Bank of England

LCA of Management Options for Polymer Waste from Bank Notes

Final Study Report

15/01/2015

PE INTERNATIONAL

On behalf of PE INTERNATIONAL AG and its subsidiaries

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ACRONYMS

ADP	Abiotic Depletion Potential
AP	Acidification Potential
BOPP	Bi-axially Oriented Polypropylene
C&I	Commercial and Industrial
CML	Centre of Environmental Science at Leiden
CHP	Combined heat and power
EfW	Energy from waste
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
ERF	Energy Recovery Facility
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MSW	Municipal Solid Waste
NCV	Net Calorific Value
PE	PE INTERNATIONAL
POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
VOC	Volatile Organic Compound

Glossary (ISO 14040/44:2006)

ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, International Organization for Standardization (ISO), Geneva.

Allocation

Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

Functional Unit

Quantified performance of a product system for use as a reference unit.

Closed loop & open loop allocation

A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.

An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

Cradle to grave

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of life.

Cradle to gate

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of the production process ("gate of the factory"). It may also include transportation until use phase.

Life cycle

A unit operation's view of consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. This includes all materials and energy input as well as waste generated to air, land and water.

Life Cycle Assessment - LCA

Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life Cycle Inventory - LCI

Phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life Cycle Impact assessment - LCIA

Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life Cycle Interpretation

Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Printing Waste

Waste arising during the banknote printing process carried out by the Bank of England. Such waste could include offcuts, notes from test runs or whole bank notes that are deemed unsuitable for circulation.

Reference flow

Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.

Unfit

Banknotes assessed as no longer being fit for recirculation and sent for disposal.

CRITICAL REVIEW STATEMENT

Background

The study "LCA of Management Options for Polymer Waste from Bank Notes" was commissioned by the Bank of England and carried out by PE International. The study was critically reviewed by a panel of experts comprising:

- Professor Adisa Azapagic (Panel Chair);
- Stuart Foster; and
- Keith James.

The aim of the review was to ensure that:

- the methods used to carry out the LCA study are consistent with the ISO 14040:2006 and 14044:2006 standards;
- the methods used are scientifically and technically valid given the goal of the study;
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretation of the results and the conclusions of the study reflect the goal and the findings of the study; and
- the study report is transparent and consistent.

The critical-review process involved the following steps and activities:

- a review of the Goal and Scope Definition at the outset of the project;
- a review of the draft report and recommendations for improvements to the study and the report;
- a review of the subsequent final study report, in which the authors of the study fully addressed the points as suggested in the draft critical review; and
- the final critical review report (this review statement).

The critical review panel did not view or review the GaBi LCA models created for this project or the parameterised "interactive report" so that all the findings of the critical review are based solely on the LCA report.

Conclusion of the critical review

The panel confirms that this LCA study follows the guidance of and is consistent with the international standards for Life Cycle Assessment (ISO 14040:2006 and 14044:2006).

Professor Adisa Azapagic (Panel Chair) — Stuart Foster — Keith James

January 2015

EXECUTIVE SUMMARY

The Bank of England is the central bank of the United Kingdom and operates with a mission to "promote the good of the people of the United Kingdom by maintaining monetary and financial stability". Alongside its roles in monetary policy and financial regulation the Bank of England is responsible for issuing banknotes and, following a public consultation, has recently taken the decision to introduce polymer bank notes for £5 and £10 denominations in 2016 and 2017 respectively.

Having taken the decision to switch to polymer bank notes the Bank of England has commissioned PE INTERNATIONAL to undertake a detailed assessment of the disposal options for bank note waste. The aim of this study is to identify the most appropriate waste treatment option and suitable waste contractors to handle the waste, and to ensure that the selected option is reliable and viable over the long-term. These various project goals are addressed in a series of work packages.

This current document relates to work package 2 - the life cycle assessment of waste treatment options. The goal is to assess the environmental performance of each waste management technology and determine the most favourable option. The expected audience for the study will, initially, be internal to the Bank of England. However, the final report, or selected results taken from the study, may be reported more widely to external stakeholders or the general public.

This study is a gate to grave life cycle assessment considering impacts across those life cycle stages following the shredding/granulation of the waste bank note material by the Bank through to final recovery of energy/material and disposal of residual waste. The waste treatment options that are considered in this study are mechanical recycling, recovery of energy from waste (both electricity only and combined heat and power), production of fuel by pyrolysis and disposal of waste to landfill.

The functional unit chosen for the assessment is:

"The treatment of 1 tonne of bank note waste after shredding/granulation by the Bank of England"

Four waste streams with polymer/paper waste ratios of 100%:0%, 75%:25%, 50%:50% and 25%:75% are considered in this study. The 100% polymer waste is the only stream for which all five waste management options assessed in this study are considered viable. It is also the preferred option specified by most waste management contractors. Mixed waste streams have been included to allow the Bank of England to assess the environmental impacts should they decide not to separate the banknote waste.

The following life cycle inventory indicators have been considered: primary energy demand (total, renewable and non-renewable) and freshwater consumption. In addition to these, the following impact categories have been assessed: abiotic depletion potential (elements), acidification, ecotoxicity, eutrophication, global warming, human toxicity (both cancer and non-cancer) and photochemical ozone creation potentials.

The results of the assessment for seven LCI and LCIA indicators are summarised in Table 0-1.

- Mechanical recycling has the lowest impacts for all seven of the categories assessed.
- CHP also has a good environmental performance with the second lowest impacts for five of the seven categories assessed. However, this option has the second highest value for water consumption and the third highest global warming potential.
- Pyrolysis performs relatively poorly compared to mechanical recycling and energy recovery.

- Landfill is generally the worst waste management option overall with the highest impacts in four of the seven categories. However, it has relatively good performance in terms of global warming potential and freshwater consumption where it is ranked second, behind mechanical recycling.

Table 0-1: Summary of results for five waste management options for 100% polymer note waste (results expressed per tonne of waste treated)

	Mechanical recycling	Energy Recovery (electricity)	Energy Recovery (CHP)	Pyrolysis	Landfill
Global Warming Potential (kg CO_2 equiv.)	-1.40	1.40	0.43	0.87	0.08
Acidification Potential (g SO_2 equiv.)	-4.67	-2.89	-3.38	0.58	0.27
Eutrophication Potential (g PO_4 equiv.)	-0.29	-0.20	-0.29	0.15	0.28
Photochemical Ozone Creation Potential (g Ethene equiv.)	-0.94	-0.18	-0.25	-0.09	0.01
Abiotic Depletion Potential – Elements (kg Sb equiv.)	-4.09×10^{-7}	4.90×10^{-9}	-7.10×10^{-9}	-1.70×10^{-9}	1.44×10^{-8}
Primary Energy Demand - Total (MJ)	-59.89	-15.40	-31.62	-16.01	1.29
Freshwater Consumption (l)	-7.83	1.99	1.93	0.89	-0.96

KEY: Best performing options — Worst performing options

Following feedback from contractors, recycling was not assessed for a mixed waste stream as it was deemed commercially unviable at the current time to separate the paper and polymer fractions after shredding to enable reprocessing. Solutions for separation do exist, which could be used to separate the shredded waste fractions should this become more commercially viable in the future. Pyrolysis was also not assessed for mixed streams as the plant on which the pyrolysis model was based is designed for a plastic-only waste stream. For the mixed paper/polymer waste streams, energy recovery at a CHP plant generally has the lowest impacts of the three remaining management options, with landfill having the highest.

More detailed breakdowns of the results for the polymer waste stream showed that for most impact categories pyrolysis has the highest impacts driven primarily by the relatively high consumption of natural gas, the combustion of off-gas to provide additional thermal energy to the process and the consumption of electricity. Mechanical recycling has higher emissions from processing than energy recovery as some electricity is required for degassing (removing the volatile ink fractions) and transforming the waste polymer into granulate. The low sulphur, nitrogen and phosphorous content of the waste means that emissions related to acidification and eutrophication are low for energy recovery facilities (ERFs). However, the global warming potential of energy recovery is high due to the high carbon content of the polymer waste.

The overall impacts from transport of waste to the waste management site were generally relatively low. For the acidification and eutrophication potentials as well as primary energy from non-renewable resources the impact of transportation is typically 10-20% of the impact of waste processing (i.e.

excluding credit). For other impact categories the contribution from transport is negligible. In general, transport represented a larger proportion of the impact for energy recovery and landfill, as these management routes had lower processing impacts for most impact categories.

Sensitivity analyses were performed to test the robustness of the results towards uncertainty and key assumptions. The first sensitivity analysis focused on applying a value correction factor to the credit for avoided production of virgin polypropylene granulate through mechanical recycling to reflect the lower quality of the recyclate. Compared the baseline assumption of a 1:1 substitution this reduced the credit received by over 50%. As a result, mechanical recycling was no longer the top-ranked treatment process for acidification potential, eutrophication potential, or primary energy demand, although it remained the best performer in the other four impact categories and may still be regarded as the best available option.

The second sensitivity analysis focused on the efficiency of the ERF. An efficiency range of 15%-30% was applied within the ERF models. This analysis showed that energy recovery results are indeed quite sensitive to the efficiency of the ERF. An ERF with an electrical efficiency of 15% was not found to perform favourably compared to mechanical recycling in the seven LCI and LCIA categories assessed, even where heat recovery is implemented. Conversely, a CHP recovery plant with a an electrical efficiency of 30% compares favourably with mechanical recycling, although even in this best-case scenario, mechanical recycling still has lower impacts in four of the seven impact categories assessed.

In summary, for a 100% polymer waste stream, mechanical recycling has the lowest impacts for all seven impact categories considered. Energy recovery via CHP has the second lowest impacts for five of the seven categories assessed: acidification potential, eutrophication potential, photochemical ozone creation potential, abiotic depletion potential and primary energy demand, but also has the second highest water consumption and the third highest global warming potential. However, for mixed paper/polymer waste streams, CHP performs better, being the best option for six of the seven impacts, freshwater consumption being the exception where landfill has the lowest impacts.

Overall recommendations from the study are:

- Recycling of the polymer bank note should be prioritised as this is the waste management route with the lowest environmental impacts for all seven impact categories assessed.

- Paper and polymer waste streams should be separated to ensure that the polymer can be reprocessed into good quality granulate suitable for applications such as injection moulding. This is also desired by waste management contractors regardless of the waste management route as it provides a more consistent material for treatment.

- If energy recovery is to be considered, recovery at CHP plants should be strongly prioritised over recovery of electricity only.

1 GOAL OF THE STUDY

The Bank of England is the central bank of the United Kingdom and operates with a mission to "*promote the good of the people of the United Kingdom by maintaining monetary and financial stability".* Alongside its roles in monetary policy and financial regulation the Bank of England is responsible for issuing banknotes and, following a public consultation, has recently taken the decision to introduce polymer bank notes for £5 and £10 denominations in 2016 and 2017 respectively.

This decision was supported by a previous study conducted by PE INTERNATIONAL for the Bank of England that assessed the life cycle environmental impacts associated with bank notes based on two different substrates: cotton-paper and bi-axially oriented polypropylene (BOPP) (hereafter referred to as "paper" and "polymer" respectively). This study looked at the impacts associated with manufacturing, distributing and disposing of UK bank notes and the baseline assumption was the polymer notes would be incinerated with energy recovery at end of life. A sensitivity analysis was undertaken to assess the impacts on the results of mechanically recycling the waste bank notes as an alternative to energy recovery.

Having taken the decision to switch to polymer for the £5 and £10 denominations, the Bank of England has commissioned PE INTERNATIONAL to undertake a more detailed assessment of the disposal options for bank note waste. The aim of this study is to identify the most appropriate waste treatment option and suitable waste contractors to handle the waste, and to ensure that the selected option is cost-effective, reliable and viable over the long-term.

PE International is undertaking five work packages for the Bank of England, comprising:

1. Identification of contractors for waste management options;
2. Life cycle assessment (LCA) of waste treatment options;
3. Assessment of the market for recycled/recovered material;
4. Additional requirements relevant to waste treatment (e.g. waste specification criteria);
5. Selection of preferred technologies.

This document covers work package 2 – life cycle assessment of waste treatment options. The goal is to assess the environmental performance of each waste management technology and determine the most favourable option. Specifically, the Bank of England is aiming to:

- Evaluate the environmental impacts associated with the end-of-life waste management options identified for polymer banknote waste;
- Assess the differences in impact between single material waste streams (polymer only) and co-mingled streams of polymer and paper. Three co-mingled ratios (75%:25%, 50%:50% and 25%:75%) have been evaluated as part of the analysis[1];

[1] These ratios were suggested by the Bank of England as representative of co-mingled mixes at different times – the ratio of polymer to paper will increase over time as printing waste becomes supplemented with increasing quantities of post-circulation notes)

- Identify the optimal waste management option in terms of environmental performance.

The expected audience for the study will, initially, be internal to the Bank of England. However, the final report, or selected results taken from the study, may be reported more widely to external stakeholders or the general public.

Since the study results are intended to support comparative assertions that may be disclosed to the public an ISO 14040/44 conformant LCA report has been prepared that has undergone critical review by a panel of independent experts.

2 SCOPE OF THE STUDY

This chapter describes the general scope of the project to achieve the stated goals. This includes the identification of the products and processes to be assessed and their functions, the boundary of the study, allocation procedures, cut-off criteria and data quality aspects.

2.1 PRODUCT SYSTEMS TO BE STUDIED

This study assesses the environmental impacts associated with waste management of both single material polymer banknote waste streams and co-mingled paper/polymer waste streams generated by the Bank of England during the banknote printing process and as a result of returned notes being deemed unfit for recirculation.

2.2 PRODUCT FUNCTION, FUNCTIONAL UNIT AND REFERENCE FLOW

This 'gate to grave' LCA study is focused exclusively on the waste treatment processes at the end of life of bank notes. The functional unit chosen for the assessment is:

"The treatment of 1 tonne of bank note waste after shredding/granulation by the Bank of England"

The corresponding reference flows will vary according to the waste mix as follows:

- [Polymer/paper ratio = 100%:0%]; reference flow = 1 t paper;
- [Polymer/paper ratio = 75%:25%]; reference flow = 0.75 t polymer, 0.25 t paper;
- [Polymer/paper ratio = 50%:50%]; reference flow = 0.5 t polymer, 0.5 t paper;
- [Polymer/paper ratio = 25%:75%]; reference flow = 0.25 t polymer, 0.75 t paper.

2.3 SYSTEM BOUNDARIES

This study is a 'gate to grave' life cycle assessment considering impacts across those life cycle stages following the shredding/granulation of the waste bank note material by the Bank through to final recovery of energy/material and disposal of residual waste. The waste treatment technologies that are considered in this study are:

- Mechanical recycling: open-loop only (i.e. the recycled plastic will not be used to make new bank notes, but will be used in other applications);
- Recovery of energy from waste: electricity only and combined heat and power (CHP);
- Pyrolysis; and
- Landfill.

