Appendix 5A - White Young Green initial Environmental Impact Analysis

White Young Green

Life cycle assessment Study:
SUMMARY REPORT

Selected Treatment Processes for WEEE Plastics Containing Brominated Flame Retardants

for

Axion Recycling

On behalf of
Waste Resources Action Programme (WRAP)

Project Ref: E4833

August 2005

thinking beyond construction

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		EMILY FREER	PHIL STUDDS	GEOFF RICHARDSON
		Environmental Consultant	**Associate**	**Regional Director**
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White Young Green Environmental Limited, Arndale Court, Headingley, Leeds. LS6 2UJ.
Telephone: 0113 278 7111 Facsimile: 0113 275 0623 E-Mail: enviro.leeds@wyg.com

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1.0 Background

The WEEE (Waste Electronic and Electrical Equipment) Directive requires the separation of plastics containing brominated flame retardants (BFR) prior to energy recovery, recycling or disposal. However, currently BFR's are considered to represent an obstacle to the closed-loop recycling of these polymers due to the fact that presently there are no commercially viable processes available to extract BFR from WEEE plastics. Also, few options exist which separate polymers containing BFR's from those that do not.

White Young Green Environmental (WYGE) were commissioned by Axion Recycling to undertake a Life Cycle Assessment (LCA) study of designated processing options for plastics containing brominated flame retardants. This forms part of the Phase 2 project: 'Develop a process to separate brominated flame retardants from WEEE polymers' funded by the Waste and Resources Action Programme (WRAP).

2.0 Aims

The aim of the Waste Recycling Action Programme (WRAP) funded study was to investigate the suitability of commercially viable techniques of extracting BFR's from WEEE polymers in order to create better opportunities for the closed–loop recycling of WEEE polymers back into new electronic and electrical equipment.

An environmental assessment is a systematic and phase-based approach used to evaluate and assess the environmental impacts of specific processes or products and enable realistic comparisons of environmental performance to be made between them. This can aid decision makers select those products or processes that produce the least impact on the environment and/or identify where environmental improvements can be made.

3.0 Introduction

Evaluating commercial and economical factors associated with innovative waste treatment options does not provide a holistic view of the viability of such processes as these maybe distorted and restricted by statutory legislative requirements, political factors, short-term taxation policies and economic instruments which favour particular disposal routes or process options. The environmental performance of waste management options is typically independent of such economic and political factors and is of primary importance in determining which process offers the best overall environmental benefits.

Environmental impact assessments assess the environmental aspects and potential impacts of a product or process on the environment and considers the trade-off's between media that may occur between different processes. This may encompass the 'life-cycle' of the product or process, which includes all processes from cradle-to-grave, including intermediate processes that are often excluded from other analyses, such as transportation, use of packaging etc.

This is achieved by compiling an inventory of input and outputs through a defined system, evaluating the potential environmental impacts of through-put material and relating potential impacts to inventory analysis and assessment.

3.1 Waste Electrical and Electronic Directive (WEEE) 2002/96/EC

The WEEE Directive (2002/96/EC) introduces collection, recycling and recovery targets for all waste electrical and electronic products, the first of which is to be achieved by December 2006. These include minimum recycling targets of certain categorises of WEEE of 50 - 80% and minimum recovery targets of 70 – 80% and compulsory household collection targets of 4kg per householder to be achieved by the end of 2006. New targets are to be established by the end of 2008.

Additional requirements of the Directive include;

- Compulsory producer responsibility funded collection and take-back schemes; private householders will be able to return their WEEE to collection facilities free of charge;
- The cost of 'orphaned' waste will be funded between current market producers, based proportionately on market share, with guarantees to be made by producers to guard against costs arising from this waste;
- Measures to be taken to reduce WEEE disposal as municipal waste by householders;

Annex 2 of the Directive also requires the separate treatment of certain components recovered from WEEE including;

- Liquid crystal displays (LCD) over 150 sq.cm
- Mercury switches
- Asbestos
- Polymers containing BFR's
- Capacitors containing PCB's
- Cathode ray tubes and gas discharge lamps
- Batteries and toner cartridges
- CFC's

Alongside the WEEE Directive, a daughter Directive, The Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) (02/95/EC) was also adopted.

This Directive requires that from 1st July 2006, new E & E equipment placed onto the market does not contain;

- Lead
- Mercury
- Cadmium
- Hexavalent chromium
- Polybrominated biphenyls (PBB)
- Polybrominated diphenylethers (PBDE)

3.2 What are Brominated Flame Retardants?

These are compounds containing bromine which when added to materials such as plastics inhibit or suppress the ability of the material to burn by either interfering with the heating, decomposition, ignition or flame dispersal process. They are widely found in electronic and electrical equipment, furniture and office equipment, paints and textiles.

There are over 75 commercial brominated flame retardants on the market, of which there are four main groups; Polybrominated biphenyls (PBB's), Hexabromocyclododecane (HBCD), Polybrominated Diphenyl ethers (PBDE's) (of which Deca-BDE, Penta-DBE and Octa-BDE are the most common) and tetrabromobisphenol-A (TBBPA).

HBCD is largely associated with textile and building applications and is not typically used in electrical and electronic applications; only one PBB compound, decabromobiphenyl (DeBB) has been used commercially and while production of this compound has now ceased, PBB's will continue to feature in the electrical and electronic plastic waste stream.

