-06	-3.3E-06	1.3E-05	1.3E-05	1.4E-05	1.6E-05	1.3E-05	1.6E-05	2.2E-05	1.9E-05	2.3E-05	2.4E-05	5.7E-06
Cesium	4.1E-07	4.9E-07	-7.2E-08	-7.6E-06	-2.0E-05	6.4E-07	-7.0E-09	-2.6E-08	3.4E-08	-7.0E-09	7.7E-08	7.1E-07	6.3E-07	8.2E-07	8.9E-07	1.7E-05
Chromium +VI	2.1E-05	6.2E-04	5.8E-05	-4.6E-04	-4.7E-04	-3.2E-04	-5.2E-04	-4.8E-04	-4.2E-04	-5.2E-04	-4.4E-04	-2.7E-04	-3.5E-04	-2.7E-04	-2.4E-04	5.1E-05
Cobalt	2.3E-05	1.8E-06	1.8E-06	8.7E-06	5.9E-06	1.1E-05	1.1E-05	1.1E-05	1.2E-05	1.1E-05	1.2E-05	1.9E-05	1.8E-05	1.9E-05	1.9E-05	2.0E-05
Copper	1.6E-05	-6.0E-06	-1.3E-04	-1.6E-04	-1.7E-04	-1.0E-04	-1.2E-04	-1.2E-04	-1.0E-04	-1.2E-04	-1.0E-04	-2.8E-05	-3.4E-05	-2.2E-05	-1.5E-05	1.5E-05
Iron	3.6E-02	2.8E-02	-1.9E-02	-6.6E-03	-1.0E-02	-5.8E-03	2.5E-03	2.6E-03	5.5E-03	2.5E-03	6.3E-03	3.4E-02	3.5E-02	3.5E-02	3.6E-02	-1.4E-04
Lead	9.8E-06	1.7E-05	-4.0E-05	-9.6E-05	-1.4E-04	-4.8E-05	-4.9E-05	-5.2E-05	-4.7E-05	-4.9E-05	-4.1E-05	1.7E-05	2.6E-05	3.7E-05	4.9E-05	1.6E-06
Manganese	6.7E-04	7.4E-05	-1.5E-03	1.5E-04	-3.6E-04	-1.6E-04	5.0E-04	4.9E-04	4.9E-04	5.0E-04	5.1E-04	5.9E-04	6.2E-04	6.8E-04	7.4E-04	4.5E-05
Mercury	4.5E-07	6.6E-06	-4.6E-06	-2.8E-05	-2.9E-05	-2.7E-05	-4.9E-05	-4.6E-05	-4.3E-05	-4.9E-05	-4.3E-05	-1.0E-04	-1.3E-04	-1.1E-04	-1.0E-04	5.6E-13
Molybdenum	4.2E-06	7.3E-05	-2.8E-04	-6.2E-05	-5.8E-05	-6.7E-05	-7.8E-05	-7.9E-05	-7.0E-05	-7.8E-05	-6.7E-05	-1.7E-05	-1.5E-05	4.0E-06	2.0E-05	7.0E-06
Nickel	2.0E-05	-3.8E-07	-2.3E-04	-2.1E-04	-1.7E-04	-1.6E-04	-1.2E-04	-1.2E-04	-1.1E-04	-1.2E-04	-1.0E-04	-2.1E-05	-2.5E-05	-1.2E-05	-4.2E-06	2.8E-11
Selenium	4.5E-06	6.7E-04	5.6E-04	4.1E-05	3.7E-05	4.0E-05	3.5E-05	4.0E-05	4.7E-05	3.5E-05	4.4E-05	5.3E-05	4.2E-05	5.5E-05	5.9E-05	5.0E-08
Silver	3.9E-07	4.8E-07	-5.5E-08	-6.3E-06	-1.6E-05	4.1E-07	-1.1E-07	-1.2E-07	-6.0E-08	-1.1E-07	-2.2E-08	6.1E-07	5.5E-07	7.2E-07	7.8E-07	1.4E-05
Strontium	2.5E-03	3.0E-03	-5.5E-03	-4.6E-02	-1.2E-01	1.2E-03	7.2E-05	-7.0E-05	2.8E-04	7.2E-05	5.7E-04	4.4E-03	4.0E-03	5.2E-03	5.7E-03	8.1E-05
Thallium	6.4E-07	5.0E-07	1.3E-07	3.7E-07	3.9E-07	3.3E-07	4.3E-07	4.0E-07	4.2E-07	4.3E-07	4.6E-07	6.8E-07	7.6E-07	8.3E-07	9.2E-07	8.9E-05
Tin	4.9E-05	3.3E-06	-4.4E-05	4.2E-05	4.2E-05	4.1E-05	4.1E-05	4.1E-05	4.1E-05	4.1E-05	4.2E-05	4.2E-05	4.3E-05	4.3E-05	4.3E-05	6.0E+05
Titanium	4.4E-07	7.5E-06	-2.0E-06	-7.8E-07	8.5E-07	-2.7E-06	9.7E-07	-7.4E-07	-8.2E-07	9.7E-07	1.4E-06	7.9E-06	1.2E-05	1.6E-05	2.0E-05	-4.8E+02
Tungsten	9.4E-08	4.0E-06	-3.7E-05	-2.1E-06	-1.1E-06	-3.1E-06	-9.0E-07	-1.6E-06	-1.5E-06	-9.0E-07	-5.7E-07	3.4E-06	5.2E-06	6.6E-06	8.5E-06	4.7E-03
Vanadium	8.0E-04	1.0E-03	9.4E-04	3.4E-04	3.3E-04	3.3E-04	3.4E-04	3.8E-04	4.3E-04	3.4E-04	4.0E-04	3.2E-04	2.1E-04	3.1E-04	3.4E-04	3.2E-05
Zinc	2.4E-04	-2.4E-03	-3.0E-04	-2.3E-03	-5.1E-03	-6.7E-05	-1.6E-04	-2.7E-04	-2.7E-04	-1.6E-04	-1.3E-04	3.6E-04	6.5E-04	8.7E-04	1.2E-03	5.9E-08
<b>Inorganic Emissions</b>																
Acid (calculated as H+)	1.7E-05	9.7E-07	-3.4E-03	-5.5E-03	-5.5E-03	-5.5E-03	-2.4E-02	-2.2E-02	-1.9E-02	-2.4E-02	-2.1E-02	-2.0E-02	-2.5E-02	-2.1E-02	-2.0E-02	3.3E-04
Aluminum	1.5E-02	-4.9E-04	-1.9E-03	1.3E-02	1.1E-02	1.2E-02	7.6E-03	7.9E-03	8.5E-03	7.6E-03	8.2E-03	1.3E-02	1.7E-02	1.4E-02	1.6E-02	1.7E-04