The system boundaries are described in Figure 2-1 below.

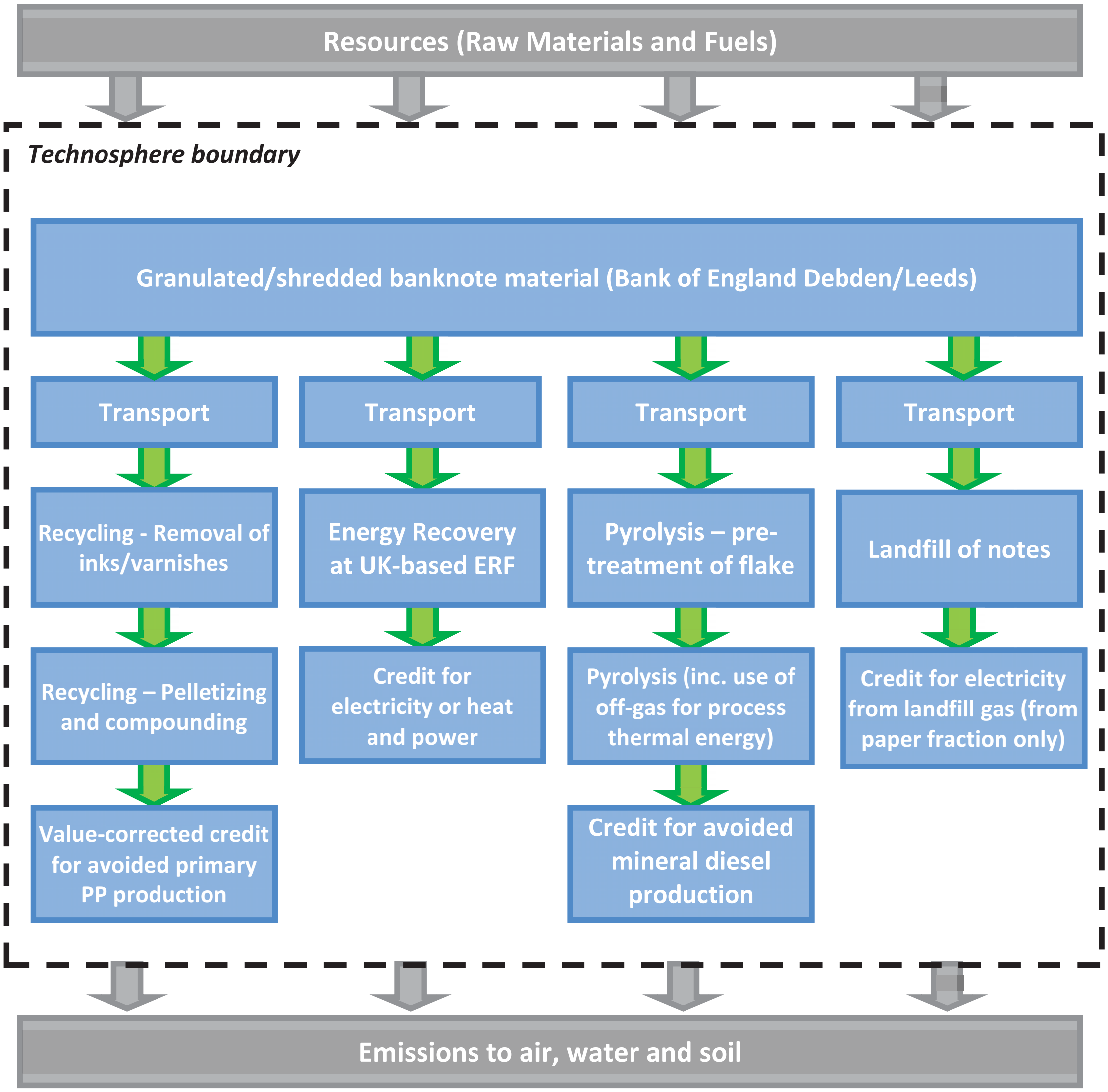

Figure 2-1: System boundary for the gate-to-grave assessment of waste management options

The following aspects are considered within the scope of this assessment:

- The transport of the shredded/granulated banknote material from the Bank's sites to the waste management facility in question (it is assumed that vehicles will be empty for the return journey).
- Recycling of the banknote waste:
  - Cleaning or sorting processes that may be required prior to reprocessing
  - Reprocessing of the plastic fraction to produce recycled granulate
  - Composting of paper fraction (in case of co-mingled waste)

- Creation of new products from recycled granulate – this will be dependent upon the quality of recyclate. Given the quantities of material available this may also involve blending the material with compatible polymer waste from other sources. In such cases impacts and credits that can be applied to the bank note fraction of the waste are reported.

- For incineration with energy recovery;
  - Incineration of the banknote material in a commercial waste incinerator. It is likely that the waste contractor will blend the material with other waste streams to achieve a consistent feedstock for the incinerator. In such cases impacts and credits that can be applied to the bank note fraction of the waste are reported
  - Production of electricity from recovered energy and system credits
  - Recovery and distribution of heat where applicable and system credits.
- For pyrolysis:
  - Any cleaning or pre-treatment processes required, such as additional shredding or separating of plastic and paper fractions (for co-mingled scenarios)
  - Pyrolysis of the plastic fraction including capture and condensation of the liquid product, combustion of the off-gas fraction to provide thermal energy for the process and recycling/disposal of the char. As for mechanical recycling, given the quantities of material available this may also involve blending the material with other compatible polymer waste. In such cases impacts and credits that can be applied to the bank note fraction of the waste are reported
  - Composting of paper fraction (in case of co-mingled waste).
- For landfill:
  - Deposition of the waste in a mixed landfill
  - Recovery of methane (from paper fraction, in case of co-mingled waste)
  - Landfill maintenance processes required over the lifetime of the landfill, such as sealing.

The following aspects have been excluded from this gate to grave LCA:

- All life cycle processes that take place prior to the granulation of unfit bank notes and printing waste by the Bank of England (including the shredding/granulation process itself).
- Construction of capital equipment – it is considered that these impacts will be negligible compared to the impacts of disposing of the bank notes themselves.

2.3.1 Time Coverage

At the start of the project it was intended to collect primary data from waste contractors for 2013 for each route they have deemed suitable for managing the banknote waste. In practice only very limited data were available from contractors. Information on the efficiency of incineration was sourced from Veolia based on data provided in the previous LCA study for the Bank of England (BANK OF ENGLAND 2013]. This is considered to be representative of current operation. Information on recycling was provided by Norplas Ltd. and is representative of current recycling equipment supplied by EREMA.

Recent data on pyrolysis were not available. Instead this was based on information from a previous study on processing of mixed waste plastics [WRAP 2008].

Representative background data (mainly raw materials, energies, fuels, and ancillary materials) have been sourced from the GaBi "Database 2013" [PE INTERNATIONAL 2013] and are representative of the years 2008-2013.

2.3.2 Technology Coverage

The technologies chosen are representative of current technologies believed to be suitable for the management of BOPP film waste or mixed paper-cotton/polymer waste generated in the UK. The use of the recycled material, fuels and electricity generated from the recovery processes is also included.

Based on research carried out during the project and on feedback from waste management contractors mixed waste stream scenarios have not been modelled for mechanical recycling or pyrolysis. The overwhelming response from waste management contractors was that the recycling route would only be viable using source separated material streams. We assume that the same requirement holds for pyrolysis since the only operating pyrolysis plant in the UK for waste polymers does not accept non-polymer waste.

We note that many recycling technologies are currently being developed such that alternative waste management routes may be viable within the next five years or so. The Bank of England may wish to reassess its waste management arrangements in future to ensure that it is still using the most appropriate technology.

2.3.3 Geographical Coverage

The waste management contractors all have established bases of operation in the UK and it is assumed that all waste is treated in this country. Background data on the electricity, fuels and auxiliary materials used in waste management processes will be reflective of the UK technology mix.

2.4 ALLOCATION

2.4.1 Treatment of Co- and By-products

No co-products or by-products are generated from processes in the foreground system so no allocation of impacts is required. Solid residue (including char) generated from pyrolysis has been considered as a waste due to the high level of non-polymer material in the banknotes (e.g. pigments) which is likely to yield a high level of non-carbon material in the solid residue.

Co-products or by-products are generated in some of the background data used in the LCA model. Allocation by mass and net calorific value is applied to all refinery products. The feedstock (crude oil) is allocated by energy, while the refinery impacts are allocated by mass. The production route of every refinery product is modelled in detail and it is possible to track the energy requirements for operating each single unit processes of the refinery. This energy demand and the corresponding emissions can be allocated specifically to each refinery product.

The feedstock of the respective unit process, which is necessary for the production of a product or an intermediate product, is allocated by energy (i.e. mass of the product * net calorific value of the product). Hence products with high caloric values (e.g. gasoline or gases) are assigned higher feedstock consumption and hence higher environmental upstream impacts compared with low caloric value products (e.g. asphalt, residual oil).

The energy demand (thermal energy, steam, electricity) of a process, e.g. atmospheric distillation, being required to create a product or an intermediate product, are allocated according to the share of the throughput of the unit process (mass allocation). In general, products which are more complex to produce and therefore pass through a lot of refinery processes (e.g. gasoline) are assigned higher energy consumption values (and hence higher emissions) compared with less processed products.

2.4.2 Recovery & Recycling

Polymer recycling is assumed to offset the need for the manufacture of products from primary material. The baseline scenario assumes a 1:1 substitution of primary with recycled material. Value corrected substitution has been applied in a sensitivity analysis to investigate the influence of this assumption.

For incineration with energy recovery it is assumed that recovered electricity offsets that provided by the average UK grid mix. Thermal energy recovery in the UK is limited but for scenarios where this is modelled it is assumed to offset that steam generated by combustion of natural gas in a boiler with 90% efficiency.

Pyrolysis is assumed to offset the need for diesel (5% biodiesel, 95% petrochemical diesel).

2.5 Cut-Off Criteria

No cut-off criteria have been defined for this assessment. All reported information has been incorporated and modelled using the best available LCI data.

2.6 Selection of LCIA Methodology and Types of Impacts

A set of impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-1 and Table 2-2.

Global warming potential and primary energy demand were chosen because of their relevance to climate change and energy efficiency, which are strongly interlinked, of high public and institutional interest, and deemed to be some of the most pressing environmental issues of our times.

Eutrophication, acidification, and photochemical ozone creation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burden associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others.

Water consumption, i.e., the removal of water from its watershed through shipment or evaporation due to human activities, has also been selected due to its high political relevance. However, it should be noted that this category is only considered at the inventory level and does not equate to an impact.

Table 2-1: Impact Assessment Category Descriptions

Impact Category	Description	Unit	Method/Reference
Global Warming Potential (GWP)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	CML [GUINÉE 2001, CML 2013]
Eutrophication Potential	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg Phosphate equivalent	CML [GUINÉE 2001, CML 2013]
Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	CML [GUINÉE 2001, CML 2013]
Photochemical Ozone Creation Potential (POCP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone, O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may affect human health and ecosystems and may also damage crops.	kg ethene equivalent	CML [GUINÉE 2001, CML 2013]
Human toxicity, **Eco-toxicity**	A measure of toxic emissions directly harmful to the health of humans and other species.	Cases Potentially affected fraction of species (PAF).m^3.day	USEtox [ROSENBAUM 2008]

Table 2-2: Other Environmental Indicators

Indicator	Description	Unit	Reference
Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) and energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ (net calorific value)	GaBi 6 Software database [PE INTERNATIONAL 2013]
Life Cycle Inventories of Water Inputs/Outputs	A measure of the net intake and release of fresh water across the life of the product system. This is not a complete indicator of environmental impact without the addition of information about regional water availability.	Litres of Water	GaBi 6 Software database [PE INTERNATIONAL 2013]

The CML impact assessment methodology framework [GUINÉE 2001, CML 2013] has been selected for assessing impacts relating to climate change, eutrophication, acidification and smog. The CML characterisation factors are applicable to the European context and are widely used and respected within the LCA community.

Additionally, the project includes an evaluation of human and ecotoxicity employing the USEtox characterisation model [Rosenbaum 2008]. The precision of the current USEtox characterisation factors is within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity [ROSENBAUM 2008]. This is a substantial improvement over previously available toxicity characterisation models, but still significantly higher than for the impacts noted above. Given the limitations of the characterisation models for each of these factors, results are reported as 'substances of high concern', but are not used to make comparative assertions.

It shall be noted that the impact categories listed above represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emitted substances would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so.

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.7 Interpretation

The interpretation of the results of this study is based on the mid-point indicators and LCI metrics. No normalisation or weighting has been applied.

2.8 Data Quality Requirements

The data used to create the model are as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under the given time and budget constraints.

- ✓ Measured primary data are considered to be of the highest precision, followed by calculated and estimated data.
- ✓ Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. No cut-off criteria have been applied in this study (see chapter 2.5).
- ✓ Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results occur due to actual differences between product systems, and not due to inconsistencies in modelling choices, data sources, emission factors, or other.
- ✓ Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope.

Data quality is assessed and reported using the pedigree matrix described in the GHG Protocol Product Life Cycle Accounting and Reporting Standard [GHG PROTOCOL 2011; WEIDEMA & WESNAES 1996]. This is presented in Appendix C). An evaluation of data quality with regard to these requirements is provided in the interpretation chapter of this report.

2.9 ASSUMPTIONS AND LIMITATIONS

2.9.1 Waste Management

Assumptions and limitations regarding the modelling of bank note waste management processes are covered in Chapter 3 'Description of Waste Management Systems'.

2.9.2 Transport

Transport from the Bank of England's sites in Debden and Leeds to the waste management contractor's site has been considered in this assessment. Onward transport from the primary waste management contractor's site to any sub-contractors or to additional sites has not been considered.

The exact transportation distances for the waste will be dependent upon the contractor that is eventually chosen to manage the waste stream and which waste management route is used. For the Debden site, contractors were considering sites as far north as Cambridge (approx. 50 miles from Debden) and as far west as the M4 corridor near Reading (approx. 70 miles from Debden). For the Leeds cash centre, sites being considered were as far west as Skelmersdale (approx. 65 miles), as far north as Middlesbrough (approx. 70 miles) and as far south as Nottinghamshire (approx. 70 miles). Given this information, a representative transport distance of 70 miles has been used. For some waste management routes, particularly landfill this might represent an over-estimation. Conversely, for other waste management routes where there is a more limited number of potential sites, (particularly pyrolysis, but also potentially energy recovery (CHP) and recycling) this may be an underestimation.