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Ammonium / ammonia	8.7E-02	2.0E-03	-1.6E-03	6.0E-02	5.9E-02	6.1E-02	5.8E-02	5.9E-02	6.0E-02	5.8E-02	6.0E-02	6.3E-02	6.1E-02	6.3E-02	6.3E-02	-4.7E+02
Barium	5.8E-04	4.6E-04	-4.2E-05	-6.5E-03	-1.7E-02	6.9E-04	1.3E-04	1.1E-04	1.7E-04	1.3E-04	2.1E-04	7.6E-04	6.9E-04	8.7E-04	9.4E-04	6.4E-05
Beryllium	5.7E-07	3.3E-07	2.3E-07	4.4E-07	4.4E-07	4.3E-07	4.4E-07	4.4E-07	4.5E-07	4.4E-07	4.5E-07	4.7E-07	4.7E-07	4.9E-07	5.0E-07	-2.6E-01
Boron	3.9E-04	1.3E-04	-4.9E-03	3.4E-04	2.8E-04	3.7E-04	3.8E-04	3.7E-04	3.6E-04	3.8E-04	3.8E-04	4.1E-04	4.5E-04	4.9E-04	5.3E-04	-5.7E-05
Bromate	9.1E-07	6.8E-03	1.1E-03	3.9E-04	3.9E-04	4.0E-04	4.0E-04	4.5E-04	5.4E-04	4.0E-04	4.8E-04	1.1E-03	1.1E-03	1.1E-03	1.1E-03	2.7E-04
Bromine	2.3E-03	6.7E-02	5.9E-02	3.3E-03	-8.6E-03	9.1E-03	7.5E-03	7.8E-03	8.3E-03	7.5E-03	8.1E-03	1.0E-02	9.6E-03	1.1E-02	1.1E-02	-2.2E-04
Calcium	1.9E-02	9.3E-02	-9.4E-01	-3.9E-01	-7.7E-01	-1.3E-01	-1.5E-01	-1.4E-01	-1.2E-01	-1.5E-01	-1.3E-01	3.9E-02	4.1E-02	5.4E-02	6.4E-02	4.6E-05
Carbonate	1.7E-05	9.4E-05	-4.2E-01	-3.5E-01	-3.5E-01	-3.5E-01	-3.6E-01	-3.3E-01	-2.9E-01	-3.6E-01	-3.2E-01	-1.1E-02	-1.3E-02	-1.1E-02	-1.1E-02	-4.1E-02
Chlorate	4.5E-02	1.2E-01	-1.8E-01	-1.4E+00	-3.5E+00	-4.0E-02	-1.5E-01	-1.4E-01	-1.2E-01	-1.5E-01	-1.2E-01	1.2E-01	1.0E-01	1.3E-01	1.5E-01	2.9E-03
Chloride	1.8E+00	5.3E+01	-1.3E+01	-2.7E+00	-7.5E+00	-8.4E+00	1.8E-01	7.6E-01	2.0E+00	1.8E-01	1.3E+00	1.0E+01	1.0E+01	1.1E+01	1.1E+01	8.8E-04
Chlorine (dissolved)	1.8E-06	7.1E-06	-6.3E-05	1.2E-05	-5.3E-05	-8.4E-05	-5.3E-05	-5.4E-05	-4.9E-05	-5.3E-05	-4.7E-05	1.1E-05	3.0E-04	2.0E-05	1.8E-04	-1.5E-03
Cyanide	2.7E-05	-1.8E-05	-1.6E-04	-2.7E-04	-3.1E-04	-1.5E-04	-2.2E-04	-2.1E-04	-1.9E-04	-2.2E-04	-1.9E-04	-8.1E-05	-9.9E-05	-7.3E-05	-6.1E-05	4.8E-05
Fluoride	6.4E-05	1.2E-03	-4.6E-03	-8.0E-04	-1.5E-03	-1.7E-03	-1.6E-03	-1.4E-03	-1.4E-03	-1.6E-03	-1.4E-03	-7.7E-03	-9.5E-03	-7.9E-03	-7.5E-03	2.7E-07
Hydrogen sulphide	3.2E-07	2.2E-07	-1.9E-06	-2.6E-06	-2.7E-06	-1.5E-06	-1.3E-06	-1.4E-06	-1.3E-06	-1.3E-06	-1.1E-06	5.7E-07	9.4E-07	1.3E-06	1.8E-06	-3.9E+00
Hydroxide	6.5E-08	1.2E-06	-7.4E-07	-1.4E-06	-1.6E-06	-1.4E-06	-1.1E-06	-1.1E-06	-9.8E-07	-1.1E-06	-9.5E-07	2.6E-07	2.8E-07	3.0E-07	3.2E-07	4.3E-03
Hypochlorite	8.7E-07	4.7E-05	-1.9E-05	-2.8E-05	-2.4E-05	-3.5E-05	-1.7E-05	-2.3E-05	-2.1E-05	-1.7E-05	-1.3E-05	3.1E-05	4.7E-05	5.9E-05	7.5E-05	1.4E-04
Iodide	4.1E-05	5.1E-05	-2.4E-05	-7.7E-04	-2.0E-03	6.1E-05	-2.0E-06	-4.2E-06	1.9E-06	-2.0E-06	6.7E-06	7.2E-05	6.5E-05	8.5E-05	9.3E-05	1.5E-05
Magnesium	2.8E-02	3.9E-03	-1.6E-01	-4.0E-02	-4.4E-02	2.5E-02	2.3E-02	2.2E-02	2.2E-02	2.3E-02	2.4E-02	2.6E-02	2.7E-02	2.9E-02	2.9E-02	5.8E-09
Metal ions (unspecific)	2.8E-04	7.1E-06	-1.9E-05	1.3E-04	1.2E-04	1.2E-04	1.3E-04	1.4E-04	1.4E-04	1.3E-04	1.4E-04	1.5E-04	1.3E-04	1.5E-04	1.5E-04	4.5E-09
Nitrate	3.2E-01	4.1E-02	-4.8E-02	2.3E-01	2.2E-01	2.3E-01	2.2E-01	2.2E-01	2.3E-01	2.2E-01	2.3E-01	2.5E-01	2.4E-01	2.5E-01	2.5E-01	9.4E-03
Nitrite	1.8E-03	1.1E-04	3.0E-06	1.3E-03	1.3E-03	1.3E-03	1.3E-03	1.3E-03	1.3E-03	1.3E-03	1.3E-03	1.4E-03	1.4E-03	1.4E-03	1.4E-03	1.9E-05
Nitrogen	2.4E-03	8.3E-04	-5.2E-04	4.8E-04	-4.7E-05	7.8E-04	-7.6E-04	-6.3E-04	-3.9E-04	-7.6E-04	-4.1E-04	-9.6E-04	-1.5E-03	-7.2E-04	-4.0E-04	-5.6E+00
Nitrogen organic bounded	3.7E-05	1.0E-04	-1.4E-04	-1.8E-03	-1.5E-03	-1.7E-04	-1.9E-04	-1.9E-04	-1.7E-04	-1.9E-04	-1.6E-04	7.6E-05	8.0E-05	1.0E-04	1.1E-04	1.8E-06
Phosphate	7.6E-05	5.7E-04	1.2E-05	-3.4E-04	-1.6E-04	2.0E-05	4.5E-06	9.1E-06	2.5E-05	4.5E-06	2.3E-05	1.4E-04	1.4E-04	1.5E-04	1.5E-04	-3.9E+00
Phosphorus	2.8E-06	3.4E-05	-4.8E-04	-4.8E-04	-5.4E-04	-4.3E-04	-8.8E-04	-8.1E-04	-7.1E-04	-8.8E-04	-7.7E-04	-1.9E-04	-2.3E-04	-1.9E-04	-1.8E-04	-2.6E+00
Potassium	8.5E-03	1.1E-02	-6.5E-02	-7.4E-02	-1.3E-01	-3.9E-02	-6.3E-02	-5.9E-02	-5.1E-02	-6.3E-02	-5.4E-02	-2.7E-02	-3.5E-02	-2.5E-02	-2.2E-02	8.1E-06
Rubidium	4.1E-06	5.0E-06	-7.6E-07	-7.6E-05	-2.0E-04	6.4E-06	-2.5E-08	-2.5E-07	3.4E-07	-2.5E-08	8.2E-07	7.2E-06	6.6E-06	8.6E-06	9.4E-06	-2.9E-05
Scandium	4.4E-08	1.9E-06	-3.3E-05	-3.5E-07	7.8E-07	-1.3E-06	3.8E-07	-2.0E-07	-2.5E-07	3.8E-07	4.9E-07	2.5E-06	4.0E-06	5.0E-06	6.6E-06	-9.3E-11
Sodium	2.2E-01	4.7E-01	-2.5E+00	-4.5E+00	-8.2E+00	-1.9E+00	-2.2E+00	-2.1E+00	-1.8E+00	-2.2E+00	-1.9E+00	1.2E-01	4.3E-02	1.5E-01	1.8E-01	2.0E-05
Sulphate	3.5E-02	6.6E-01	-6.8E-01	-2.2E-01	-2.4E-01	-4.8E-01	-1.8E-01	-1.7E-01	-1.4E-01	-1.8E-01	-1.4E-01	1.1E-01	1.2E-01	1.6E-01	1.9E-01	6.5E-05
Sulphide	2.1E-06	4.3E-06	-2.9E-05	-8.5E-05	-8.6E-05	-6.5E-05	-5.5E-04	-4.9E-04	-4.7E-04	-5.5E-04	-4.8E-04	-1.9E-03	-2.4E-03	-2.0E-03	-1.9E-03	2.9E-05
Sulphite	2.3E-06	1.2E-04	-1.6E-03	-4.9E-05	-3.0E-05	-7.2E-05	-2.0E-05	-4.0E-05	-3.8E-05	-2.0E-05	-1.1E-05	9.8E-05	1.5E-04	1.9E-04	2.5E-04	3.2E-08
Sulphur	5.1E-05	-1.9E-05	-9.1E-06	-1.4E-03	-3.7E-03	1.1E-04	-5.2E-07	-1.0E-05	-3.2E-06	-5.2E-07	1.1E-05	1.3E-04	1.3E-04	1.7E-04	1.9E-04	-3.5E-07