Waste is assumed to be loaded into a 40 yard roll-on/roll-off (ro-ro) skip with a total capacity of 30.6 m^3 or 15 t. Trucks are assumed to be empty on the outbound journey and fully loaded by volume on the return.

2.10 Sensitivity Analyses

Sensitivity analyses help understand the influence of poorly understood or uncertain data on the results of the LCA study or to assess those aspects that are important but may be less variable.

In this study sensitivity analyses have been carried out on the following aspects which are considered to have a significant effect on the results:

- For mechanical recycling the effect of applying a value corrected substitution to the credit given for the avoided burden of virgin granulate production is examined. In this case the credit applied is scaled according to the relative values of the virgin and recycled material. This is an alternative methodological choice that is often used in LCA studies to account for quality differences and can have large influence on the size of the credit applied;

- The effect of the efficiency of the incinerator on the impacts of energy recovery, this is assessed as there is significant uncertainty regarding how energy recovery efficiency varies from site to site.

These are discussed in more detail in Chapter 7.

2.11 Software and Database

The LCA model has been created using the GaBi 6 Software system for life cycle engineering, developed by PE INTERNATIONAL AG. The GaBi 2013 LCI database provides the life cycle inventory data for several of the raw and process materials required in the background system.

2.12 Critical Review

As this study is intended to provide comparative assertions that may be made available to the public ISO 14040/44 requires that it undergo a critical review. This critical review has been conducted by a panel of three experts:

- Professor Adisa Azapagic (Panel Chair) – LCA Expert and Professor of Sustainable Chemical Engineering at the University of Manchester[2]

- Stuart Foster – CEO of Recoup a UK-based organisation set up to improve plastics recycling and resource management

- Keith James – Special Advisor on Environmental Research at WRAP, an organisation focused on reducing resource use and preventing waste in the UK

The panel has reviewed the Goal and Scope Definition Document produced at the start of the project and as well as the Final Study Report provided as the main deliverable from the project.

A short biography of each reviewer is provided in Appendix D.

[2] Acting in a personal capacity; not representing the University of Manchester.

3 Description of Waste Management Systems

This chapter provides description of the different waste management processes considered in this assessment.

3.1 Mechanical Recycling

Mechanical recycling is based on information supplied by Norplas Ltd., the UK agent for EREMA, an Austrian manufacturer of recycling equipment. EREMA recycling lines are currently used for the reprocessing of polymer banknote waste generated in Romania. The recycling plant used as the basis for the model provides two major functions:

- Removal of volatiles produced from the printing inks and varnish in a 'degassing' process to reduce contamination in the recycled granulate and increases its value. A detailed description of this degassing process was not available so impacts associated with emissions of VOCs (potentially contributing to photochemical ozone creation potential) or from the combustion of these materials (contributing to global warming potential, amongst other impacts) have not been assessed. It is assumed that the total mass of inks and varnish is removed and therefore that this proportion of the mass of the note is lost. It has been assumed that opacifying pigments used in substrate manufacture remain in the substrate, acting as pigment and/or filler.

- Granulate production: producing the granulate from the de-inked flake waste. Opacifying pigments used in the note substrate contain high concentrations of titanium dioxide which is non-volatile and will not be removed in the degassing process but will remain in the recycled granulate. This means that the recycled granulate cannot be used to produce clear products but otherwise does not significantly compromise the quality of the granulate as it acts as filler, which may even be desirable for some applications – particularly injection-moulding.

The only major inputs to the recycling process are electricity and process water, which is circulated through the vacuum pump system. In addition to the mass reduction due to the removal of printing volatiles, there is a 2.5% material loss in the process. Unit process data for the mechanical recycling process are contained in Appendix A.

Notes are granulated into flakes by the Bank of England and would arrive for processing in this form. At this stage, no compaction of this waste at the Bank of England's sites is anticipated. The process modelled is for a polymer-only waste stream. The feedback received from contractors indicated that a single material waste stream would significantly increase the viability of recycling by reducing contamination, lowering processing requirements and, at the same time, increasing the quality and value of the recycled granulate.

Following feedback from waste contractors and Norplas, it is not anticipated that any cleaning or sorting processes will be required for the polymer bank note waste, beyond the separation of polymer and paper notes by the Bank of England.

It has been assumed that the recycled polypropylene granulate substitutes virgin polypropylene granulate on a 1:1 basis. Although not suitable for all applications (e.g. film production), where substitution of virgin granulate with recycled granulate is possible, there is no difference in the functionality or the quantity of material required.

A sensitivity analysis has been undertaken to explore the sensitivity of the results to the credit applied to recycling. This sensitivity analysis (section 7) applies a 'value corrected substitution', where the credit awarded for the avoided production of virgin granulate is reduced to reflect the difference in economic value between the primary and recycled polypropylene granulate.

3.2 ENERGY RECOVERY

Energy recovery is assumed to take place at a UK energy recovery facility. Two scenarios have been modelled for energy recovery. One for ERFs that produce electricity from the waste they receive, but that do not collect or distribute heat (referred to as the "electricity only" scenario) and one for ERFs recovering both electricity and heat (CHP scenario). As discussed in the *Identification of Contractors and Additional Information* report, the majority of UK ERFs do not recover heat (only occurs in six of the 21 ERFs currently operating in England).

In contrast to mechanical recycling, a mixed paper/polymer stream is considered a viable option for energy recovery, so the four scenarios for paper/polymer mixes presented in section 2.2 have been modelled.

The efficiency of the energy recovery facility (ERF) is a critical parameter in determining the overall impacts associated with the two energy recovery waste management routes (energy recovery - electricity only and energy recovery – CHP). In this study, the ERF efficiency is designated as being the ratio of the net calorific value (NCV) of the material entering the incinerator to the electricity produced and exported to the grid.

Primary data related to the efficiency of the ERF were provided by Veolia and relate to an ERF recovering electricity only. The effect of varying the electrical efficiency between an upper bound of 30% and a lower bound of 15% is explored in a sensitivity analysis in section 7.

When assessing the CHP scenario the amount of heat that can be recovered can vary significantly between incinerators and is influenced by a number of factors including:

- Capacity of heat distribution network (i.e. number of buildings/businesses served by district heating network)
- Efficiency of heat recovery process
- Losses in heat distribution network

In this study, inventory data from GaBi, which itself is based on data from the Confederation of European Energy Waste-to-Energy Plants (CEWEP), have been combined with energy recovery data related to the operation of the Sheffield incinerator to model CHP recovery facilities. Sheffield incinerator supplies heat to over 140 municipal and commercial buildings around the city through a district heating scheme, recovering 17 MW of electrical and 39 MW of thermal energy [DEFRA 2013]. The only other CHP processing Municipal Solid Waste (MSW) and Commercial & Industrial (C&I) waste with a comparable heat recovery is operated by FCC in Nottingham. Based on the operation of the Sheffield incinerator the ratio of heat recovery to electricity is assumed to be 2.29:1. Data collected for the energy recovery process are presented in Appendix A.

As noted previously, it is likely that the waste contractor will blend the material with other waste streams to achieve a consistent feedstock for the incinerator. This study only reports on the impacts and credits that can be applied to the bank note fraction of the waste. Waste characterisation information provided by the Bank of England was used to calculate key waste characteristics that govern the emissions profile and quantity of recovered energy from the ERF. These include:

- The elemental composition;
- The proportion of inert material;
- The proportion of biogenic carbon;
- The estimated calorific value.

Data related to the waste characterisation of polymer notes are provided in Appendix B.

Paper notes are not the main focus of this study, but have been included in order to model the impacts associated with mixed waste streams. Incineration of a mixed paper/polymer waste stream included modelling of incineration and energy recovery processes for cotton.

Credits related to the avoided production of UK grid electricity and, for CHP plants, thermal energy in the form of steam from natural gas have been included in the results.

3.3 Pyrolysis

The pyrolysis plant is assumed to produce liquid fuel (diesel), off-gas and char. Off-gas is assumed to be syngas (a mixture of hydrogen and carbon monoxide) and is fed back into the pyrolysis plant to fuel the process. The solid residue is a mixture of non-polymer elements such as titanium dioxide pigment, metal/mineral salts used in inks and varnishes and carbon-rich char. Due to the impurities in this solid residue it is assumed to have no value and to be disposed of to landfill.

The data for pyrolysis are based on that from Ozmotech, an Australian manufacturer of pyrolysis plants. The data used in this study are sourced from a 2008 study for a plant processing 10 tonnes of polymer waste per day, which makes the data relatively old (see discussion on representativeness in section 8.2.3). More positively, the Avonmouth pyrolysis plant, operated by SITA and believed to be the only commercially operating pyrolysis plant for plastics in the UK and was built by Cynar Plc who are licenced to use Ozmotech's technology.

Ozmotech's data relate to a pyrolysis process for a post-industrial waste stream consisting of a mix of polypropylene (50%) polyethylene (43%) and nylon (7%). A pre-treatment process is used to achieve melting and mixing of the material. This material is then charged into the vessel and pyrolysed over a period of time in a batch process. The polymer bank note waste differs from the mixed plastic waste stream for which the data were originally generated as there is no nylon, almost no polyethylene and a higher inert content than the mixed waste on which the data are based.

The pyrolysis process consumes electricity, natural gas (combusted to produce thermal energy) and gaseous nitrogen. Water for cooling is cycled through a closed system, so water consumption is effectively zero. The main product of the process is pyrolysis oil which can be used as a diesel substitute. Off-gas is produced as a co-product and has been assumed to be combusted and used in the process. Wastes from the process include a solid residue, solid waste and waste water from the centrifuge and waste from scrubbers. The largest of these three is the solid residue. This consists of non-pyrolysed impurities in the plastic and carbon known as char which is generated as a result of chain shortening during the pyrolysis process. Unit process data for the pyrolysis process is contained in Appendix A.

The polymer bank note waste differs from the mixed plastic waste stream for which the data were originally generated in two major ways. The first is that the polymer banknote waste is not a mixed waste – there is no nylon and almost no polyethylene, so the waste stream is relatively homogenous. The second is that the polymer banknote waste contains a higher inert content than the mixed waste on which the data are based. Data indicate that the pyrolysis feedstock should not include more than 7% to 10% inert material and suggests that above 15% the viability of the technology would be severely reduced. The inert content of the notes may be as high as 25%, so it is likely that the banknote waste would have to be mixed with other waste polymer streams with lower inert content to make the process viable. In this study, we only consider the impacts and co-products associated with the polymer bank note fraction of the feedstock.

The data used to model the pyrolysis process have been adapted with the proportion of solid residue increased to reflect the proportion of inert material. This in turn, reduces the oil and off-gas output. No adjustments have been made to the process with respect to the plastic mix as it is not clear how a mix not containing polyethylene or nylon would affect the inputs and outputs of the process if at all. The Ozmotech pyrolysis process is designed for use with plastics only so mixed paper/polymer waste streams have not been assessed. A credit is given in the model for the avoided production of diesel from crude oil.

3.4 LANDFILL

Landfill is included in assessment as a reference baseline scenario. As other processing routes are available for the polymer banknote waste, there seems to be no reason why the material should be sent to landfill. Landfill has been modelled using secondary datasets developed by PE INTERNATIONAL. These datasets are based on the emissions profiles of materials in a modern landfill within the EU. Processes related to the construction, management and sealing of the landfill are also included. As with energy recovery, both single material (polymer only) and mixed paper/polymer waste streams have been modelled.

As paper notes are biodegradable, landfill gas is produced as a result of their decomposition. The landfill gas is assumed to have a 50:50 methane to carbon dioxide ratio by volume [Eunomia 2011]. The landfill is assumed to be a modern "Type 3" landfill (large modern landfill with comprehensive gas collection) with a landfill gas extraction efficiency of 50%. Of this collected gas, 50% is assumed to be flared, with 50% combusted for electricity production (i.e. 25% of the total). Electricity produced from landfill gas is credited as avoiding the production of UK grid electricity.

Landfill was found generally to have the highest impacts of the waste management routes studied and has been included primarily as a reference baseline (if other treatment technologies cannot perform better than this "best case" landfill, they would be considered to have poor environmental performance). On this basis, additional scenarios related to disposal of banknote waste in landfills with lower gas extraction efficiencies (e.g. Type 1 or Type 2) have not been considered.

4 DATA COLLECTION

This chapter outlines the data collection procedure and explains the source of background data used in the model.

4.1 DATA COLLECTION & QUALITY ASSESSMENT PROCEDURE

Primary data were collected from equipment manufacturers and waste contractors. During the initial stages of the project, the aim had been to collect to primary data from a minimum of three waste contractors for each waste management route, assuming that this many existed. Ultimately, we were unable to obtain data from this many contractors and were limited to data from a smaller number of participating companies. The following primary data sources were used:

- Recycling: Primary recycling data were sourced from EREMA, a manufacturer of recycling equipment. EREMA lines are currently used to reprocess waste polymer banknotes in Romania and Innovia Security, the manufacturer of the polymer bank note substrate, is currently negotiating with EREMA to purchase equipment to reprocess waste generated by their manufacturing process.

- Energy recovery: Primary data related to the efficiency of energy recovery were provided by Veolia for an incinerator recovering electricity. No primary data were provided for CHP plants recovering both electricity and heat. Heat recovery is based on literature data for the Sheffield incinerator [DEFRA 2013], which provides heat for a network of buildings through a district heating scheme.

- Pyrolysis: Data on plastics pyrolysis come from Ozmotech, an Australian manufacturer of pyrolysis plants. These data were sourced by PE from publicly available sources for a previous project conducted on waste management routes of plastics [WRAP 2008]. Some adjustments were made to account for the specific feedstock characteristics of the polymer bank note waste stream based on expert judgment. Cynar Plc, the company responsible for building the Avonmouth plastics pyrolysis plant currently operated by SITA are exclusively licensed to use Ozmotech's ThermoFuel technology in the UK and Ireland [BPF 2014], giving some degree of confidence regarding the representativeness of the data, although it is likely that the process itself will have been further developed in recent years.

The key primary data used in this study are presented in Appendix A.

Data received were cross-checked for completeness and plausibility, including checks against PE INTERNATIONAL's existing models, previous projects and available literature data. If gaps, outliers, or other inconsistencies were identified, PE INTERNATIONAL engaged with the data provider to resolve any open issues.

A number of barriers that prevented data collection on a wider scale were identified during the project. These included:

- Uncertainty surrounding the recycling route: polymer recycling of this type is evolving rapidly leading to uncertainty about the exact processing requirements. In addition, many companies sub-contract the management of plastic recycling/reprocessing, adding a layer of complexity to the data collection process.