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
<b>Organic Emissions</b>																
Chlorous dissolvent	9.5E-08	1.6E-05	-6.5E-05	-8.5E-05	-8.3E-05	-8.3E-05	-8.3E-05	-7.9E-05	-6.9E-05	-8.3E-05	-7.3E-05	2.5E-06	2.4E-06	2.6E-06	2.5E-06	-6.2E-02
Dichloroethane	1.2E-08	2.0E-07	-8.5E-06	-3.3E-05	-3.3E-05	-3.3E-05	-3.3E-05	-3.3E-05	-2.9E-05	-3.3E-05	-2.9E-05	1.2E-07	1.8E-07	2.2E-07	2.8E-07	8.7E-09
Dichloromethane	4.0E-06	-3.5E-05	-1.2E-06	-9.7E-05	-2.4E-04	1.7E-06	-5.9E-06	-6.4E-06	-5.8E-06	-5.9E-06	-5.1E-06	4.7E-06	4.7E-06	6.2E-06	6.9E-06	8.9E-04
Trichloromethane	7.4E-15	2.8E-14	-1.8E-13	1.6E-13	-9.2E-14	-1.9E-13	-8.1E-14	-8.1E-14	-7.3E-14	-8.1E-14	-7.0E-14	2.1E-14	1.1E-12	2.7E-14	6.2E-13	2.7E-12
Vinyl chloride	7.2E-09	6.9E-08	-2.5E-04	-2.3E-04	-2.3E-04	-2.3E-04	-2.3E-04	-2.1E-04	-1.9E-04	-2.3E-04	-2.0E-04	1.5E-08	1.5E-08	1.6E-08	1.7E-08	5.6E-04
Acenaphthene	2.5E-09	3.0E-09	-4.5E-10	-4.7E-08	-1.2E-07	4.0E-09	-4.3E-11	-1.6E-10	2.1E-10	-4.3E-11	4.8E-10	4.4E-09	3.9E-09	5.1E-09	5.5E-09	4.3E-06
Acenaphthylene	1.6E-10	1.9E-10	-2.8E-11	-3.0E-09	-7.8E-09	2.5E-10	-2.7E-12	-1.0E-11	1.3E-11	-2.7E-12	3.0E-11	2.8E-10	2.4E-10	3.2E-10	3.5E-10	3.3E-08
Acetic acid	4.2E-07	3.7E-06	1.7E-06	-4.4E-06	-8.0E-06	-1.7E-06	-1.5E-06	-1.5E-06	-1.2E-06	-1.5E-06	-1.2E-06	8.1E-07	8.1E-07	9.7E-07	1.1E-06	-2.5E-03
Alkane (unspecified)	5.3E-05	6.3E-05	-9.4E-06	-9.9E-04	-2.6E-03	8.4E-05	-9.1E-07	-3.4E-06	4.4E-06	-9.1E-07	1.0E-05	9.2E-05	8.2E-05	1.1E-04	1.2E-04	3.4E-05
Alkene (unspecified)	4.9E-06	5.8E-06	-8.7E-07	-9.2E-05	-2.4E-04	7.7E-06	-8.4E-08	-3.1E-07	4.1E-07	-8.4E-08	9.2E-07	8.5E-06	7.6E-06	9.8E-06	1.1E-05	7.5E-05
Aromatic hydrocarbons																
(unspecified)	2.2E-04	1.8E-04	-3.4E-05	-4.1E-03	-1.1E-02	3.4E-04	4.0E-07	-1.3E-05	1.7E-05	4.0E-07	4.4E-05	3.8E-04	3.5E-04	4.6E-04	5.0E-04	2.4E-06
Benzene	3.2E-05	7.1E-05	2.3E-05	-6.0E-04	-1.5E-03	1.1E-05	-3.5E-05	-3.6E-05	-2.8E-05	-3.5E-05	-2.4E-05	5.6E-05	5.0E-05	6.5E-05	7.0E-05	1.8E-05
Butene	1.2E-10	9.1E-09	-1.1E-08	-2.0E-09	-1.9E-09	-2.7E-09	-1.0E-09	-1.5E-09	-1.3E-09	-1.0E-09	-6.2E-10	3.1E-09	5.3E-09	5.4E-09	7.3E-09	3.0E-08
Ethene	3.8E-06	1.5E-05	1.1E-05	-7.5E-05	-1.9E-04	4.7E-06	-1.2E-06	-1.4E-06	-6.0E-07	-1.2E-06	-9.5E-08	7.6E-06	6.9E-06	9.1E-06	1.0E-05	4.4E-11
Ethyl benzene	7.7E-06	8.2E-06	-1.1E-06	-1.2E-04	-3.2E-04	1.1E-05	2.9E-07	2.9E-08	1.0E-06	2.9E-07	1.7E-06	1.2E-05	1.1E-05	1.4E-05	1.5E-05	1.1E-04
Ethylene oxide	5.1E-04	1.7E-04	-1.2E-04	-1.5E-02	-3.8E-02	1.1E-03	-8.5E-05	-1.6E-04	-7.1E-05	-8.5E-05	4.7E-05	1.2E-03	1.2E-03	1.5E-03	1.7E-03	1.7E-04
Fatty acids (calculated as																
total carbon)	1.2E-03	1.3E-03	-1.6E-04	-1.9E-02	-4.9E-02	1.6E-03	4.5E-05	4.2E-06	1.6E-04	4.5E-05	2.6E-04	1.8E-03	1.6E-03	2.1E-03	2.3E-03	2.9E-04
Formaldehyde	3.1E-07	2.1E-06	1.3E-06	-2.1E-04	-2.1E-04	-2.0E-04	-2.0E-04	-2.0E-04	-1.8E-04	-2.0E-04	-1.8E-04	4.9E-07	4.9E-07	6.1E-07	6.9E-07	-1.2E-04
Glutaraldehyde	1.2E-07	-6.3E-06	3.6E-07	-3.2E-06	-8.2E-06	4.0E-07	3.7E-07	4.7E-08	-8.2E-08	3.7E-07	2.9E-07	7.1E-07	1.5E-06	1.9E-06	-3.4E-02	4.9E-05
Hydrocarbons																
(unspecified)	5.0E-05	-9.3E-04	-3.5E-03	-5.5E-02	-5.5E-02	-5.4E-02	-9.1E-02	-8.7E-02	-7.9E-02	-9.1E-02	-8.1E-02	-3.4E-02	-4.1E-02	-3.5E-02	4.0E-04	3.0E-08
Methanol	2.0E-07	-2.4E-04	-1.5E-06	-1.0E-04	-9.7E-05	-9.4E-05	-9.3E-05	-9.5E-05	-9.0E-05	-9.3E-05	-8.7E-05	-1.9E-05	-1.4E-05	-1.8E-05	-1.8E-05	4.0E-07
Methyl tert-butylether	5.9E-07	9.3E-07	-2.2E-07	-1.7E-05	-4.4E-05	1.3E-06	-1.3E-07	-1.8E-07	-6.4E-08	-1.3E-07	3.8E-08	1.4E-06	1.2E-06	1.6E-06	1.8E-02	-2.5E+00
Oil (unspecified)	2.0E-02	2.1E-02	-9.2E-03	-5.2E-01	-1.4E+00	3.8E-02	-2.7E-02	-2.8E-02	-2.3E-02	-2.7E-02	-1.9E-02	2.1E-02	1.4E-02	3.5E-02	2.6E-02	9.1E-04
Phenol	3.9E-05	4.6E-05	-1.3E-04	-1.0E-03	-2.2E-03	-1.9E-04	-1.5E-03	-1.4E-03	-1.3E-03	-1.5E-03	-1.4E-03	-1.6E-03	-1.9E-03	-1.6E-03	3.8E-05	2.9E-06
Polycyclic aromatic																
hydrocarbons (unspec.)	2.6E-06	4.3E-06	-1.1E-06	-5.4E-05	-1.2E-04	-2.2E-06	-5.7E-06	-5.8E-06	-4.9E-06	-5.7E-06	-4.5E-06	4.7E-06	4.3E-06	5.5E-06	7.3E-06	-2.3E-04
Propene	2.8E-06	1.8E-05	1.0E-05	-4.9E-05	-4.6E-05	-1.8E-05	-1.9E-05	-1.9E-05	-1.7E-05	-1.9E-05	-1.6E-05	4.1E-06	3.9E-06	4.7E-06	7.4E-07	5.0E-05
Propylene oxide	1.0E-06	1.0E-06	1.4E-07	-1.0E-05	-2.3E-06	-5.3E-07	-5.1E-07	-4.8E-07	-3.3E-07	-5.1E-07	-3.3E-07	6.8E-07	6.1E-07	7.1E-07	3.7E-08	8.7E-09
Sodium formate	5.5E-10	2.1E-07	8.9E-09	-1.0E-08	-1.1E-09	-3.6E-09	-2.2E-10	9.2E-10	4.7E-09	-2.2E-10	3.7E-09	3.4E-08	3.5E-08	3.7E-08	7.1E-05	-1.6E-06
Toluene	5.1E-05	6.0E-05	-7.3E-06	-9.7E-04	-2.5E-03	8.3E-05	3.4E-07	-2.0E-06	5.4E-06	3.4E-07	1.1E-05	8.9E-05	7.9E-05	1.0E-04	9.9E-05	2.9E-07

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Triethylene glycol	1.1E-07	-2.0E-04	-1.5E-06	-3.6E-05	-2.9E-05	-2.8E-05	-2.7E-05	-2.8E-05	-2.9E-05	-2.7E-05	-2.8E-05	-1.6E-05	-1.1E-05	-1.5E-05	-3.0E-06	1.3E-08
Xylene	4.1E-05	4.8E-05	-7.5E-06	-7.8E-04	-2.1E-03	6.5E-05	-1.2E-06	-3.2E-06	2.9E-06	-1.2E-06	7.3E-06	7.2E-05	6.4E-05	8.3E-05	3.2E-05	3.5E-04
Cumene	5.6E-06	4.6E-05	2.8E-05	-1.1E-04	-1.2E-04	-4.9E-05	-5.0E-05	-5.0E-05	-4.4E-05	-5.0E-05	-4.3E-05	9.7E-06	9.2E-06	1.1E-05	2.5E-04	8.9E-04
Ethylenediamine	4.9E-11	9.7E-11	-1.1E-09	-2.7E-10	-1.0E-10	-2.6E-10	-1.1E-10	-1.2E-10	-1.0E-10	-1.1E-10	-8.7E-11	8.2E-11	1.1E-10	1.4E-10	0.0E+00	6.0E-06
VOC	1.4E-04	1.8E-04	-2.7E-05	-2.7E-03	-7.0E-03	2.2E-04	5.2E-07	-8.7E-06	1.2E-05	5.2E-07	3.0E-05	2.6E-04	2.4E-04	3.1E-04	9.6E-05	-1.3E+00

<b>Analytical Measures</b>																
Adsorbable organic																
halogen compounds	3.1E-07	8.6E-07	-1.6E-04	-1.4E-04	-1.5E-04	-1.3E-04	-1.3E-04	-1.2E-04	-1.1E-04	-1.3E-04	-1.2E-04	1.0E-06	1.3E-06	1.6E-06	2.0E-06	-2.8E-01
Biological oxygen demand	1.4E-01	9.2E-02	-1.3E-02	-1.7E+00	-4.4E+00	4.0E-02	-1.1E-01	-1.2E-01	-9.4E-02	-1.1E-01	-7.6E-02	1.4E-01	1.2E-01	1.8E-01	2.2E-01	1.8E+00
Chemical oxygen demand	2.9E-01	1.2E-01	-2.2E-02	-1.1E+01	-1.3E+01	-8.9E+00	-9.1E+00	-9.1E+00	-8.3E+00	-9.1E+00	-8.0E+00	2.1E-01	1.8E-01	2.6E-01	2.9E-01	-4.8E+02
Solids (dissolved)	4.1E-03	1.3E-01	-6.0E-01	-3.8E-01	-3.6E-01	-4.3E-01	-3.9E-01	-3.7E-01	-3.2E-01	-3.9E-01	-3.4E-01	-1.2E-01	-1.5E-01	-1.1E-01	-1.0E-01	3.1E-04
Solids (suspended)	5.6E-03	-1.8E-01	-1.0E-01	-2.3E-01	-3.8E-01	-1.1E-01	-3.3E-01	-3.1E-01	-2.9E-01	-3.3E-01	-3.0E-01	-8.6E-01	-1.0E+00	-8.5E-01	7.5E-02	0.0E+00
Total dissolved organic																
bounded carbon	7.6E-02	4.0E-02	5.5E-03	-5.0E-01	-1.3E+00	3.9E-02	-1.1E-03	-2.8E-03	4.9E-03	-1.1E-03	9.7E-03	8.1E-02	7.8E-02	9.6E-02	1.1E-01	5.2E-07
Total organic bounded																
carbon	7.8E-02	4.0E-02	4.9E-03	-5.0E-01	-1.3E+00	4.0E-02	-1.9E-04	-1.8E-03	6.0E-03	-1.9E-04	1.1E-02	8.3E-02	7.9E-02	9.7E-02	1.1E-01	5.6E-06

## Material emissions, discharged as solid, kg/tonne waste

	A - Landfill	B - Incineration	C - SRF	D - BP pyrolysis	E - Ozmotech pyrolysis	F - Redox agent	G - Stadler & Titech	H - Stadler & Pellenc	I - Stadler & Qinetiq	J - Stadler & Sims	K - KME & Titech	L - Stadler & TLT	M - Swiss Polymera	N - B+B	O - Herbold	P - Flottweg
<b>Heavy Metals</b>																
Antimony	2.0E-10	3.5E-11	-2.2E-13	-6.8E-11	-1.1E-11	-8.7E-12	-6.3E-12	5.1E-13	1.8E-11	-6.3E-12	1.5E-11	1.0E-10	9.0E-11	1.0E-10	1.1E-10	1.0E-10
Arsenic	6.3E-08	-5.2E-07	-4.9E-09	-1.5E-06	-3.8E-06	5.0E-08	-6.1E-08	-7.7E-08	-7.1E-08	-6.1E-08	-5.0E-08	1.1E-07	1.3E-07	1.7E-07	2.0E-07	1.3E-07
Cadmium	4.2E-08	1.0E-07	2.7E-08	-2.4E-07	-3.4E-08	-7.5E-08	-5.3E-08	-6.7E-08	-5.9E-08	-5.3E-08	-3.7E-08	9.5E-08	1.3E-07	1.7E-07	2.1E-07	1.3E-07
Chromium (unspecified)	1.2E-06	-3.5E-06	3.8E-07	-3.1E-05	-5.3E-05	-5.8E-06	-7.0E-06	-7.3E-06	-6.6E-06	-7.0E-06	-6.0E-06	2.5E-06	3.0E-06	3.8E-06	4.6E-06	3.1E-06
Chromium +VI	2.8E-06	1.8E-05	-2.7E-06	-2.5E-05	-2.8E-05	-1.8E-05	-1.8E-05	-1.7E-05	-1.5E-05	-1.8E-05	-1.5E-05	5.2E-06	5.5E-06	5.7E-06	5.9E-06	5.7E-06
Cobalt	4.9E-10	1.1E-07	4.1E-08	8.7E-08	1.2E-07	6.5E-08	8.8E-08	6.8E-08	6.0E-08	8.8E-08	8.4E-08	9.4E-08	1.5E-07	1.9E-07	2.4E-07	2.4E-06
Copper	2.5E-06	2.0E-05	-2.4E-07	-4.0E-05	-3.1E-05	-2.5E-05	-2.4E-05	-2.4E-05	-2.1E-05	-2.4E-05	-2.1E-05	5.7E-06	6.3E-06	6.9E-06	7.6E-06	4.1E-04
Iron	4.4E-04	5.9E-03	-2.5E-02	-1.4E-02	-2.6E-02	-1.1E-02	-6.7E-03	-6.9E-03	-6.1E-03	-6.7E-03	-5.7E-03	2.5E-03	2.9E-03	3.5E-03	4.0E-03	2.5E-03
Lead	2.2E-07	1.7E-06	3.2E-07	-3.2E-06	-1.4E-06	-1.6E-06	-1.5E-06	-1.5E-06	-1.3E-06	-1.5E-06	-1.2E-06	6.6E-07	8.3E-07	1.0E-06	1.2E-06	1.3E-04
Manganese	6.8E-06	-3.6E-05	2.8E-05	-6.3E-05	-2.5E-04	6.9E-05	8.3E-05	5.8E-05	4.9E-05	8.3E-05	7.8E-05	9.5E-05	1.5E-04	2.0E-04	2.6E-04	8.5E-06
Mercury	4.0E-11	1.7E-08	1.6E-09	1.1E-09	1.4E-09	8.6E-10	1.3E-09	1.2E-09	1.4E-09	1.3E-09	1.5E-09	3.1E-09	3.4E-09	3.8E-09	4.1E-09	3.4E-08
Molybdenum	1.3E-10	6.0E-08	1.4E-08	2.0E-08	2.7E-08	1.6E-08	2.0E-08	1.6E-08	1.5E-08	2.0E-08	2.0E-08	2.5E-08	3.6E-08	4.5E-08	5.6E-08	6.7E-07
Nickel	3.6E-07	2.1E-06	3.5E-07	-8.4E-06	-4.4E-06	-4.5E-06	-4.4E-06	-4.4E-06	-4.0E-06	-4.4E-06	-3.8E-06	7.5E-07	8.9E-07	1.0E-06	1.2E-06	2.1E-07
Silver	1.1E-09	4.6E-08	5.5E-09	-2.4E-07	-1.4E-07	-1.4E-07	-1.4E-07	-1.4E-07	-1.3E-07	-1.4E-07	-1.2E-07	7.8E-09	7.7E-09	8.2E-09	8.1E-09	1.1E-08
Strontium	1.6E-06	-1.4E-05	-4.8E-07	-3.9E-05	-9.6E-05	6.4E-07	-2.3E-06	-2.6E-06	-2.3E-06	-2.3E-06	-2.0E-06	1.9E-06	1.9E-06	2.5E-06	2.7E-06	2.2E-06
Tin	5.9E-10	2.4E-07	3.6E-08	1.3E-08	1.3E-08	1.4E-08	1.4E-08	1.6E-08	1.9E-08	1.4E-08	1.7E-08	3.9E-08	3.9E-08	4.1E-08	4.0E-08	9.1E-06
Titanium	3.2E-08	1.1E-06	2.0E-06	6.3E-06	8.8E-06	4.6E-06	6.3E-06	4.7E-06	4.0E-06	6.3E-06	5.9E-06	6.0E-06	1.0E-05	1.3E-05	1.7E-05	2.6E-07
Vanadium	9.2E-10	3.1E-08	5.8E-08	1.8E-07	2.5E-07	1.3E-07	1.8E-07	1.3E-07	1.1E-07	1.8E-07	1.7E-07	1.7E-07	2.9E-07	3.7E-07	5.0E-07	1.3E-05
Zinc	3.5E-05	2.6E-05	5.8E-06	-1.7E-04	-1.6E-04	-2.1E-05	-2.1E-05	-2.2E-05	-1.7E-05	-2.1E-05	-1.4E-05	3.3E-05	3.6E-05	4.3E-05	5.0E-05	3.7E-04
Antimony	2.0E-10	3.5E-11	-2.2E-13	-6.8E-11	-1.1E-11	-8.7E-12	-6.3E-12	5.1E-13	1.8E-11	-6.3E-12	1.5E-11	1.0E-10	9.0E-11	1.0E-10	1.1E-10	1.0E-10
Arsenic	6.3E-08	-5.2E-07	-4.9E-09	-1.5E-06	-3.8E-06	5.0E-08	-6.1E-08	-7.7E-08	-7.1E-08	-6.1E-08	-5.0E-08	1.1E-07	1.3E-07	1.7E-07	2.0E-07	1.3E-07
Cadmium	4.2E-08	1.0E-07	2.7E-08	-2.4E-07	-3.4E-08	-7.5E-08	-5.3E-08	-6.7E-08	-5.9E-08	-5.3E-08	-3.7E-08	9.5E-08	1.3E-07	1.7E-07	2.1E-07	1.3E-07
Chromium (unspecified)	1.2E-06	-3.5E-06	3.8E-07	-3.1E-05	-5.3E-05	-5.8E-06	-7.0E-06	-7.3E-06	-6.6E-06	-7.0E-06	-6.0E-06	2.5E-06	3.0E-06	3.8E-06	4.6E-06	3.1E-06
Chromium +VI	2.8E-06	1.8E-05	-2.7E-06	-2.5E-05	-2.8E-05	-1.8E-05	-1.8E-05	-1.7E-05	-1.5E-05	-1.8E-05	-1.5E-05	5.2E-06	5.5E-06	5.7E-06	5.9E-06	5.7E-06
Cobalt	4.9E-10	1.1E-07	4.1E-08	8.7E-08	1.2E-07	6.5E-08	8.8E-08	6.8E-08	6.0E-08	8.8E-08	8.4E-08	9.4E-08	1.5E-07	1.9E-07	2.4E-07	2.4E-06
Copper	2.5E-06	2.0E-05	-2.4E-07	-4.0E-05	-3.1E-05	-2.5E-05	-2.4E-05	-2.4E-05	-2.1E-05	-2.4E-05	-2.1E-05	5.7E-06	6.3E-06	6.9E-06	7.6E-06	4.1E-04