- Uncertainty surrounding the favoured management route: given the relatively novel nature of the material, contractors were unable to commit to a management route and were therefore not willing to supply data for a route that they might later regard as unfeasible.
- Lack of data on pyrolysis: we were only able to identify one commercial pyrolysis plant for plastics currently operating in the UK but were unable to obtain data on this plant.
- Landfill: although landfill is included in this study as a baseline/worst case scenario, none of the contractors regarded it is a preferred waste management option for the polymer bank note waste. This was due to the costs associated with landfill and their requirement as companies to meet targets for reducing material sent to landfill. Secondary data on the landfill of plastics have been used to model this route.

4.2 Fuels and Energy – Background Data

National and regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 6 database 2013. Table 4-1 shows the most relevant LCI datasets used in modelling the product systems.

Table 4-1: Key energy datasets used in inventory analysis

Energy	Dataset name	Primary source	Year	Region	Project-specific*
Diesel	Diesel mix at refinery	PE	2010	UK	no
Electricity	Electricity grid mix	PE	2010	UK	no
Steam	Process steam from natural gas (90% efficiency)	PE	2010	UK	no
Thermal energy	Thermal energy from natural gas	PE	2010	UK	no

* Applies if data were developed on-demand by PE for this specific project.

4.3 Raw Materials and Processes – Background Data

Data for up- and downstream raw materials and unit processes were obtained from the GaBi 6 database 2013. Table 4-2 shows the most relevant LCI datasets used in modelling the product systems. Documentation for all non-project-specific datasets can be found at www.gabi-software.com/support/gabi/gabi-6-lci-documentation.

Table 4-2: Key material datasets used in inventory analysis

Material/Process	Dataset name	Primary source	Year	Region	Project-specific*
Energy Recovery (paper note)	Cotton in waste incineration plant	PE	2012	EU-27	no
Energy Recovery (polymer note)	Incineration Polypropylene (PP)	PE/ Veolia	2012/ 2013	GB	yes
Thermal energy from off-gas combustion	Gas CHP (set for heat only)	PE	2012	Global	no
Hazardous waste disposal	Hazardous waste (non-specific) (c rich, worst case scenario)	PE	2012	Global	no
Landfill of plastic	Landfill of plastic waste	PE	2012	EU-27	no
Landfill of inert waste	Landfill of glass/inert waste	PE	2012	EU-27	no
Nitrogen	Nitrogen (gaseous)	PE	2012	GB	no
Polymer Note Reprocessing	Granulator (Adjustable)	EREMA	2014	AT	yes
Polymer Note Reprocessing	Granulateizing and compounding (Adjustable)	EREMA	2014	AT	yes
Polypropylene Granulate (primary)	Polypropylene granulate (PP)	PE	2012	EU-27	no
Process Water	Water (desalinated; deionised)	PE	2012	EU-27	no
Pyrolysis pre-treatment	Pyrolysis (pre-treatment)	Ozmotech	2008	AU	yes
Pyrolysis	Pyrolysis – waste plastic	Ozmotech	2008	AU	yes
Waste Water Treatment (general)	Municipal waste water treatment (mix)	PE	2012	EU-27	no
Waste Water Treatment (organic load)	Waste water treatment (contains organic load)	PE	2010	EU-27	no

* Applies if data were developed on-demand by PE for this specific project

4.4 TRANSPORTATION

A representative transport distance of 70 miles has been used in this study (the basis for this assumption is discussed in section 2.9.2). An empty outbound journey for collection vehicles has been modelled. Any onward transport to sub-contractors or alternative processing facilities and transport of the final products or wastes created by the waste management process have not been modelled.

The GaBi database for transportation vehicles and fuels has been used to model transportation. These are representative datasets for a wide range of transport options representing different vehicle types, sizes and technologies (e.g. different Euro-rated engines for trucks). A 40-yard roll-on/roll-off skip (volume capacity = 30.6 m^3, maximum allowed mass capacity varies by company, but is generally in the range of 14 t to 16 t) has been assumed to be used for collecting the waste. The granulated waste is assumed not to be compacted, and to have a density of 481 kg/m^3 [INEOS 2014]. This gives a mass for a fully loaded container of 14.7t.

4.5 EMISSIONS TO AIR, WATER AND SOIL

No gate-to-gate emissions were recorded by companies submitting data to PE INTERNATIONAL. However, as noted in section 3.1, a detailed description of the 'degassing' process used in mechanical recycling was not available so impacts associated with emissions of VOCs or from the combustion of VOCs have not been assessed (it is expected that volatilised material would be processed through an oxidiser to reduce VOC emissions). Hence, unrecorded site emissions associated with mechanical recycling are most likely to lead to unreported impacts for photochemical ozone creation potential, global warming potential and toxicity impacts.

Some wastes that required disposal/further treatment from recycling and pyrolysis processes were reported. However, existing secondary datasets were used to model the treatment or final disposal of these wastes. For energy recovery and landfill gate-to-gate emissions were based on existing models of these processes developed by PE INTERNATIONAL.

Data for all upstream materials, electricity, transport and energy carriers were obtained from the GaBi 6 database 2013. Emissions due to the use of electricity are accounted for with the use of the database processes.

5 LIFE CYCLE INVENTORY ANALYSIS

ISO 14044 defines the Life Cycle Inventory Analysis result as the "outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment". The complete inventory comprises hundreds of flows so in this section we only report on the two key indicators selected for assessment in this project[3]. These are primary energy demand (segregated into renewable and non-renewable energy) and water consumption.

Results have been calculated for the four banknote waste mixes outlined in section 2.2. For mechanical recycling the general feedback from contractors/reprocessors was that a mixed stream was highly unfavourable, so only a 100% polymer scenario has been modelled. Similarly, the plant on which the pyrolysis data are based is only designed to accept plastic waste, so mixed paper/polymer waste scenarios have not been calculated.

As explained in section 3, the production of secondary materials or recovered energy is credited with the avoided production of virgin materials or energy. These credits are displayed as a negative contribution to the total, reducing the impact of the overall waste management system.

These results are presented in two formats:

- A heat map table, reflecting the performance of each management route for the note waste mix in question. Options with the lowest impact values are highlighted in green, options with higher impacts are highlighted in red, with those in between highlighted with a range of colours from lighter green, through yellow to orange depending on their impact relative to the 'best' and 'worst' options in a given category;

- A graph for the 100% polymer route, showing the contribution to the total from transport to the management site, the management process and the credit for the avoided production of virgin materials/fuels. Labels showing the net total value for each management route are shown above or below each stacked bar.

5.1 PRIMARY ENERGY DEMAND

Table 5-1 gives the total primary energy demand (PED) from renewable and non-renewable resources, with better performing options for each note waste mix highlighted in green, and worse performing options highlighted in red.

The overall primary energy demand for the 100% polymer not scenario is lowest for mechanical recycling. For mixed note waste, energy recovery in a CHP has the lowest primary energy demand. The total PED associated with incineration in an ERF with electricity recovery only is similar to that from pyrolysis. Landfill has the highest primary energy demand across all four note waste mix scenarios as little or no energy is recovered from the process.

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[3]The full life cycle inventory is available upon request from the study authors provided the Bank of England gives consent to release these data.

Table 5-1: Overall results for primary energy demand (renewable & non-renewable resources)

Primary Energy Demand - Renewable and Non-Renewable (MJ)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	-59.9	-	-	-
Energy Recovery (electricity only)	-15.4	-13.8	-12.3	-10.7
Energy Recovery (CHP)	-31.6	-28.5	-25.4	-22.3
Pyrolysis	-16.0	-	-	-
Landfill	1.29	0.575	-0.138	-0.852

Figure 5-1 illustrates the contribution made by each life cycle stage to the overall primary energy demand for the 100% polymer waste stream. This graph shows that the total PED credit for mechanical recycling is almost double that for energy recovery (CHP) and pyrolysis. The impact from EoL processing is higher for mechanical recycling than energy recovery. Energy recovery in an ERF requires very little energy input from fuels or electricity, while mechanical recycling and pyrolysis both consume some fuels and electricity in order to transform the plastic waste into recycled granulate and diesel respectively. This leads to a lower overall impact for CHP compared to pyrolysis, but does not have the same effect with recycling, where the size of the credit dwarfs the impacts from processing. The contribution to PED from transport is negligible.

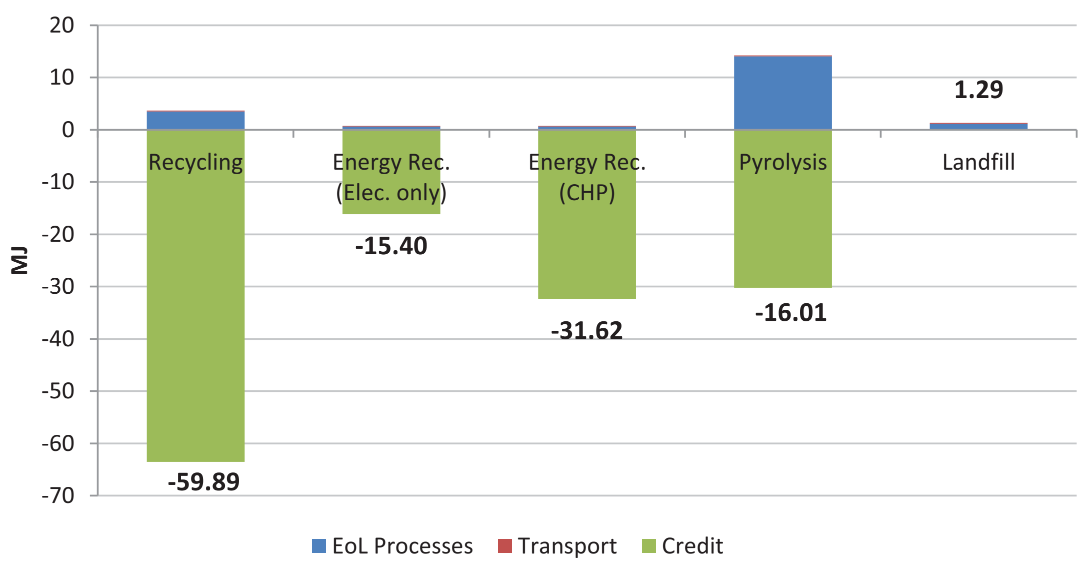

Figure 5-1: Contribution by lifecycle stage to total primary energy demand for 100% polymer scenario (data labels indicate net total impact)

Table 5-2 gives the primary energy demand (PED) from non-renewable resources and Table 5-3 gives the primary energy demand from renewable resources. The majority of the total primary energy demand comes from non-renewable resources (more than 90% for all end-of-life management options other than landfill). This is mainly attributable to the credits, which dominate the impacts and are assumed to avoid primary, non-renewable energy sources and materials. The use of renewable raw materials/energy sources in the waste management processes is negligible.

Table 5-2: Overall results for primary energy demand (non-renewable resources)

Primary Energy Demand - Non-Renewable (MJ)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	-59.2	-	-	-
Energy Recovery (electricity only)	-14.6	-13.1	-11.6	-10.1
Energy Recovery (CHP)	-30.8	-27.8	-24.7	-21.7
Pyrolysis	-16.3	-	-	-
Landfill	1.23	0.561	-0.113	-0.786

Table 5-3: Overall results for primary energy demand (renewable resources)

Primary Energy Demand - Renewable (MJ)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	-0.717	-	-	-
Energy Recovery (electricity only)	-0.823	-0.742	-0.662	-0.581
Energy Recovery (CHP)	-0.830	-0.748	-0.667	-0.586
Pyrolysis	0.268	-	-	-
Landfill	0.0542	0.0141	-0.0259	-0.0660

5.2 Freshwater Consumption

Table 5-4 gives the total freshwater consumption for the various waste management routes and note waste mixes with better performing options for each note waste mix highlighted in green and worse performing options highlighted in red. A breakdown of the results by lifecycle phase for the 100% polymer note waste stream is shown in Figure 5-2.

Table 5-4: Overall results for freshwater consumption

Freshwater Consumption (l)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	-7.83	-	-	-
Energy Recovery (electricity only)	1.99	2.10	2.22	2.34
Energy Recovery (CHP)	1.93	2.06	2.18	2.30
Pyrolysis	0.885	-	-	-
Landfill	-0.955	-1.11	-1.26	-1.41

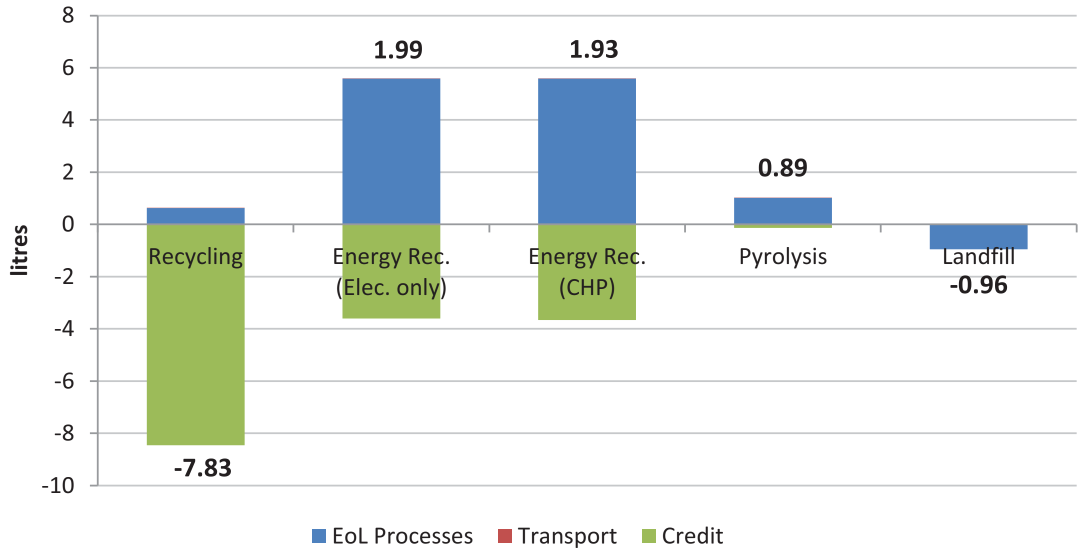

Figure 5-2: Contribution by lifecycle stage to freshwater consumption for 100% polymer scenario (data labels indicate net total impact)

Mechanical recycling has the lowest freshwater consumption of the five management options assessed for the 100% polymer stream. This is due to the low water consumption of the recycling process and the large credit for avoided consumption. The production of virgin polypropylene has a considerably higher water consumption than the production of recycled granulate (cooling water, losses from steam cracker) resulting in this large credit. The only other management option with an overall negative value is landfill where a water credit is given due to the capture and treatment of rainwater that falls on the landfill. Conversely, energy recovery in an ERF has the highest water consumption due to uncondensed steam and water vapour from driving the turbine. The water used in the pyrolysis plant is in a closed cooling system, so the consumption recorded is primarily from the upstream production of materials and fuels.