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Iron	4.4E-04	5.9E-03	-2.5E-02	-1.4E-02	-2.6E-02	-1.1E-02	-6.7E-03	-6.9E-03	-6.1E-03	-6.7E-03	-5.7E-03	2.5E-03	2.9E-03	3.5E-03	4.0E-03	2.5E-03
Lead	2.2E-07	1.7E-06	3.2E-07	-3.2E-06	-1.4E-06	-1.6E-06	-1.5E-06	-1.5E-06	-1.3E-06	-1.5E-06	-1.2E-06	6.6E-07	8.3E-07	1.0E-06	1.2E-06	1.3E-04
Manganese	6.8E-06	-3.6E-05	2.8E-05	-6.3E-05	-2.5E-04	6.9E-05	8.3E-05	5.8E-05	4.9E-05	8.3E-05	7.8E-05	9.5E-05	1.5E-04	2.0E-04	2.6E-04	8.5E-06
Mercury	4.0E-11	1.7E-08	1.6E-09	1.1E-09	1.4E-09	8.6E-10	1.3E-09	1.2E-09	1.4E-09	1.3E-09	1.5E-09	3.1E-09	3.4E-09	3.8E-09	4.1E-09	3.4E-08
Molybdenum	1.3E-10	6.0E-08	1.4E-08	2.0E-08	2.7E-08	1.6E-08	2.0E-08	1.6E-08	1.5E-08	2.0E-08	2.0E-08	2.5E-08	3.6E-08	4.5E-08	5.6E-08	6.7E-07

<b>Inorganic Emissions</b>																
Aluminum	1.6E-04	-1.2E-03	1.2E-05	-3.7E-03	-9.4E-03	1.4E-04	-1.3E-04	-1.7E-04	-1.6E-04	-1.3E-04	-9.8E-05	3.1E-04	3.7E-04	4.7E-04	5.6E-04	2.1E-04
Barium	7.9E-05	-6.9E-04	-2.3E-05	-1.9E-03	-4.8E-03	3.3E-05	-1.2E-04	-1.3E-04	-1.2E-04	-1.2E-04	-1.0E-04	9.3E-05	9.2E-05	1.2E-04	1.4E-04	1.3E-04
Chlorine	8.2E-03	2.6E-03	1.0E-03	-3.2E-02	-3.7E-02	-2.7E-03	-3.2E-03	-3.0E-03	-2.0E-03	-3.2E-03	-1.9E-03	5.4E-03	4.9E-03	5.8E-03	6.1E-03	5.6E-03
Fluoride	9.7E-06	-5.6E-05	-4.1E-06	-2.1E-04	-5.0E-04	-9.1E-06	-2.4E-05	-2.4E-05	-2.2E-05	-2.4E-05	-2.0E-05	1.3E-05	1.3E-05	1.6E-05	1.4E-04	1.1E-04
Phosphorus	8.1E-06	-6.1E-05	1.2E-05	-1.5E-04	-4.2E-04	3.6E-05	3.3E-05	2.1E-05	1.7E-05	3.3E-05	3.2E-05	5.2E-05	8.1E-05	1.0E-04	1.6E-04	5.0E-02
Sulphur	9.5E-05	-6.3E-04	1.4E-05	-2.3E-03	-5.7E-03	8.1E-05	-8.7E-05	-1.1E-04	-9.7E-05	-8.7E-05	-6.8E-05	1.8E-04	2.1E-04	2.7E-04	5.9E-02	5.5E-04

<b>Organic Emissions</b>																
Carbon (unspecified)	4.7E-04	-2.0E-03	1.9E-04	-1.1E-02	-2.9E-02	3.4E-04	-5.3E-04	-6.0E-04	-5.0E-04	-5.3E-04	-4.1E-04	9.5E-04	9.8E-04	1.2E-03	8.2E-04	5.0E-02
Metaldehyde	9.5E-11	4.1E-10	-3.9E-09	-1.1E-09	-5.7E-10	-1.9E-09	-9.4E-10	-9.3E-10	-8.3E-10	-9.4E-10	-8.0E-10	-1.3E-10	-1.3E-10	2.0E-11	5.9E-02	3.2E-03
Oil (unspecified)	1.9E-02	3.1E-02	-6.5E-03	-5.6E-01	-1.5E+00	4.2E-02	-4.3E-03	-6.0E-03	-2.2E-03	-4.3E-03	1.2E-03	4.6E-02	4.1E-02	5.4E-02	6.1E-03	2.2E-04

<b>Other Emissions</b>																
Pesticides to agricultural soil	5.0E-07	5.0E-06	-2.6E-05	-6.3E-06	-4.7E-06	-1.0E-05	-5.2E-06	-5.3E-06	-4.7E-06	-5.2E-06	-4.4E-06	1.0E-06	1.4E-06	2.0E-06	5.9E-03	1.1E-06
Other pollutants	1.2E-03	-8.5E-03	4.9E-04	-2.6E-02	-6.6E-02	2.0E-03	4.5E-04	-2.3E-04	-2.8E-04	4.5E-04	5.7E-04	3.5E-03	4.9E-03	6.3E-03	2.0E-03	1.6E-03
Solid Waste	1.0E+03	4.9E+01	5.2E+01	4.9E+02	4.6E+02	4.2E+02	4.3E+02	4.6E+02	5.0E+02	4.3E+02	4.8E+02	4.9E+02	4.1E+02	4.8E+02	4.9E+02	4.8E+02

## Resource consumption, material resources, kg/tonne waste

	A - Landfill	B - Incineration	C - SRF	D - BP pyrolysis	E - Ozmotech pyrolysis	F - Redox agent	G - Stadler & Titech	H - Stadler & Pellenc	I - Stadler & Qinetiq	J - Stadler & Sims	K - KME & Titech	L - Stadler & TLT	M - Swiss Polymera	N - B+B	O - Herbold	P - Flottweg
<b>Non-renewable Elements</b>																
Aluminum	6.5E-03	1.8E-02	-7.4E-02	-1.1E-01	-7.4E-02	-8.0E-02	-7.6E-01	-6.7E-01	-6.6E-01	-7.6E-01	-6.7E-01	-3.7E+00	-4.5E+00	-3.8E+00	-3.7E+00	-3.7E+00
Chromium	5.2E-03	2.2E-02	-3.3E-03	-1.3E-01	-8.1E-02	-8.0E-02	-7.8E-02	-7.8E-02	-7.0E-02	-7.8E-02	-6.8E-02	8.2E-03	9.2E-03	1.0E-02	1.2E-02	9.2E-03
Cobalt	1.2E-07	-2.4E-05	1.7E-07	-1.8E-06	-1.0E-05	-1.4E-06	-1.7E-06	-1.9E-06	-2.1E-06	-1.7E-06	-1.9E-06	-1.7E-06	-1.3E-06	-1.6E-06	-1.7E-06	-1.7E-06
Copper	1.9E-03	1.4E-02	-2.0E-02	-9.5E-02	-6.1E-02	-5.9E-02	-5.7E-02	-5.7E-02	-5.1E-02	-5.7E-02	-5.0E-02	5.1E-03	6.0E-03	6.5E-03	7.3E-03	5.8E-03
Fluorine	2.6E-05	7.2E-04	1.4E-04	-1.1E-03	-1.6E-03	-3.3E-04	-3.5E-04	-3.6E-04	-3.1E-04	-3.5E-04	-2.9E-04	2.0E-04	2.1E-04	2.4E-04	2.5E-04	2.1E-04
Iron	3.5E-01	-3.6E-01	-2.1E+00	-2.7E+00	-3.2E+00	-1.5E+00	-1.6E+00	-1.5E+00	-1.4E+00	-1.6E+00	-1.3E+00	-1.1E-01	-1.1E-01	3.3E-02	1.6E-01	-2.3E-02
Lead	5.8E-03	5.7E-03	1.2E-04	-2.0E-02	-1.3E-02	-6.8E-03	-6.4E-03	-6.2E-03	-5.1E-03	-6.4E-03	-5.0E-03	4.1E-03	3.9E-03	4.4E-03	4.7E-03	4.3E-03
Magnesium	1.2E-08	3.1E-07	-2.1E-06	-1.0E-06	-6.0E-07	-1.9E-06	-6.2E-07	-6.4E-07	-5.8E-07	-6.2E-07	-5.4E-07	1.0E-07	1.5E-07	2.0E-07	2.6E-07	1.5E-07
Manganese	7.0E-04	3.4E-03	-8.5E-03	-1.3E-02	-9.9E-03	-9.7E-03	-7.9E-03	-7.9E-03	-7.1E-03	-7.9E-03	-6.9E-03	1.2E-03	1.3E-03	1.5E-03	1.8E-03	1.3E-03
Molybdenum	7.6E-04	3.7E-03	-9.3E-03	-1.5E-02	-1.1E-02	-1.1E-02	-9.1E-03	-9.1E-03	-8.2E-03	-9.1E-03	-7.9E-03	1.4E-03	1.5E-03	1.8E-03	2.0E-03	1.6E-03
Nickel	1.5E-02	4.7E-02	-3.8E-02	-3.3E-01	-2.2E-01	-2.0E-01	-1.9E-01	-1.9E-01	-1.7E-01	-1.9E-01	-1.7E-01	1.9E-02	2.1E-02	2.5E-02	2.9E-02	2.2E-02
Palladium	2.0E-08	2.9E-08	-5.5E-09	-8.4E-06	-1.3E-06	4.1E-08	-2.4E-09	-3.8E-09	-3.2E-10	-2.4E-09	2.6E-09	4.3E-08	3.8E-08	5.0E-08	5.4E-08	4.6E-08
Phosphorus	1.1E-04	2.9E-03	5.1E-04	-4.5E-03	-6.3E-03	-1.3E-03	-1.5E-03	-1.5E-03	-1.3E-03	-1.5E-03	-1.2E-03	7.2E-04	9.3E-04	8.8E-04	1.0E-03	9.3E-04
Platinum	6.9E-10	1.4E-09	4.1E-10	-2.6E-07	-3.9E-08	2.4E-09	1.7E-09	1.1E-09	1.1E-09	1.7E-09	1.8E-09	3.3E-09	4.5E-09	5.8E-09	7.4E-09	4.5E-09
Rhenium	2.4E-10	2.9E-10	-1.2E-11	-1.9E-08	-1.3E-08	4.4E-10	4.6E-11	3.7E-11	6.8E-11	4.6E-11	9.1E-11	4.2E-10	3.7E-10	4.8E-10	5.2E-10	4.5E-10
Rhodium	5.4E-10	8.1E-10	-1.5E-10	-2.3E-07	-3.7E-08	1.1E-09	-6.4E-11	-1.0E-10	-7.0E-12	-6.4E-11	7.4E-11	1.2E-09	1.0E-09	1.4E-09	1.5E-09	1.3E-09
Silver	5.8E-09	7.0E-08	-4.5E-08	-8.5E-08	-9.1E-08	-8.4E-08	-6.5E-08	-6.4E-08	-5.7E-08	-6.5E-08	-5.5E-08	1.6E-08	1.8E-08	1.9E-08	2.0E-08	1.8E-08
Sulphur	1.3E-04	9.1E-05	-1.4E-01	-1.1E-01	-1.1E-01	-1.1E-01	-1.5E-01	-1.4E-01	-1.2E-01	-1.5E-01	-1.3E-01	-1.4E-01	-1.7E-01	-1.4E-01	-1.4E-01	-1.4E-01
Tin	6.7E-06	5.6E-05	-7.3E-06	-2.7E-04	-1.6E-04	-1.6E-04	-1.6E-04	-1.6E-04	-1.4E-04	-1.6E-04	-1.4E-04	1.4E-05	1.5E-05	1.7E-05	1.9E-05	1.5E-05
Zinc	1.3E-03	1.4E-02	-8.8E-04	-7.4E-02	-4.5E-02	-4.4E-02	-4.3E-02	-4.3E-02	-3.9E-02	-4.3E-02	-3.8E-02	3.1E-03	3.3E-03	3.4E-03	3.6E-03	3.4E-03