6 Life Cycle Impact Assessment (LCIA)

Impact assessment results have been calculated for the four banknote waste mixes outlined in section 2.2. For mechanical recycling and pyrolysis only a 100% polymer scenario has been modelled, following feedback from contractors.

These results are presented in two formats:

- A heat map table, reflecting the performance of each management route for the note waste mix in question. Options with the lowest impact values are highlighted in green, options with higher impacts are highlighted in red, with those in between highlighted with a range of colours from lighter green, through yellow to orange depending on their impact relative to the 'best' and 'worst' options in a given category;
- A graph for the 100% polymer route, showing the contribution to the total from transport to the management site, the management process and the credit for the avoided production of virgin materials/fuels. Labels showing the net total value for each management route are shown above or below each stacked bar.

It shall be reiterated at this point that the reported impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emitted substances would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so.

Therefore LCIA results are relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

6.1 Global Warming Potential

Table 6-1 gives the overall global warming potential (GWP) for the various waste management routes and note waste mixes with better performing options for each note waste mix highlighted in green and worse performing options highlighted in red. A breakdown of the results by lifecycle phase for the 100% polymer note waste stream is shown in Figure 6-1.

Table 6-1: Overall global warming potential results

Global Warming Potential (kg CO_2 equiv.)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	-1.40	-	-	-
Energy Recovery (electricity only)	1.40	1.34	1.28	1.22
Energy Recovery (CHP)	0.43	0.47	0.50	0.53
Pyrolysis	0.87	-	-	-
Landfill	0.08	0.50	0.92	1.34

The overall results show that for the 100% polymer waste stream, mechanical recycling has the lowest GWP. Mechanical recycling is the only one of the five waste management options to have an overall negative value. The second lowest value for a polymer note waste stream is for landfill. As the polymer notes are inert, the only GHG emissions associated with landfill come from landfill management processes such as sealing or water treatment. Energy recovery without heat recovery has the highest GWP emissions of the five waste management options considered for a polymer note waste stream.

The waste management option with the lowest impacts for the mixed stream is energy recovery in a CHP. Energy recovery of electricity only is the worst performing management option for waste streams with high proportions of polymer notes. However, for a 75% paper/25% polymer scenario, landfill has the highest overall impact due to the emission of carbon dioxide and methane in the form of landfill gas from the breakdown of the paper notes. It should be noted that as this is a 'gate to grave' study, carbon sequestration in the cotton biomass during cultivation is not considered.

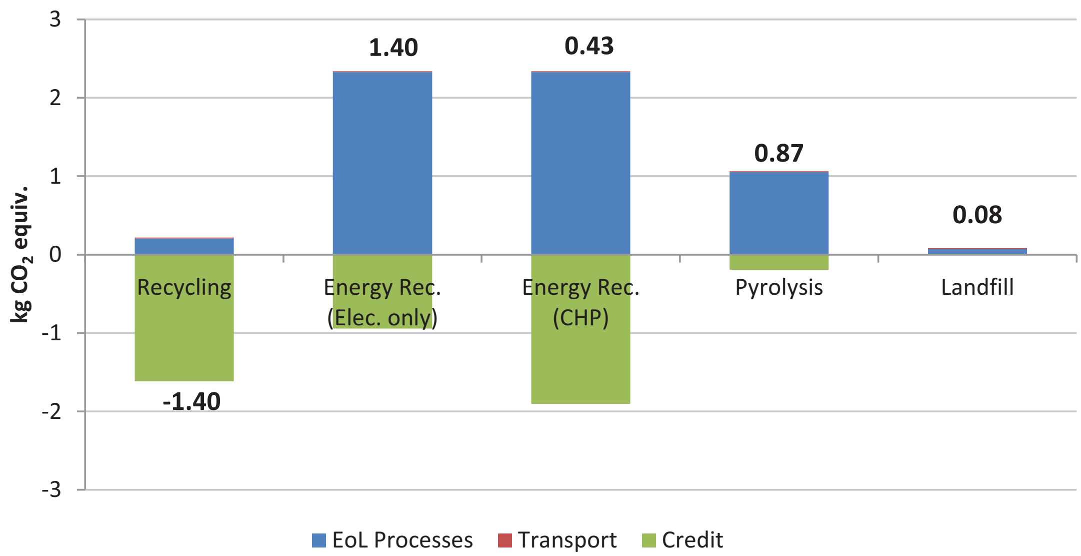

Figure 6-1: Contribution by lifecycle stage to global warming potential for 100% polymer scenario (data labels indicate net total impact)

The more detailed breakdown in Figure 6-1 shows that the lowest processing emissions are associated with landfill and mechanical recycling. Although energy recovery is awarded large credits for the avoided production of electricity and thermal energy, these are not as large as the impact of the emissions from the incineration of the waste. Pyrolysis is assigned a relatively low credit, as the GWP impact of primary diesel production is not high relative to the production of virgin polypropylene granulate or the electricity/thermal energy credited for energy recovery. Transport makes a negligible contribution to the GWP of the waste management processes.

6.2 Acidification Potential

Table 6-2 gives the overall acidification potential for the various waste management routes and note waste mixes. A breakdown of the results by lifecycle phase for the 100% polymer note waste stream is shown in Figure 6-2.

The management route with the lowest overall acidification potential for the 100% polymer note stream is mechanical recycling. For mixed note waste streams energy recovery from a CHP has the lowest acidification potential – this receives large credits for avoided electricity (primarily due to the coal component in the UK grid mix). Mechanical recycling has higher acidification potential associated with processing than energy recovery due to the consumption of electricity in reprocessing the polymer waste. However, the magnitude of the credit for avoided primary granulate production means that mechanical recycling is the option with the lowest impacts overall. Pyrolysis has the highest acidification potential of all management options for a 100% polymer waste stream. This is due to emissions from the combustion of natural gas and by-product off-gas to provide energy to the process. The acidification potential of landfill is only slightly lower than that of pyrolysis for the 100% polymer waste stream. For mixed streams, landfill has the highest acidification potential.

Table 6-2: Overall acidification potential results

Acidification Potential (g SO_2 equiv.)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	-4.67	-	-	-
Energy Recovery (electricity only)	-2.89	-2.39	-1.90	-1.41
Energy Recovery (CHP)	-3.38	-2.84	-2.30	-1.77
Pyrolysis	0.58	-	-	-
Landfill	0.27	0.85	1.42	2.00

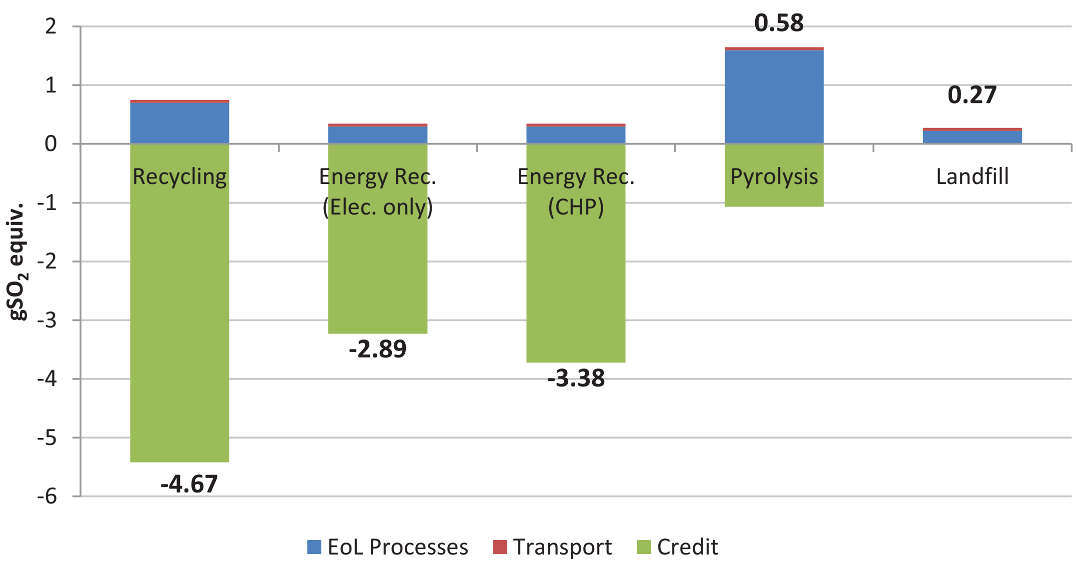

Figure 6-2: Contribution by lifecycle stage to acidification potential for 100% polymer scenario (data labels indicate net total impact)

6.3 Eutrophication Potential

Table 6-3 gives the overall eutrophication potential for the various waste management routes and note waste mixes. A breakdown of the results by lifecycle phase for the 100% polymer note waste stream is shown in Figure 6-3.

For the 100% polymer stream, the eutrophication potential of mechanical recycling and energy recovery in a CHP are the same to two decimal places. Again, mechanical recycling benefits from a large credit for avoided virgin granulate production, while for CHP, the large credit is associated with avoided electricity and to a lesser extent avoided thermal energy production. Neither pyrolysis nor landfill have overall negative eutrophication potentials – the impacts of these two options are considerably higher than those of recycling or energy recovery through an ERF. Transport is of slightly higher importance for eutrophication than GWP or acidification. Looking only at the impact of collection and processing (i.e. ignoring credits), transport accounts for around 10% of the eutrophication potential for mechanical recycling and around 17% for energy recovery.

Table 6-3: Overall eutrophication potential results

Eutrophication Potential (g PO_4 equiv.)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	-0.29	-	-	-
Energy Recovery (electricity only)	-0.20	-0.13	-0.07	0.00
Energy Recovery (CHP)	-0.29	-0.21	-0.14	-0.06
Pyrolysis	0.15	-	-	-
Landfill	0.28	0.25	0.22	0.20

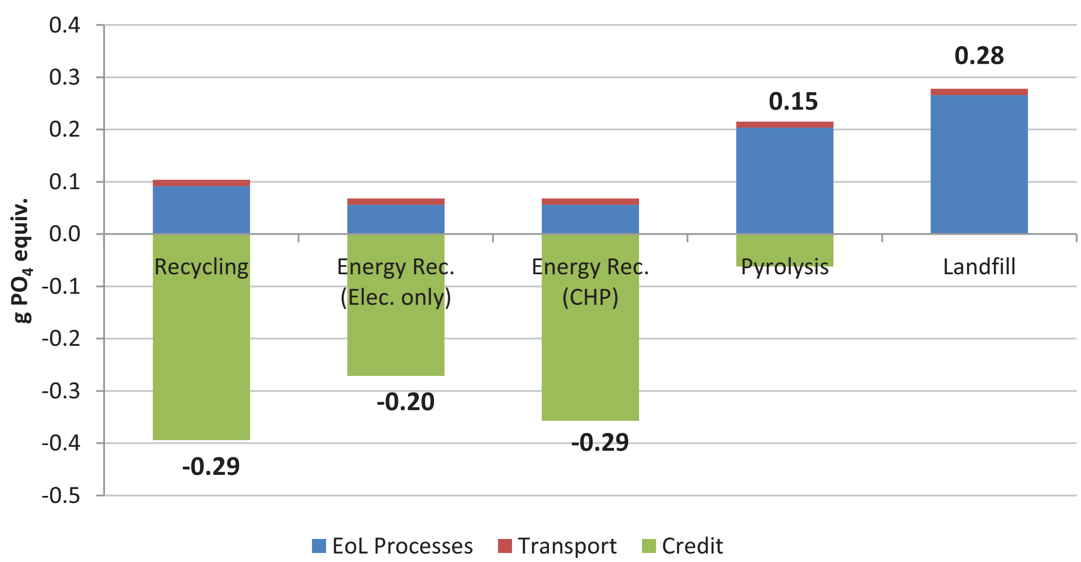

Figure 6-3: Contribution by lifecycle stage to eutrophication potential for 100% polymer scenario (data labels indicate net total impact)

6.4 PHOTOCHEMICAL OZONE CREATION POTENTIAL

Table 6-4 gives the overall photochemical ozone creation potential (POCP) for the various waste management routes and note waste mixes. A breakdown of the results by lifecycle phase for the 100% polymer note waste stream is shown in Figure 6-4.

Table 6-4: Overall photochemical ozone creation potential results

Photochemical Ozone Creation Potential (g Ethene equiv.)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	-0.94	-	-	-
Energy Recovery (electricity only)	-0.18	-0.15	-0.13	-0.10
Energy Recovery (CHP)	-0.25	-0.22	-0.18	-0.15
Pyrolysis	-0.09	-	-	-
Landfill	0.01	0.11	0.21	0.32

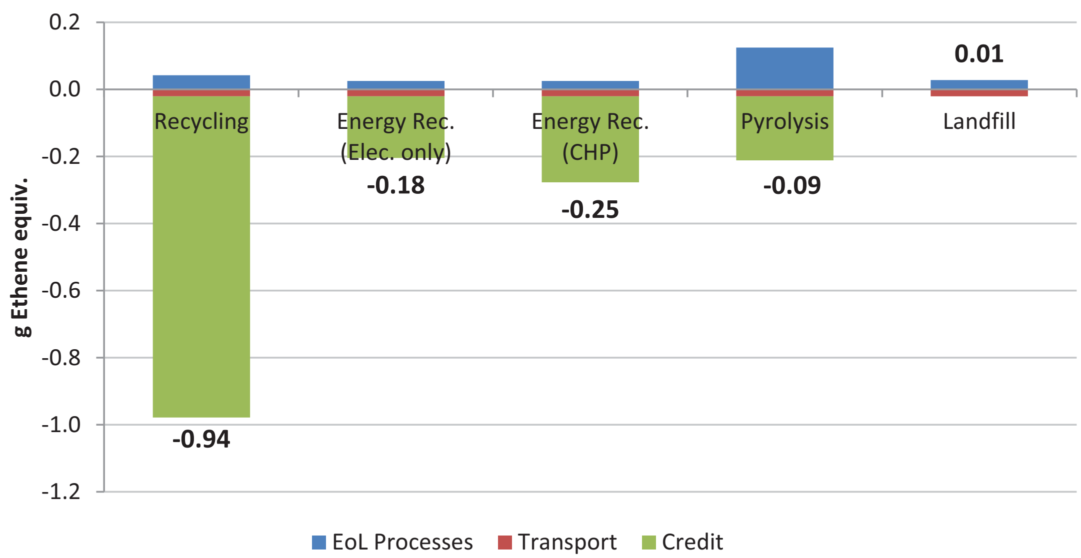

Figure 6-4: Contribution by lifecycle stage to photochemical ozone creation potential for 100% polymer scenario (data labels indicate net total impact)

Mechanical recycling has the lowest POCP impact of the five waste management routes assessed for the polymer note waste stream, followed by energy recovery from a CHP plant. Landfill is the only management option that does not have an overall negative POCP impact. The value for mechanical recycling is driven by the very large POCP credit given for the avoided production of virgin polypropylene granulate.

Pyrolysis is the only waste management option that has significant POCP in processing. This impact is driven by emissions resulting from the combustion of natural gas and off-gas. Transport makes a small negative contribution to the POCP impact. This can be viewed as a quirk of the CML method for assessing POCP which assumes that the reaction between nitrogen oxide (NO) and ozone which yields nitrogen dioxide and oxygen (and consequently removes ozone from the troposphere) counteracts the smog creating potential of the other nitrogen oxides emitted from diesel combustion. This reflects the background model used in CML and is not shared by other impact category providers such as ReCiPe or TRACI.

6.5 Abiotic Depletion Potential (Elements)

Table 6-5 gives the overall abiotic depletion potential of elements (ADPe) for the various waste management routes and note waste mixes. A breakdown of the results by lifecycle phase for the 100% polymer note waste stream is shown in Figure 6-5.

Table 6-5: Overall abiotic depletion potential results

Abiotic Depletion Potential - Elements (kg Sb equiv.)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	-4.09×10^{-7}	-	-	-
Energy Recovery (electricity only)	4.90×10^{-9}	5.28×10^{-9}	5.66×10^{-9}	6.04×10^{-9}
Energy Recovery (CHP)	-7.10×10^{-9}	-5.58×10^{-9}	-4.06×10^{-9}	-2.54×10^{-9}
Pyrolysis	-1.70×10^{-9}	-	-	-
Landfill	1.44×10^{-8}	1.30×10^{-8}	1.15×10^{-8}	1.01×10^{-8}

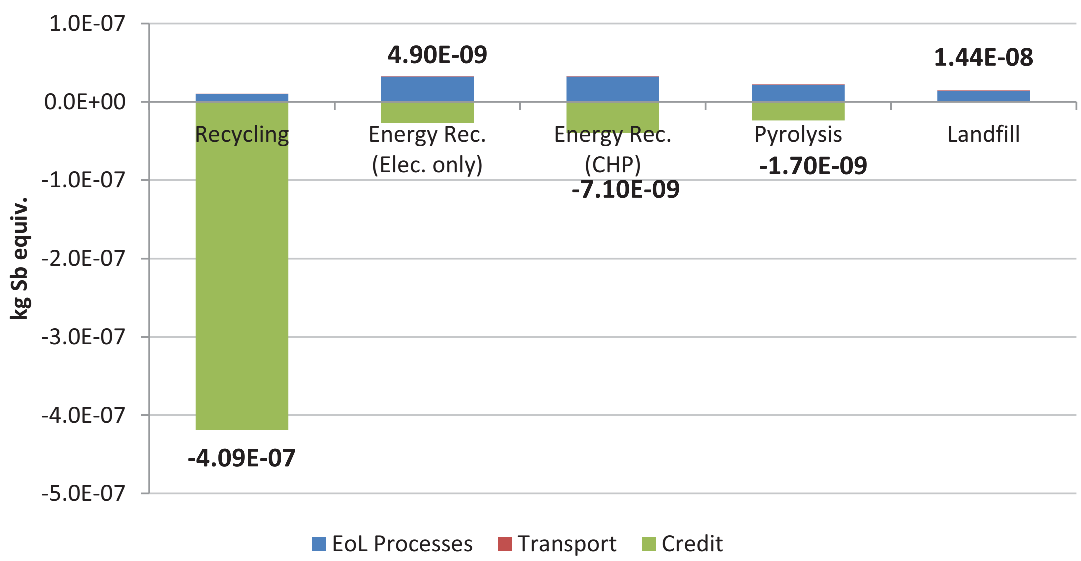

Figure 6-5: Contribution by lifecycle stage to abiotic depletion potential for 100% polymer scenario (data labels indicate net total impact)

Mechanical recycling has a significantly lower elemental abiotic depletion potential than any of the other waste management options. As well as having the lowest abiotic depletion from processing, there is also a large credit for the avoided abiotic depletion of elemental resources from the production of virgin granulate. For mixed waste streams, energy recovery from a CHP plant has the lowest ADPe. Landfill has the highest ADPe for all the waste mixes modelled, as there is little or no recovery of energy or resources which might result in an ADPe credit.

6.6 Human Toxicity Potential (Cancer and Non-cancer Effects)

Table 6-6 and Table 6-7 give human toxicity potentials excluding credits due to cancer and non-cancer effects for the various waste management routes and note waste mixes. As discussed in Section 2.6, due to the limitations of the characterisation models for this impact category the results can be used to identify 'substances of high concern' but should not be used to make comparative assertions. Consequently, the results are not presented in the heat map format used for other impact categories. Credits have been omitted from this analysis as substances of concern should be identified within the product system rather than in negative credit systems.

Table 6-6: Human toxicity potential (cancer) – waste processing and transport

Human Toxicity Potential - Cancer (CTUh)[4]	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	7.58×10^{-11}	-	-	-
Energy Recovery (electricity only)	3.78×10^{-11}	9.19×10^{-11}	1.46×10^{-10}	2.00×10^{-10}
Energy Recovery (CHP)	3.78×10^{-11}	9.19×10^{-11}	1.46×10^{-10}	2.00×10^{-10}
Pyrolysis	4.80×10^{-10}	-	-	-
Landfill	2.33×10^{-10}	2.30×10^{-10}	2.27×10^{-10}	2.24×10^{-10}

Table 6-7: Human toxicity potential (non-cancer) – waste processing and transport

Human Toxicity Potential - Non. Cancer (CTUh)	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	8.74×10^{-9}	-	-	-
Energy Recovery (electricity only)	2.94×10^{-9}	9.60×10^{-9}	1.63×10^{-8}	2.29×10^{-8}
Energy Recovery (CHP)	2.94×10^{-9}	9.60×10^{-9}	1.63×10^{-8}	2.29×10^{-8}
Pyrolysis	5.24×10^{-8}	-	-	-
Landfill	3.66×10^{-8}	3.34×10^{-8}	3.01×10^{-8}	2.69×10^{-8}

Those substances making the largest contribution to human toxicity potential for the processing and transport of the 100% polymer note waste stream are shown in Figure 6-6 (cancer effects) and Figure

[4] CTUh = Comparative toxicity units (human toxicity). From USEtox: "the estimated increase in morbidity in the total human population, per unit mass of a chemical emitted, assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue."

6-7 (non-cancer effects). Substances grouped as “other” contribute less than 5% individually and 20% cumulatively.

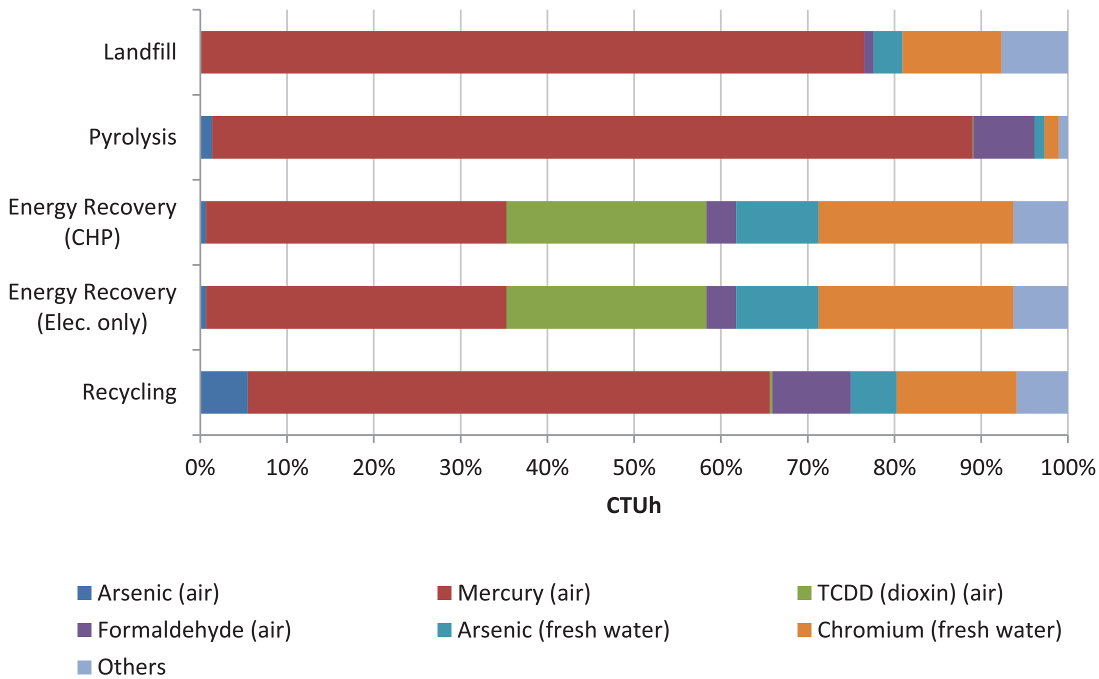

Figure 6-6: Contribution by substance to human toxicity potential (cancer) – Processing and transport only, 100% polymer waste stream

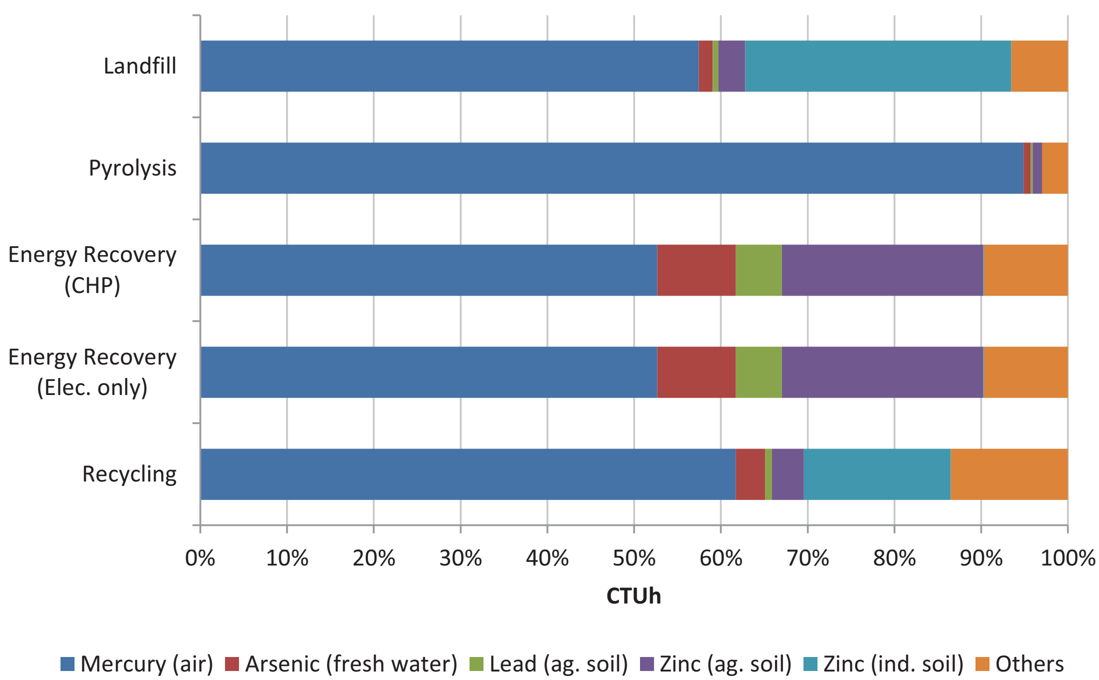

Figure 6-7: Contribution by substance to human toxicity potential (non-cancer) – Processing and transport only, 100% polymer waste stream

Human toxicity (cancer) impacts are dominated by emissions of mercury and 2,3,7,8-tetrachlorodibenzodioxin (TCDD) to air and the emission of chromium VI to fresh water. For the human toxicity (non-cancer) impact category, mercury to air is again the most significant individual emission for all five waste management routes, with zinc emissions to soil also making a contribution for all routes except pyrolysis. The majority of these emissions are attributable to emissions in the upstream production of electricity and fuels. The same emissions make the largest contribution to the energy recovery and landfill of mixed waste streams.

6.7 Eco-Toxicity Potential

Table 6-8 gives the eco-toxicity potential excluding credits for the various waste management routes and note waste mixes. A breakdown of the results by lifecycle phase for the 100% polymer note waste stream is shown in Figure 6-8. As discussed in Section 2.6, due to the limitations of the characterisation models for this impact category the results can be used to identify 'substances of high concern' but should not be used to make comparative assertions. Consequently, the results are not presented in the heat map format used for other impact categories.

Table 6-8: Eco-toxicity potential – waste processing and transport

Eco-toxicity Potential (CTUe)[5]	100% Polymer	75% Polymer/ 25% Paper	50% Polymer/ 50% Paper	25% Polymer/ 75% Paper
Mechanical recycling	4.71×10^{-3}	-	-	-
Energy Recovery (electricity only)	2.12×10^{-3}	2.15×10^{-3}	2.18×10^{-3}	2.21×10^{-3}
Energy Recovery (CHP)	2.12×10^{-3}	2.15×10^{-3}	2.18×10^{-3}	2.21×10^{-3}
Pyrolysis	6.08×10^{-3}	-	-	-
Landfill	1.37×10^{-2}	1.17×10^{-2}	9.70×10^{-3}	7.68×10^{-3}

Substances that make the largest contribution to eco-toxicity potential for the processing and transport of the 100% polymer note waste stream are shown in Figure 6-8. Substances grouped as "other" contribute less than 5% individually and 20% cumulatively.

In contrast to human toxicity impacts, no single emission is dominant for eco-toxicity. However, all substances of concern are heavy metals. The ten individual emissions come from five metals: Arsenic, copper, mercury, nickel and zinc. The majority of these emissions are attributable to emissions in the upstream production of electricity and fuels. The same emissions make the largest contribution to the energy recovery and landfill of mixed waste streams.

[5] CTUe = Comparative toxicity units (ecotoxicity). From USEtox: an estimate of the potentially affected fraction of species (PAF) integrated over time and volume, per unit mass of a chemical emitted.