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
<b>Non-renewable Resources</b>																
Antimonite	3.2E-10	8.8E-10	5.7E-11	-2.6E-09	-1.2E-09	-1.3E-09	-1.2E-09	-1.2E-09	-1.1E-09	-1.2E-09	-1.0E-09	4.8E-10	5.9E-10	7.1E-10	8.6E-10	5.8E-10
Barium sulphate	2.6E-02	-2.1E-01	1.9E-02	-6.4E-01	-1.6E+00	2.4E-02	-2.2E-02	-3.1E-02	-2.8E-02	-2.2E-02	-1.8E-02	6.0E-02	7.4E-02	9.2E-02	1.1E-01	7.4E-02
Basalt	2.3E-03	5.5E-02	-5.5E-03	-3.4E-01	-2.1E-01	-2.0E-01	-2.0E-01	-2.0E-01	-1.8E-01	-2.0E-01	-1.8E-01	1.2E-02	1.2E-02	1.3E-02	1.3E-02	1.2E-02
Bentonite	5.9E-03	-1.9E-02	-3.0E-02	-8.3E-02	-1.4E-01	-3.2E-02	-4.1E-02	-4.1E-02	-3.7E-02	-4.1E-02	-3.6E-02	-4.4E-03	-3.2E-03	3.2E-03	8.6E-03	-7.5E-04
Borax	3.1E-07	9.7E-06	-9.6E-07	-5.2E-05	-3.1E-05	-3.1E-05	-3.1E-05	-3.0E-05	-2.8E-05	-3.1E-05	-2.7E-05	2.1E-06	2.3E-06	2.5E-06	2.8E-06	2.3E-06
Chrysotile	1.7E-07	1.3E-03	2.1E-04	7.4E-05	7.4E-05	7.7E-05	7.7E-05	8.5E-05	1.0E-04	7.7E-05	9.2E-05	2.1E-04	2.0E-04	2.1E-04	2.1E-04	2.1E-04
Cinnabar	1.6E-08	1.2E-04	2.0E-05	6.9E-06	6.8E-06	7.1E-06	7.1E-06	7.9E-06	9.4E-06	7.1E-06	8.5E-06	1.9E-05	1.9E-05	2.0E-05	1.9E-05	1.9E-05
Clay	2.5E-01	2.9E+00	-3.2E-02	-7.5E+00	-4.9E+00	-4.7E+00	-4.7E+00	-4.6E+00	-4.2E+00	-4.7E+00	-4.1E+00	1.0E-01	6.4E-02	1.5E-01	2.4E-01	1.8E-01
Colemanite ore	5.5E-04	5.2E-05	-1.2E-05	1.7E-04	1.7E-04	1.8E-04	1.9E-04	2.1E-04	2.3E-04	1.9E-04	2.2E-04	2.7E-04	2.5E-04	2.8E-04	3.0E-04	2.8E-04
Diatomite	3.1E-09	8.4E-09	5.5E-10	-2.5E-08	-1.2E-08	-1.3E-08	-1.2E-08	-1.2E-08	-1.1E-08	-1.2E-08	-9.7E-09	4.6E-09	5.7E-09	6.9E-09	8.3E-09	5.6E-09
Dolomite	7.3E-04	-8.7E-04	-5.0E-03	-7.1E-03	-8.3E-03	-4.2E-03	-4.7E-03	-4.6E-03	-4.1E-03	-4.7E-03	-4.1E-03	-7.8E-04	-9.3E-04	-4.6E-04	-1.7E-04	-6.2E-04
Feldspar	1.1E-09	2.8E-09	-2.1E-08	-2.6E-05	-2.6E-05	-2.6E-05	-2.6E-05	-2.6E-05	-2.4E-05	-2.6E-05	-2.3E-05	2.4E-09	1.5E-07	3.2E-09	8.3E-08	1.3E-07
Fluorspar	7.1E-04	1.4E-02	2.0E-03	-2.0E-02	-2.8E-02	-6.1E-03	-5.5E-02	-4.8E-02	-4.8E-02	-5.5E-02	-4.8E-02	-2.7E-01	-3.3E-01	-2.8E-01	-2.7E-01	-2.7E-01
Granite	2.1E-04	1.1E-05	1.5E-06	1.5E-05	3.6E-05	3.9E-05	-4.5E-02	-3.9E-02	-4.0E-02	-4.5E-02	-4.0E-02	-2.6E-01	-3.2E-01	-2.7E-01	-2.6E-01	-2.7E-01
Gypsum	7.1E-06	1.0E-04	-5.3E-04	-2.1E-03	-1.9E-03	-1.9E-03	-6.7E-03	-6.2E-03	-5.6E-03	-6.7E-03	-5.9E-03	-4.7E-03	-5.8E-03	-4.9E-03	-4.7E-03	-4.8E-03
Kaolinite	6.0E-05	2.8E-04	-5.0E-03	-6.3E-04	-2.2E-04	-9.4E-04	-2.6E-04	-3.2E-04	-2.9E-04	-2.6E-04	-2.1E-04	3.0E-04	4.6E-04	5.7E-04	7.4E-04	4.2E-04
Kieserite	1.2E-06	2.3E-06	-1.2E-05	-5.3E-06	-2.0E-06	-4.0E-06	-2.2E-06	-2.4E-06	-2.0E-06	-2.2E-06	-1.7E-06	1.8E-06	2.4E-06	3.0E-06	3.7E-06	2.4E-06
Limestone	6.7E-01	2.3E+01	-2.3E+01	2.4E+01	-2.4E+00	-1.8E+00	-1.8E+00	-1.6E+00	-9.9E-01	-1.8E+00	-1.1E+00	2.7E+00	2.7E+00	3.3E+00	3.7E+00	3.0E+00
Magnesium carbonate	4.9E-03	-2.7E-03	-2.9E-02	-3.8E-02	-4.3E-02	-2.2E-02	-1.6E-02	-1.6E-02	-1.4E-02	-1.6E-02	-1.3E-02	4.7E-03	6.4E-03	6.9E-03	8.6E-03	6.3E-03
Natural Aggregate	1.9E+02	2.6E+01	-2.5E+01	5.1E+01	5.4E+01	5.2E+01	6.4E+01	7.0E+01	7.9E+01	6.4E+01	7.5E+01	9.2E+01	7.9E+01	9.2E+01	9.7E+01	9.3E+01
Olivine	4.7E-07	3.8E-07	-1.3E-04	-4.6E-04	-4.6E-04	-4.6E-04	-8.3E-04	-7.8E-04	-7.1E-04	-8.3E-04	-7.3E-04	-5.2E-04	-6.3E-04	-5.3E-04	-5.2E-04	-5.2E-04
Peat	1.1E-04	-3.1E-04	-1.6E-02	-1.5E-02	-1.4E-02	-1.4E-02	-7.4E-01	-6.7E-01	-5.9E-01	-7.4E-01	-6.5E-01	-1.1E-01	-1.4E-01	-1.2E-01	-1.1E-01	-1.2E-01
Rutile	3.4E-10	2.6E-09	1.5E-09	-2.6E-05	-2.6E-05	-2.6E-05	-2.6E-05	-2.6E-05	-2.4E-05	-2.6E-05	-2.3E-05	4.0E-10	3.5E-10	5.2E-10	6.1E-10	4.6E-10
Sand	5.6E-05	7.5E-05	-8.6E-02	-7.5E-02	-7.5E-02	-7.5E-02	-1.2E-01	-1.1E-01	-9.7E-02	-1.2E-01	-1.1E-01	-6.4E-02	-7.9E-02	-6.6E-02	-6.4E-02	-6.5E-02
Slate	2.8E-06	3.0E-06	-9.1E-04	-4.1E-03	-4.1E-03	-4.1E-03	-6.6E-03	-6.3E-03	-5.7E-03	-6.6E-03	-5.8E-03	-3.0E-03	-3.7E-03	-3.1E-03	-3.0E-03	-3.1E-03
Sodium chloride	3.4E-02	4.5E+01	-5.4E+01	-4.7E+01	-4.7E+01	-4.7E+01	-5.0E+01	-4.6E+01	-3.9E+01	-5.0E+01	-4.3E+01	-7.0E+00	-1.0E+01	-7.2E+00	-6.9E+00	-7.3E+00
Sodium sulphate	1.4E-04	4.2E-03	8.9E-04	-6.5E-03	-9.1E-03	-1.8E-03	-2.0E-03	-2.0E-03	-1.7E-03	-2.0E-03	-1.7E-03	1.1E-03	1.2E-03	1.3E-03	1.4E-03	1.2E-03
Sylvite	7.5E-05	6.7E-04	-7.6E-01	-6.2E-01	-6.2E-01	-6.2E-01	-6.2E-01	-5.7E-01	-4.9E-01	-6.2E-01	-5.4E-01	-3.0E-04	-3.9E-04	-2.9E-04	-2.6E-04	-2.9E-04
Talc	2.1E-06	1.7E-04	-5.1E-04	-3.7E-05	-1.1E-05	-8.7E-05	-1.5E-05	-1.9E-05	-1.5E-05	-1.5E-05	-8.4E-06	4.8E-05	8.8E-05	7.4E-05	1.0E-04	8.2E-05
Titanium dioxide	6.2E-04	3.1E-02	-1.5E-01	-1.1E-02	-1.4E-02	-2.1E-03	-2.7E-03	-3.0E-03	-2.3E-03	-2.7E-03	-1.6E-03	5.6E-03	6.7E-03	8.7E-03	1.1E-02	6.9E-03
Ulexite	1.4E-07	6.0E-06	-2.5E-06	-3.7E-06	-3.2E-06	-4.6E-06	-2.2E-06	-3.0E-06	-2.7E-06	-2.2E-06	-1.7E-06	3.9E-06	5.9E-06	7.3E-06	9.4E-06	5.4E-06
Vermiculite	2.8E-06	1.0E-06	-8.8E-05	1.0E-04	-3.0E-05	-8.2E-05	-2.9E-05	-3.0E-05	-2.7E-05	-2.9E-05	-2.6E-05	7.6E-06	5.7E-04	1.1E-05	3.2E-04	5.1E-04