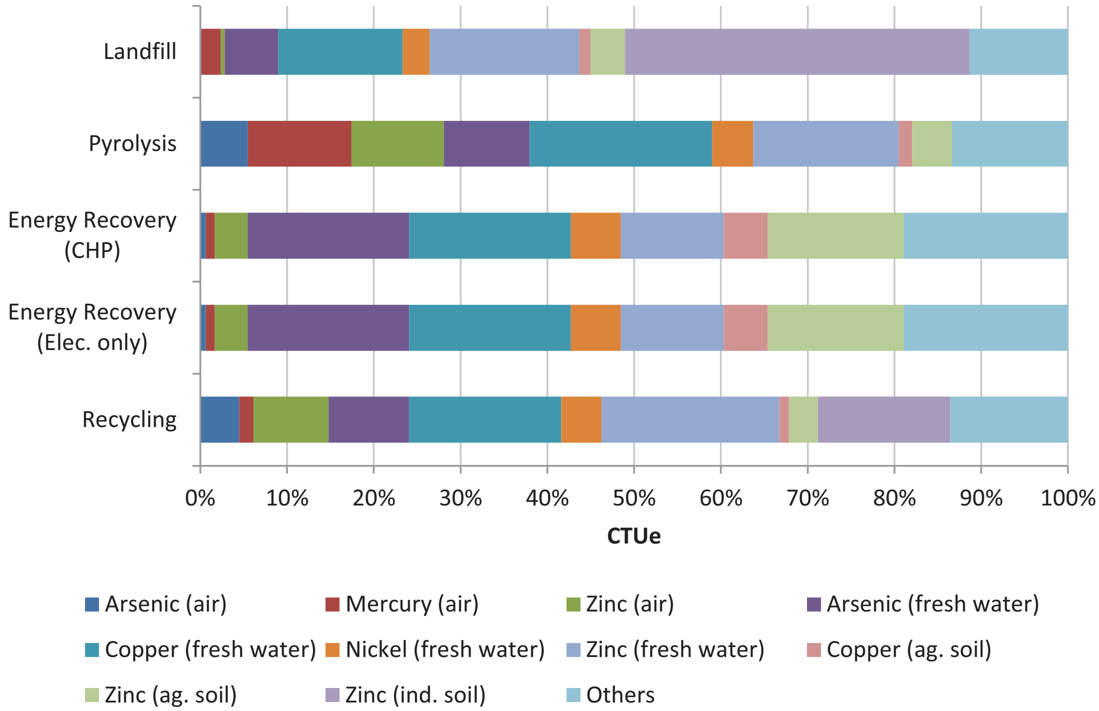

Figure 6-8: Contribution by lifecycle stage to eco-toxicity potential – Processing and transport only, 100% polymer waste stream

7 Sensitivity Analysis

This chapter presents the results of the sensitivity analyses described in Section 2.10. The following analyses have been carried out assessing:

- The effect of using value corrected substitution in place of mass-based substitution to calculate the avoided burden of virgin granulate for mechanical recycling;
- The effect of the efficiency of the incinerator on the impacts of energy recovery.

For these sensitivity analyses, only a 100% polymer note waste stream has been considered, as this is the only scenario for which all five management options are viable. However, it is expected that the results observed on incinerator efficiency for the 100% polymer route should also translate to the mixed polymer/paper routes.

7.1 Sensitivity to Recycling Credit – Value Correction

The recycled granulate generated from the plant specified by EREMA can be used for a variety of high-grade applications such as injection moulding. In these applications, the recycled granulate substitutes virgin polypropylene granulate on a 1:1 basis. This 1:1 substitution forms the basis for the credit applied in the main results section. However, there are applications for which the recycled granulate is not suitable. For example, the recycled granulate cannot be used to produce new banknotes and there are other specific applications where the recycled granulate will not be suitable (e.g. where clear plastic is required).

'Value corrected substitution' is an approach that takes account of the difference in quality between virgin and recycled granulate. Using this method it is assumed that price is a good proxy for quality so the environmental credit awarded for the avoided production of virgin granulate is reduced in line with the relative economic value of recycled and virgin material.

Granulate prices are volatile and are affected by consumer demand both in the UK and abroad, as well as the price of oil and other raw materials. In this study, it has been assumed that recycled granulate produced from waste polymer banknotes can be used in injection moulding applications. Norplas Ltd indicated a typical price range of £450-£650 per tonne of recycled granulate. In this sensitivity analysis a median value of £550 has been used. For virgin polypropylene granulate, information related to spot market prices over the past 12 months were used to provide a range of values [Plastics Exchange 2014]. During this time, the lowest price for primary granulate was £1,073 per tonne with a highest price of £1,192. Using the November 2014 price of £1,164 per tonne, a value correction of 0.472 (550/1164) was applied to the credit for avoided virgin polypropylene production to take account of the difference in quality between the primary and recycled granulate.

Table 7-1 presents a summary of the impact results for seven key LCI and LCIA categories is shown in including an additional value-corrected scenario.

For global warming potential, applying a value corrected credit for recycling leads to an increase in GWP from -1.40 kg CO_2e to -0.55 kg CO_2e. For other impacts, similar increases are seen, as the value corrected credit is less than half the 1:1 substitution credit and the credit is of much greater magnitude than the impacts of processing and transportation.

Table 7-1: Summary of results including mechanical recycling with value corrected credit

	Recycling - 1:1	Recycling - Value corrected	Energy Recovery (electricity)	Energy Recovery (CHP)	Pyrolysis	Landfill
Global Warming Potential (kg CO_2 equiv.)	-1.40	-0.55	1.40	0.43	0.87	0.08
Acidification Potential (g SO_2 equiv.)	-4.67	-1.81	-2.89	-3.38	0.58	0.27
Eutrophication Potential (g PO_4 equiv.)	-0.29	-0.08	-0.20	-0.29	0.15	0.28
Photochemical Ozone Creation Potential (g Ethene equiv.)	-0.94	-0.43	-0.18	-0.25	-0.09	0.01
Abiotic Depletion Potential - Elements (kg Sb equiv.)	-4.09×10^{-7}	-1.88×10^{-7}	4.90×10^{-9}	-7.10×10^{-9}	-1.70×10^{-9}	1.44×10^{-8}
Primary Energy Demand - Total (MJ)	-59.89	-26.33	-15.40	-31.62	-16.01	1.29
Freshwater Consumption (l)	-7.83	-3.37	1.99	1.93	0.89	-0.96

Despite these significant changes in the impact values, the overall "ranking" of waste management options within each impact category is unchanged for four of the seven impact categories when applying value corrected substitution. For GWP, POCP, abiotic depletion and freshwater consumption, the value corrected substitution scenario still has lower impacts than any of the other management options for the polymer waste stream. For acidification and eutrophication, mechanical recycling with a value corrected credit has higher impacts than energy recovery (CHP) and energy recovery of electricity but is still lower than for pyrolysis or landfill. Mechanical recycling with a value corrected credit has a higher overall primary energy demand than energy recovery from a CHP, but a lower primary energy demand than all other waste treatment options.

This analysis shows that while the impact values are sensitive to the application of a value correction factor, the value corrected scenario still has the lowest impacts for four of the seven impact categories assessed and is no lower than third for the other three (acidification, eutrophication and primary energy demand). Even with a value corrected credit, mechanical recycling remains the only waste management option with a negative value (i.e. a net credit) for all seven impact categories.

The rapidly falling price of oil is having an effect on the price of virgin granulate and this could affect the value correction ratio. At least in the short term, if recycled granulate prices do not fall as quickly, this is likely to increase the ratio (bringing it closet to the 1:1 substitution used in the main results section). As it is the ratio of primary to recycled price that affects the value correction factor rather than the absolute prices, it may well be the case that the price of recycled granulate may also fall as primary granulate prices drop, thereby remaining at a ratio close to the one used in this sensitivity analysis.

7.2 Sensitivity to Energy Recovery Facility Efficiency

Primary data related to the energy recovery efficiency of a typical UK ERF were provided by Veolia. From previous research it is estimated that the typical ERF electrical efficiency range is 15%-30% [WRAP 2008]. A sensitivity analysis was undertaken to investigate the effect of managing the polymer bank note waste at ERFs with efficiencies at the top and bottom of this range. The results of this analysis are presented in Table 7-2.

This analysis shows that the results are highly sensitive to the efficiency of the ERF facility. As seen in Chapter 6, for most impact categories (the notable exception being global warming potential), the direct impacts associated with the ERF are relatively low. Therefore most of the impact is related to the amount of energy recovered and the credit calculated for the avoided production of energy from virgin sources. An ERF with an electrical efficiency of 15% does not perform favourably compared to mechanical recycling, even where heat recovery is implemented. Another notable result is that even with an extremely high electrical efficiency of 30%, an ERF recovering electricity only does not perform better than mechanical recycling in six of the seven impact categories assessed (eutrophication the exception). Conversely, a CHP recovery plant with an efficiency of 30% compares relatively favourably with mechanical recycling, although even in this best-case scenario mechanical recycling has lower global warming potential, photochemical ozone creation potential, abiotic depletion potential, primary energy demand and freshwater consumption.

Table 7-2: Summary of results for ERF efficiency sensitivity analysis

	Mechanical Recycling	Electricity Only			CHP			Pyrolysis	Landfill
		Low Efficiency	Standard Efficiency	High Efficiency	Low Efficiency	Standard Efficiency	High Efficiency		
Global Warming Potential (kg CO_2 equiv.)	-1.40	1.63	1.40	0.91	0.90	0.43	-0.54	0.87	0.08
Acidification Potential (g SO_2 equiv.)	-4.67	-2.10	-2.89	-4.54	-2.47	-3.38	-5.29	0.58	0.27
Eutrophication Potential (g PO_4 equiv.)	-0.29	-0.14	-0.20	-0.34	-0.20	-0.29	-0.47	0.15	0.28
Photochemical Ozone Creation Potential (g Ethene equiv.)	-0.94	-0.14	-0.18	-0.27	-0.19	-0.25	-0.38	-0.09	0.01
Abiotic Depletion Potential - Elements (kg Sb equiv.)	-4.09×10^{-7}	1.16×10^{-8}	4.90×10^{-9}	-9.12×10^{-9}	2.50×10^{-9}	-7.10×10^{-9}	-2.72×10^{-8}	-1.70×10^{-9}	1.44×10^{-8}
Primary Energy Demand - Total (MJ)	-59.89	-11.47	-15.40	-23.67	-23.73	-31.62	-48.19	-16.01	1.29
Freshwater Consumption (l)	-7.83	2.86	1.99	0.14	2.82	1.93	0.06	0.89	-0.96

8 INTERPRETATION

This chapter summarises the overall results of the study considering the quality of the data used, discusses the key trends and conclusions, and provides recommendations on the best performing option along with suggestions for further work.

8.1 IDENTIFICATION OF RELEVANT FINDINGS

Impact results for the 100% polymer note waste stream for seven LCIA and LCI categories are summarised in Table 8-1.

Table 8-1: Summary of results for five waste management options for polymer note waste (100% polymer)

	Mechanical recycling	Energy Recovery (electricity)	Energy Recovery (CHP)	Pyrolysis	Landfill
Global Warming Potential (kg CO_2 equiv.)	-1.40	1.40	0.43	0.87	0.08
Acidification Potential (g SO_2 equiv.)	-4.67	-2.89	-3.38	0.58	0.27
Eutrophication Potential (g PO_4 equiv.)	-0.29	-0.20	-0.29	0.15	0.28
Photochemical Ozone Creation Potential (g Ethene equiv.)	-0.94	-0.18	-0.25	-0.09	0.01
Abiotic Depletion Potential – Elements (kg Sb equiv.)	-4.09×10^{-7}	4.90×10^{-9}	-7.10×10^{-9}	-1.70×10^{-9}	1.44×10^{-8}
Primary Energy Demand - Total (MJ)	-59.89	-15.40	-31.62	-16.01	1.29
Freshwater Consumption (l)	-7.83	1.99	1.93	0.89	-0.96

KEY: Best performing options … Worst performing options

Recycling has the lowest impacts for all seven categories assessed. CHP has the second lowest impacts for five of the seven categories assessed: acidification potential, eutrophication potential, photochemical ozone creation potential, abiotic depletion potential (elements) and primary energy demand. However, this option has the second highest impacts for water consumption and the third highest impacts for global warming potential.

Recycling is the only end-of-life management option that has a net negative value for all seven LCI and LCIA categories included in the comparison, suggesting environmental savings for these impacts. Landfill has the highest impacts in four of the seven categories but its GWP is second-best, after recycling. Polymer note waste is inert and will not biodegrade (within a meaningful timescale) so no energy from landfill gas capture would be recovered from this route.

Following feedback from contractors, recycling was not assessed for a mixed waste stream as it was generally deemed commercially unviable at present by those contractors contacted. However, it should be noted that technologies to separate material of this type do exist, so this situation may change in future. Pyrolysis was also not assessed for mixed streams as the plant on which the pyrolysis model was based is designed for a plastic-only waste stream. For the mixed paper/polymer waste streams, energy recovery at a CHP plant generally has the lowest impacts of the three remaining management options, with landfill having the highest.

For the two energy recovery options (electricity only and CHP) assessed it is generally observed that the environmental impacts increase as the proportion of paper in the mixed waste stream increases. This is because the lower calorific value of the paper compared to the polymer results in less energy being recovered and a smaller credit applied.

More detailed breakdowns of the results (see Figure 5-1 and Figure 6-5) showed that for most impact categories, pyrolysis has the highest processing impacts due to the combustion of natural gas and off-gas and the consumption of electricity. Mechanical recycling has higher emissions from processing than energy recovery as some electricity is required for degassing (removing the volatile ink fractions) and transforming the waste polymer into granulate. The low sulphur, nitrogen and phosphorous content of the waste means that emissions related to acidification and eutrophication are low for ERFs. However, the global warming potential of energy recovery is high due to the high carbon content of the polymer waste.

The overall impacts from transport were generally relatively low. For the acidification and eutrophication potentials as well as primary energy from non-renewable resources the impact of transportation is typically 10-20% of the impact of the processing (i.e. excluding credit) (see Figure 5-1 and Figure 6-5). For other impact categories the contribution from transport is negligible. In general, transport represented a larger proportion of the impact for energy recovery and landfill, as these management routes reported lower processing impacts for most impact categories.

8.2 Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied on a study serving as a data source) and representativeness (geographical, temporal, and technological). A detailed data quality assessment presented in the form of pedigree matrices can be found in Appendix C.

8.2.1 Precision and completeness

- ✓ **Precision:** Wherever possible the relevant foreground data are primary data or modelled based on primary information sources of the owner of the technology. This is the case for mechanical recycling, pyrolysis with the ERF efficiency also from a primary source. Further primary data from additional contractors or equipment manufacturers would represent an improvement as an average could be made that could potentially be more representative of the current technology mix. All background data are GaBi data with the documented precision.

- ✓ **Completeness:** Each unit process has been checked for mass balance and completeness of the emission inventory. No data were knowingly omitted except as described in Section 2.9.

8.2.2 Consistency and reproducibility

- ✓ **Consistency:** To ensure consistency, all available primary data relevant to the waste management processes studied were collected while all background data were sourced from the GaBi databases. Allocation and other methodological choices have been made consistently throughout the model.

- ✓ **Reproducibility:** Reproducibility is warranted as much as possible through the disclosure of input-output data, dataset choices and modelling approaches in this report. Based on this information, any third party should be able to replicate the study and produce approximately equivalent results using the same data and modelling approaches.

8.2.3 Representativeness

- ✓ **Temporal:** The majority of primary data were collected for the years 2013 and 2014 and are considered to be of very good temporal representativeness. The exception is pyrolysis data which were collected for a study in 2008 and are based on still older source documents (we are unable to verify the age of this source). As these data on pyrolysis are more than five years old their temporal representativeness is considered to be 'fair'. The decision was taken to use these data despite its age as it was by the far the most technologically representative and complete data available on this route. All secondary data come from the GaBi 6 2013 databases and are representative of the years 2010-2013. As the study is intended to compare the product systems for the reference year 2014, temporal representativeness is warranted.

- ✓ **Geographical:** Most primary and secondary data were collected specific to the countries/regions under study. Where country/region specific data were unavailable, best available proxy data were used. For example, although pyrolysis data were provided for an Australian equipment manufacturer, similar equipment is known to be used in the UK. Geographical representativeness is considered to be very good in most cases. Again, the pyrolysis data are of lower quality and are rated as 'fair'.

- ✓ **Technological:** Most primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be very good for mechanical recycling and energy recovery. For pyrolysis, it is considered to be good based on the pedigree matrix presented in Appendix C.

8.3 Completeness, Sensitivity and Consistency

8.3.1 Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete with regard to the goal and scope of this study.

8.3.2 Sensitivity

Sensitivity analyses were performed to test the robustness of the results towards uncertainty and key assumptions. Detailed results can be found in Chapter 7.

The first sensitivity analysis focused on the effect of applying a value correction factor to the credit for avoided production of virgin polypropylene granulate. By comparing current average prices of virgin and recycled polypropylene granulate (as of November 2014), a value correction factor of 0.472 was applied.

Despite relatively significant changes to the impact values themselves, the overall "ranking" of waste management options within each impact category is unchanged for four of the seven impact categories when applying value corrected substitution. For GWP, POCP, abiotic depletion and freshwater consumption, the value corrected substitution still has lower impacts than any of the other management options for the polymer waste stream. For acidification and eutrophication, mechanical recycling with a value corrected credit has higher impacts than energy recovery (CHP) and energy recovery of electricity only. Mechanical recycling with a value corrected credit has a higher overall primary energy demand than energy recovery from a CHP, but a lower primary energy demand than energy recovery of electricity only.

The second sensitivity analysis focused on the efficiency of the ERF. An electrical efficiency range of 15%-30% was applied within the ERF models. This analysis showed that energy recovery results are indeed quite sensitive to the efficiency of the ERF.

Mechanical recycling has lower impacts than an electricity-only ERF with a maximum electrical efficiency of 30% for six of the seven impact categories (eutrophication being the exception). However, a CHP recovery plant with an electrical efficiency of 30% compares relatively favourably with mechanical recycling, although even in this best-case scenario mechanical recycling has lower impacts in five of the seven impact categories assessed.

The results of the overall ranking of waste treatment options do vary depending on whether a best case or worst case scenario is considered. Hence the study results are seen to be sensitive to the efficiency of energy recovery that is assumed in the model.

8.3.3 Consistency

All assumptions, methods, and data are consistent with the study's goal and scope. Differences in background data quality were minimised by using all background LCI data from the GaBi 6 2013 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

8.4 Conclusions, Limitations and Recommendations

8.4.1 100% polymer waste

Mechanical recycling has the lowest impacts for the seven impact categories assessed. On this basis, we conclude that this is the best option overall for the 100% polymer waste stream.

Energy recovery using CHP has the second lowest impacts for five of the seven categories assessed. However, this option has the second highest impacts for water consumption and the third highest impacts for global warming potential.

Pyrolysis generally does not seem to perform too well compared to recycling or energy recovery – primarily due to the relatively high energy requirement for sustaining the pyrolysis reaction and the lower credit received compared to mechanical recycling. It should also be noted that there is a lack of infrastructure for pyrolysis in the UK at present. The location of the one identified site (Avonmouth) is not well suited for treating waste from either the Leeds or Debden sites.

Landfill has the highest impacts in four out of the seven impact categories, although it does perform quite well for global warming potential and freshwater consumption.

8.4.2 Mixed paper/polymer waste

The overwhelming majority of waste contractors did not consider mechanical recycling to be economically feasible at the present time for mixed polymer/paper waste streams due to the increased processing required and the possible impact on recyclate quality. However, technologies to separate mixed paper/polymer waste do exist so this situation may change in the future. The pyrolysis option is also not viable for mixed waste for the technology considered here.

Hence energy recovery and landfill were the only options assessed for mixed polymer/paper waste. Energy recovery with CHP had the best performance in every impact category except freshwater consumption. Energy recovery of electricity only had a better performance than landfill for every category except freshwater consumption and global warming potential.

Hence, for mixed waste streams, we regard energy recovery with CHP to be the preferred choice.

8.4.3 Other considerations

One potential issue affecting both mechanical recycling and energy recovery with CHP is the number of plants able to manage waste by these two routes. There are currently only six CHP energy recovery facilities in England for commercial and industrial waste. Of these, only four are within 70 miles of the Bank's sites. The exact number of recyclers able to manage the polymer bank note waste is uncertain, but a search of the Recoup "Find a Reprocessor" tool [Recoup 2014] and the BPF's Plastics Recycling Buyers' Guide [BPF 2014] indicate that there could be as many as 20 reprocessors able to handle polypropylene film waste. However, the variations in feedback from waste contractors indicate that not all contractors or sub-contractors currently have access to the technology required to reprocess the polymer note waste.

8.4.4 Limitations & assumptions

The main assumptions relating to the data used in the model are described in detail in section 2.9 and are summarised below.

- A value-corrected credit for the avoided production of virgin polypropylene has been applied in a sensitivity analysis in this study. It has been assumed that the recycled granulate is most likely to be used for injection moulding and is likely to command a price in the region of £450-£650/t. Virgin polypropylene currently trades at a price of £1,164/t, with the price over the last year varying between £1,073/t and £1,192/t. Using a median value of £550/t for recycled granulate and the current virgin granulate price of £1,164/t gives a value correction ratio of 0.472.

- As part of the recycling process the waste polymer is de-inked. It is assumed that the total mass of inks and varnish is removed and therefore that this proportion of the mass of the note is lost. In addition, indications from EREMA are that there is a typical polymer yield loss of around 2.5% during the recycling process.

- The baseline recovery efficiency used in this study is based on primary data from Veolia for one of their ERFs. The effect of varying the recovery efficiency between an upper bound of 30% and a lower bound of 15% is explored in a sensitivity analysis in Chapter 5.

- Data related to the operation of the Sheffield incinerator has been used to model CHP recovery facilities. Sheffield incinerator supplies heat to wa network of buildings around the city through a district heating scheme, recovering 17 MW of electrical and 39 MW of thermal energy. Based on the operation of the Sheffield incinerator the ratio of heat recovery to electricity is assumed to be 2.29:1.

- Ozmotech's data relate to a pyrolysis process for a post-industrial waste stream consisting of a mix of polypropylene (50%) polyethylene (43%) and nylon (7%). The polymer bank note waste differs from the mixed plastic waste stream for which the data were originally generated as there is no nylon, almost no polyethylene and a higher inert content than the mixed waste on which the data are based.

- Feedback indicated that the pyrolysis feedstock should not include more than 7% to 10% inert material and suggests that above 15% the viability of the technology would be severely reduced. The inert content of the notes may be as high as 25%, so it is likely that the banknote waste would have to be mixed with other waste polymer streams with lower inert content to make the process viable. In this study, only the impacts and co-products associated with the polymer bank note fraction of the feedstock have been considered. The data used to model the pyrolysis process has been adapted with the proportion of solid residue increased to reflect the proportion of inert material. This in turn, reduces the oil output.

- Polymer notes are assumed to be inert in landfill. As paper notes are biodegradable, landfill gas is produced as a result of their decomposition. The landfill is assumed to be a modern "Type 3" landfill (large modern landfill with comprehensive gas collection) with a landfill gas extraction efficiency of 50%. Landfill was found to generally have the highest impacts of the waste management routes studied and has been included primarily as a "worst-case" baseline. On this basis, additional scenarios related to disposal of banknote waste in landfills with lower gas extraction efficiencies (e.g. Type 1 or Type 2) has not been considered.

- Transport from the Bank's two sites in Debden and Leeds to the waste management contractor's site has been considered in this assessment. Onward transport from the primary waste management contractor's site to any sub-contractors or to additional sites has not been considered. A representative transport distance of 70 miles has been used. Waste is assumed to be loaded into a 40 yard roll-on/roll-off (ro-ro) skip with a total capacity of 30.6 m3 or 15 t. Trucks are assumed to be empty on the outbound journey and fully loaded by volume on the return.

8.4.5 Recommendations

- Recycling of the polymer bank note should be prioritised as this is the waste management route with the lowest environmental impacts.

- The Bank of England should separate the paper and polymer note streams to ensure that the polymer can be reprocessed into good quality recycled granulate suitable for applications such as injection moulding. This is also desired by waste management contractors regardless of the waste management route as it provides a more consistent material for treatment.
- If energy recovery is to be considered, recovery at CHP plants should be strongly prioritised over recovery at ERFs recovering electricity only.

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Appendix A: Unit Process Data

The unit process data collected and applied in this assessment is reported in this section.

Mechanical Recycling

Table A-1: Primary data on recycling process

Inputs	Value	Unit	Outputs	Value	Unit
Electricity	0.35	kWh/kg	**Recycled granulate**	86.8	%
Water	140	l/day	**Losses (de-inking and yield loss)**	13.2	%

Energy Recovery

- ERF baseline efficiency = 19.8%
- ERF efficiency lower bound = 15%
- ERF efficiency upper bound = 30%

Pyrolysis

Table A-2: Primary data on pyrolysis

Inputs	Value	Unit	Outputs	Value	Unit
Feed	10	t/day	**Oil**	8125	l/day
Electricity	2000	kWh/day	**Off-gas**	929	kg/day
Natural gas	1791	kg/day	**Residue**	2479	kg/day
Water	0 (closed loop)	l	**Ammoniated waste water**	80	kg/day
Nitrogen (gaseous)	6.8	Nm^3/day	**Waste from centrifuge**	10	kg/day
			Scrubber waste	3.3	kg/day

APPENDIX B: POLYMER NOTE WASTE CHARACTERISATION

<<removed to preserve data confidentiality >>

Appendix C – Data Quality Assessment

The quality of the foreground and background data used in this study have been summarised in the pedigree matrices shown in Tables C-2 and C-3 (based on that used in the GHG Protocol Product Life Cycle Accounting and Reporting Standard). This based on the scoring system presented in Table C-1 below.

Table C-1: Scoring system for pedigree matrix

Data Quality Indicator	Score			
	Very Good	Good	Fair	Poor
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions or a qualified estimate (e.g., by sector expert)	Non-qualified estimate
Completeness	Data from all relevant process sites over an adequate time period to even out normal fluctuations	Data from more than 50% of sites for an adequate time period to even out normal fluctuations	Data from less than 50% of sites for an adequate time period to even out normal fluctuations or from more than 50% of sites but for shorter time period	Data from less than 50% of sites for shorter time period or representativeness is unknown
Temporal	Data with less than 3 years of difference	Data with less than 6 years of difference	Data with less than 10 years of difference	Data with more than 10 years of difference or the age of the data are unknown
Geographical	Data from the same area	Data from a similar area	Data from a different area	Data from an area that is unknown
Technological	Data generated using the same technology	Data generated using a similar but different technology	Data generated using a different technology	Data where technology is unknown

Table C-2: Pedigree matrix for foreground data used in this study

Data Point	Data Quality Indicator				
	Reliability	Completeness	Temporal	Geographical	Technological
Mechanical Recycling	Very Good	Poor	Very Good	Very Good	Very Good
Energy Recovery (electricity only)	Good	Poor	Very Good	Very Good	Very Good
Energy Recovery (CHP)	Good	Poor	Very Good	Very Good	Very Good
Pyrolysis	Poor	Poor	Fair	Fair	Good
Landfill	Good	Fair	Very Good	Very Good	Very Good
Transport	Good	Good	Very Good	Very Good	Very Good

Table C-3: Pedigree matrix for background data used in this study

Data Point	Data Quality Indicator				
	Reliability	Completeness	Temporal	Geographical	Technological
Diesel	Very good	Good	Good	Very Good	Very Good
Electricity	Very good	Very good	Good	Very Good	Very Good
Steam	Very good	Very good	Good	Very Good	Very Good
Thermal energy	Very good	Very good	Good	Very Good	Very Good
Hazardous waste disposal	Good	Fair	Very Good	Good	Good
Nitrogen	Very good	Fair	Very Good	Very Good	Very Good
Polypropylene Granulate (primary)	Good	Fair	Very Good	Good	Very Good
Process Water	Very good	Fair	Very Good	Good	Very Good
Waste Water Treatment	Good	Fair	Good	Good	Good

APPENDIX D – BIOGRAPHIES OF CRITICAL REVIEW PANEL

Adisa Azapagic (Panel Chair)

Adisa Azapagic *FREng FIChemE FRSC HonFSE* is Professor of Sustainable Chemical Engineering at the University of Manchester. She obtained both her Dipl. Eng. and MSc degrees from University of Tuzla (Bosnia) and a PhD from University of Surrey (England). She leads the Sustainable Industrial Systems group, an internationally-leading research group applying the principles of sustainable development and life cycle thinking in industrial practice. Her research interests include life cycle sustainability assessment, carbon footprinting, sustainable production and consumption, and corporate sustainability. She is a founding partner of Ethos Research and has acted as a consultant for a large number of organisations, including blue chip companies, the United Nations and the European Commission.

Stuart Foster

Stuart Foster works in a business development, strategic and project management role for PPS Ltd, primarily on the Recoup activity where he is the Chief Executive Officer. He represents the UK at the European Association of Plastics Recycling Organisations (EPRO), of which he is also a Director, and specifically sits on the plastic bottle and mixed plastic working groups. He also represents Recoup within the British Plastic Federation Recycling Council and other associated government and industry stakeholder groups.

Stuart has expert knowledge of all aspects of the packaging and plastic recycling chain including design, collection, sorting, reprocessing, markets and legislation. He been involved in a range of including process reviews for recyclables in waste and recycling systems, options assessments of collection and sorting systems for local authorities, packaging reviews and operational trials and development of plastic recycling strategies.

Keith James

Keith James is a special advisor on environmental research at WRAP, where his role is to provide leadership on environmental research and impacts in all of WRAP's programmes, providing expert advice to policy teams in Governments across UK and contributing to the delivery of WRAP's forward strategy. Keith is a technical expert in life cycle assessment and water footprinting.