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
<b>Renewable Resources</b>																
Water	4.3E+02	1.2E+03	-9.5E+04	-1.4E+04	-1.1E+04	-1.2E+04	-2.9E+04	-2.8E+04	-2.5E+04	-2.9E+04	-2.6E+04	-2.0E+04	-1.9E+04	-1.7E+04	-1.2E+04	-1.5E+04

### Resource consumption, energy resources, kg/tonne waste

	A - Landfill	B - Incineration	C - SRF	D - BP pyrolysis	E - Ozmotech pyrolysis	F - Redox agent	G - Stadler & Titech	H - Stadler & Pellenc	I - Stadler & Qinetiq	J - Stadler & Sims	K - KME & Titech	L - Stadler & TLT	M - Swiss Polymera	N - B+B	O - Herbold	P - Flottweg
<b>Non-renewable Energy Resources</b>																
Crude oil	7.9E+00	8.6E+00	-3.2E+01	-3.5E+02	-3.8E+02	-5.7E+01	-3.9E+02	-3.6E+02	-3.2E+02	-3.9E+02	-3.5E+02	-4.6E+02	-5.6E+02	-4.7E+02	-4.5E+02	-4.6E+02
Hard coal	5.8E-01	9.7E+00	-1.5E+03	1.2E+01	2.4E+01	-8.3E+02	-7.4E+00	-1.2E+01	-1.2E+01	-7.4E+00	-4.8E+00	-7.8E+00	3.6E+00	2.5E+01	4.7E+01	6.7E+00
Lignite	4.0E-01	1.7E+01	-1.4E+01	-2.4E+01	-2.5E+01	-2.4E+01	-2.0E+01	-2.0E+01	-1.8E+01	-2.0E+01	-1.8E+01	5.2E-01	2.5E-01	9.8E-01	1.4E+00	8.4E-01
Natural gas	7.5E-01	-2.8E+02	-5.0E+01	-1.3E+02	-1.2E+02	-1.3E+02	-3.0E+02	-2.9E+02	-2.6E+02	-3.0E+02	-2.7E+02	-2.0E+02	-2.3E+02	-2.0E+02	-1.8E+02	-2.0E+02
Uranium	5.7E-05	8.9E-04	-3.2E-03	-2.4E-03	-2.1E-03	-2.7E-03	-4.2E-03	-4.1E-03	-3.7E-03	-4.2E-03	-3.7E-03	-2.9E-03	-3.2E-03	-2.0E-03	-1.3E-03	-2.5E-03

<b>Renewable Energy Resources</b>																
Wood	2.8E-06	1.7E-05	-1.9E-03	-1.7E-03	-1.7E-03	-1.7E-03	-2.3E-03	-2.1E-03	-1.9E-03	-2.3E-03	-2.0E-03	-9.7E-04	-1.2E-03	-1.0E-03	-9.7E-04	-9.9E-04

# Appendix 4 Assumptions & Uncertainty

The main assumptions made in the study and their likely effect on uncertainty in the results are described below

## ■ Feedstock composition

As discussed in detail in Section 3.6.2, there is a very wide variation in the composition of the feedstock material leaving the MRF. As different technologies recover polymer types from the waste stream with varying efficiency this will potentially have a large effect on the overall results. Because of the importance of the feedstock composition it has been assessed in more detail in the sensitivity analyses in Section 6.1.

## ■ Quantities of black plastic

As discussed in Section 3.6.2, NIR technologies often have difficulty detecting black plastic and it is assumed that this is correctly sorted only 50% of the time. Typically, black plastic accounts for about 10% of the total but may vary significantly as for the feedstock composition in general. This will add some uncertainty to the results for scenarios using NIR technology. If the quantity of black plastic doubles from the default 10% to 20%, it is likely that there will be an accompanying reduction in recycling efficiency of 5%. As such, given likely variations in black plastic composition, the results are not considered to be particularly sensitive to this assumption.

## ■ Incinerator efficiency

The efficiency of electricity recovery at municipal incinerators can vary. The published literature gives a range of between 15 – 30%, with 23% being a typical value for a modern incinerator. This is potentially quite significant for the incineration scenario and so has been included in the sensitivity analyses in Section 6.2.

## ■ Basis for substitution of electricity production from incineration

In line with UK Government best practise guidelines the default assumption is that electricity generated at municipal incineration facilities displace that produced by a combined cycle gas turbine power plant. However, this is a relatively clean technology and so incineration will appear less favourable than if a dirtier technology is assumed to be displaced. The effects of this assumption have been assessed in the sensitivity analysis in Section 6.4, by comparing against coal power electricity generation and electricity sourced from the UK grid.

## ■ Basis for substitution of recycled plastic/effect of impurities on recyclate quality

The effect of impurities affecting the quality of the recyclate has not been considered in detail. The default assumption in this study is that recycled plastic obtained from the recycling processes is of high quality and substitutes directly for virgin plastic on a 1:1 basis. If a lower quality recyclate is produced it is likely that this will have a large effect on the results by significantly reducing the benefits accrued from recycling. The effects of this assumption have been assessed in more detail in the sensitivity analysis in Section 6.3.

## ■ Basis for substitution of redox agent in the blast furnace

Blast furnace chemistry is extremely complicated and so the basis for the determining the amount of alternative redox agent includes a number of assumptions and simplifications as described in Section 3.9. However this figure was developed after consulting with Corus experts and it is felt that it represents a good estimate for the situation in UK blast furnaces.

## ■ Power supplied using average UK average electricity mix

In all cases this is the most likely source of power for running the processes.

#### ■ Maturity of technology – use of pilot plants and test rigs

Several of the technologies assessed in this study are currently only operating at pilot plant scale, or as test rigs for demonstrating the technology. It is expected that full size plants will more efficient due to benefits of scale and process optimisation and that these differences could be quite significant depending on the maturity of the technology. The technology providers were asked to estimate the performance (energy consumption, etc.) of a full-size plant but in many cases this information was not available.

#### ■ Quality of data on pyrolysis technologies

Available data on pyrolysis in the published literature is poor. The BP process has been further developed with significant efficiency gains since the available data were published but this process is no longer current and will not be resurrected. As such, the results from the LCA model cannot be taken to represent the best performance available from modern pyrolysis plants. Likewise only basic data on the Ozmotech process are available and the details have been based on discussions with Bowman Process Technologies. The uncertainties associated with both these processes are considered to be quite large.

#### ■ Secondary (background) data

The secondary data used in this study and its relevance to the UK situation is described in Appendix 2. In most cases European average data have been used. In some cases, such as for landfill and incineration, data for the Swiss situation have been used – in these cases it is expected that practices in the UK would be similar to those in Switzerland. Data sourced from the Ecoinvent database often includes impacts associated with infrastructure (buildings, capital equipment, etc.) which are considered outside the scope of this assessment. This will lead to some overestimation of impacts from these process (or benefits if they are “avoided” processes) but for the processes used in this study this is invariably very small compared to impacts of the main process because the throughput is so great over the lifetime of the infrastructure.

#### ■ Transport modes and distances

Transport distances for different scenarios are discussed in Section 3.6.4. These are assumptions of typical transport distances in the UK. However, for any particular location in the UK the actual distances could vary significantly. It is also assumed that all transport in the scenarios uses 32 tonne (gross weight) lorries with a full outward load and an empty return trip. Clearly these assumptions could also vary significantly in practise. However, in the context of the overall results, impacts from transport are generally small and it is not expected that this would affect the overall results.

#### ■ Disposal options for non-recycled stream are either landfill or incineration

It is assumed that all waste that is not recycled is sent for landfill or incineration (according to the UK mix for these options). As this waste has no value and would not be sent for recycling elsewhere it is expected that this assumption is closely representative of the actual UK situation.

#### ■ Incineration all has electricity recovery and no heat recovery

This assumption is discussed in Section 3.6.3, and is broadly correct for the UK situation.

## Appendix 5 Peer Review

**FINAL**

Peer review of the report:

LCA of Management Options for  
Mixed Waste Plastics, Final Draft  
Report, dated April 2008

For WRAP

Mike Holland, EMRC

Ian Boustead, Boustead Consulting

Bernie Thomas, ERM

## Introduction

The study concerning LCA of mixed waste plastics has been commissioned by WRAP to identify whether waste plastic recycling has the potential to deliver significant environmental benefits over existing waste management options. The authors of the report state that the work will inform WRAP's strategic planning process and determine whether this should be a priority area for further work. It is expected that recyclers and other stakeholders will also find the study useful in shaping their decisions regarding technology options for managing domestic mixed plastic waste.

This paper brings together the comments of the peer reviewers, the peer review team being made up of the following (in alphabetical order):

- Ian Boustead, Boustead Consulting.
- Mike Holland, EMRC.
- Bernie Thomas, ERM.

These comments relate to the report 'LCA of Management Options for Mixed Waste Plastics', Final Draft dated April 2008. They do not relate to any subsequent version of the report. Selective quotations from the peer review should be avoided.

WRAP may require that the reports issued under the study are revised to reflect the comments made here. Should this be done it is suggested that an additional appendix is provided to show how the authors have responded to the peer review. Comments have been given unique numbers in the summary (a to n) and then running through the series of reviews (1 to 54) to facilitate this.

**Summary statement on the peer review of the study:  
LCA of Management Options for Mixed Waste Plastics  
Final Draft Report, April 2008  
Produced by Scott Wilson for WRAP**

This is an agreed summary by a panel of three independent experts, performed on the draft final LCA report, dated April 2008. Full reviews by each peer reviewer have also been submitted to WRAP.

The scope of the overall project, involving trials of various near-infra red and density separation technologies for plastics separation to generate good quality recyclate is to be commended, and the work commissioned by WRAP has the potential to make a significant contribution to knowledge in this field.

The three peer reviewers identified a number of areas where the LCA report should be improved. Whilst some of these improvements were relatively minor others were not and require a significant level of action or reworking to ensure that the project fulfils its potential. It should be noted that further peer review of the final version of the report has not been performed, and so the review team cannot take a position on the extent to which subsequent changes resolve the issues raised in their review of the earlier draft report.

**Overview of comments on methodology**

- a) There is a need for a systematic presentation of input data. As part of this there needs to be discussion of how the results of the trials performed in the broader study have been factored into the analysis. This should say how the differing levels of maturity for the different technologies has been addressed. Similarly, there is a need for more information on the GABI software used.

There then needs to be consideration of the relevance of the input data to plastics recycling in the UK. Lack of information in these areas in the draft report prevents the peer review reaching a conclusion on the validity of the analysis.

- b) Clarity is needed on the treatment of energy through the analysis. In particular, it is not clear whether there is consistent and correct use of gross and net calorific values, and whether process and feedstock energy are treated appropriately.
- c) Some of the assumptions on the efficiency of incineration with energy recovery are pessimistic – particularly the lower end of the efficiency range (15%) and the fact that no account is taken of heat recovery.
- d) There is a need for a comprehensive presentation of assumptions with a similarly comprehensive review of uncertainties. At the end of the analysis this would permit a much more detailed discussion of the robustness of the results than is currently the case.
- e) A commentary is needed on system boundary limitations.

**Overview of comments on results**

- f) There is a tendency to present results without referring to their uncertainty. The clearest example is the graph that appears to show that once virgin polymer substitution falls below 70% other waste management options become preferable. The reviewers agree that this is an important part of the analysis as it shows the trade-offs that exist between options. However, as presented it implies that the 70% figure is something of a golden rule. It is recommended to either put confidence bands around the lines or to provide a detailed discussion of the robustness of these results. Also, to make clear that (as presented) they refer to a specific comparison of one recycling scenario with the use of waste plastics as fuel at cement kilns (see also comment (i)).
- g) Consideration should be given to the effect of uncertainties in combination. The draft final report only considers a selection of sensitivity cases in isolation of each other. Whilst we acknowledge that there is tendency for uncertainties to cancel each other out, there is also potential for some of the key sensitivities identified in the report to operate additively.

### Overview of comments on discussion

- h) There is only limited information given on the meaning of the impact indicators assessed in the report. More information is needed particularly where the potential impact described by the indicators may be exaggerated as a result of legislation to limit damage or site specific factors.
- i) The report gives the impression that UK cement kilns and blast furnaces would be able to take large volumes of plastic waste. However, these facilities have finite capacity and are already burning very significant quantities of waste (shredded tyres, secondary liquid fuels, etc.). It may therefore be the case that they are unable to take any significant fraction of mixed plastic waste. This should be acknowledged. WRAP could consider undertaking further work to assess which wastes are best disposed of through cement kilns and blast furnaces.
- j) A major factor in assessing the benefits of plastic recycling (as indeed shown by the report) concerns the quality of recyclate. An issue that needs discussion in the report concerns whether increased recycling rates would lead to increased contamination, and over time a reduction in the capacity of recyclate to substitute for virgin polymer.
- k) Technologies, plastics arisings, etc. will evolve over time. This should be acknowledged in the discussion to provide WRAP with a view on the types of change that could affect the robustness of the conclusions of the report.
- l) Consideration needs to be given to the comparability of results for different technologies at different levels of maturity. Also, whether lessons been learned about the pros and cons of the technologies considered, and the relative merits of NIR- and density-separation methods, that could provide useful input for future development and refinement.
- m) Results need to be discussed against the broader context set by the wider literature on plastics recycling.
- n) Finally, there needs to be discussion of the robustness of the results. Do any of the recycling scenarios appear significantly better or worse than an average for the recycling scenarios? How robust are the apparent advantages of recycling relative to incineration and landfill?

The full text of the peer review provides a great deal more detail on these comments. Revision of the report by its authors should consider the additional information presented there also.

Mike Holland, EMRC  
Ian Boustead, Boustead Consulting  
Bernie Thomas, ERM

May 2008

## Response to peer review comments

### Overview of comments on methodology

- a) Input data from each technology trial is now presented in Appendix 1 and background data is presented in Appendix 2. Uncertainties associated with issues such as maturity of the technology are discussed with other uncertainties and assumptions in Appendix 4. Further information on GaBi Software is provided in Section 3.7. The relevance of the input data to plastics recycling in the UK is discussed in more detail in the main report.
- b) Energy is reported as the gross calorific value, this has now been made explicit in the report. Net calorific values have only been used to assess energy recovery from incinerators where energy from steam derived from water in the fuel is not recovered. The treatment of process and feedstock energy has also been clarified.
- c) The range of incinerator efficiencies was derived from a review of the literature. However it is recognised that the lower end of the range this is not representative of current technology but relates to older plants. The sensitivity analysis of this aspect has been adjusted accordingly.
- d) Assumptions and uncertainties are discussed in Appendix 4.
- e) Section 3.4 has been revised to emphasise that the study boundaries do not include the mixed waste plastic collection stage and that the results are only relevant to material sourced from MRFs.

### Overview of comments on results

- f) More comment has been added on uncertainties in the impact assessment categories and with relation to charts including Figure 6.4.2, on sensitivity of the results to the degree of virgin polymer substitution. The chart itself has been modified to emphasise the uncertainty in this assessment. Additional explanation has also been added to explain that this result only considers 2 scenarios and that comparing other scenarios would lead to different results.
- g) Assessment of uncertainties in combination has been added in Section 6.5

### Overview of comments on discussion

- h) Further discussion is provided on the impact indicators and their relevance and robustness.
- i) The finite capacity of UK kilns and cement plants to accept waste plastics is now noted explicitly in the text. The author agrees with the reviewers comments that WRAP could consider undertaking further work to assess which wastes are best disposed of through cement kilns and blast furnaces
- j) A discussion on the effects of impurities and degradation of the quality of the recyclate over many recycling steps is included in Section 3.9
- k) Consideration of future changes to recycling technologies, plastics arisings, etc. is now included in the discussion.
- l) More consideration has also been given in the discussion on the relative merits of NIR- and density-separation methods. Appendix 4 discussed the relevance of comparing technologies at different levels of maturity and their effect on the robustness of the results.
- m) The main report has more discussion on the results of the project in the context set by the wider literature on plastics recycling.
- n) The robustness of the results are considered in detail in Appendix 4 and in sensitivity analyses in Section 6. The discussion on combined uncertainties highlights those factors that are most important when considering whether recycling scenarios have better environmental performance than incineration and landfill.

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