PBDE's are a group of aromatic brominated compounds which can be divided into two groups, depending on their bromine content. The lower brominated compounds include tetra-BDE, Penta-PDE and hexa-BDE with the higher brominated compounds including Octa-BDE, Nona-BDE and Deca-BDE.

Deca-BDE is the most commercial BDE, however the manufacture and use of many of the lower brominated BDE's, including Penta-BDE and Octa-BDE have now been banned in Europe due the toxicological effects of these compounds. There are concerns that Deca-BDE can potentially degrade into lower brominated PBDE's are largely used in the manufacture of plastic housing for small office equipment and for TV and monitor housings.

TBBPA can be found as an additive or reactive flame retardant in different plastic polymers. It has replaced many of the lower PBDE's in computer and TV housings as these compounds have been banned and is also widely used in printed circuit boards and automotive parts.

BFR's may be found as reactive or additive compounds in plastic polymers. How these compounds have been added to the plastic polymers is important in being able to evaluate how the flame retardants will behave during the life-cycle of the product or during disposal processes.

Reactive or 'back-bone' flame retardants are chemically in-built into the plastic polymers in which they are found. This means that they will not bleed-out of the polymer and vaporise over time. The most common reactive brominated flame retardants are TBBPA, TBPE and brominated styrene.

Additive or 'matrix' flame retardants however, are incorporated into the plastic polymer either prior to, during or after polymerisation. As they are not chemically bound into the structure of the polymer they have the potential to bleed-out of the polymer over time and vaporise. The performance of these flame retardants therefore may decrease over time as the concentrations of the compounds are lost to the atmosphere. The most wide-spread additive brominated flame retardants are PBDE's, TBBPA and HBCD.

3.3 LCA Studies

Public concerns over the impact that industries and businesses have on the environment have continued to increase as issues such as resource depletion and environmental degradation have been repeated brought to the front of discussions on sustainability, deforestation and global warming. As a result, many businesses have started to assess how their activities affect the environment in order to provide the 'greener' products demanded by consumers, which go beyond traditional 'command and control' legislative regulation.

One tool for assessing the environmental impacts of products, services or industries is to consider the full environmental impact of these material and activities over their full life-cycle. Life-cycle assessments (LCA's) are a 'cradle-to-grave' approach for assessing industrial systems, encompassing the environmental impacts of extracting and processing raw materials, through to product manufacture, use and final disposal (landfill, incineration, recycling etc.) This can include activities and impacts such as transportation, packaging and disposal options which may not be considered in other analyses.

3.1.1 What does an LCA involve?

A life cycle assessment study is a systematic and phase-based approach comprising of four core processes; goal definition, collection of inventory data, impact assessment and interpretation.

3.1.2 Defining the goal and scope of the study;

This encompasses detailing the purpose and application of the study, the process, product or service to be studied and any alternatives, if relevant, and the audience to which the study is targeted. The system boundary of the study and the 'functional unit' should also be defined. The system boundary details the limitation of the study and identifies those activities on which data will be collected. This includes defining the processes and operations to be included, inputs and outputs of the system. System boundaries may be geographical, environmental (i.e. distinguish between the technosphere and biosphere for example) or life-cycle based. The functional unit characterises the scale of comparison for two or more processes or products and is the unit to which all data collected in the inventory will be linked. Information should also be provided relating to the quality of data used throughout the study.

3.1.3 Collecting Inventory Data

This involves quantifying all the inputs and outputs of a product, service or process by compiling an inventory of relevant energy and material inputs and associated environmental outputs. Data should be collected from all single processes in the life-cycle, but can be quantitative or qualitative in nature. While quantitative data is important to compare products or processes, descriptive qualitative data can be used for environmental aspects or processes in the life cycle that can not be quantified. It is important to consider allocation procedures for processes and systems that involve multiple products, i.e. petroleum refinery; materials, energy flows and releases should be allocated appropriately, stated and justified.

With regards to energy flows, fuels, electricity generation sources, energy efficiency conversion factors, inputs and outputs should be considered and detailed. Inventory data should also undergo validation during the study to ensure and improve data quality. Comparative data should be reported to an appropriate reference flow and where delivered in different formats, converted to the reporting standard reference flow. This should be defined and described where appropriate.

3.1.4 Impact Assessment

This involves evaluating the potential impact that these inputs and outputs have on the environment and human health. This process is considered to comprise of; category definition, classification, characterisation, normalisation and valuation or weighting. The International Organisation of Standardisation's (ISO) standard for conducting impact assessments, titled ISO 14042, *Life Cycle Impact Assessment* (ISO 1998), states that the first three stages category definition, classification and characterisation are mandatory steps in a life cycle assessment. Normalisation and weighting exercises are optional dependant on the goal and scope of the study.

- *Category Definition*

  Defining the impact categories to be considered as part of the overall LCA follows decisions made in defining the goal and scope of the assessment. Impact categories are defined as the consequences caused by the input and output streams of a process on human health, plants and animals, or the future availability of natural resources. These consequences may include harm to human health, such as the release or formation of cancer-causing agents or those causing sterility, environmental impacts, such as global warming or acid rain and ecological toxicity.

  Impact categories may include; global warming, acidification, eutrophication, stratospheric ozone depletion, ecological (aquatic and terrestrial) toxicity, human toxicity, resource depletion, land use and photochemical oxidation potential.

- *Classification*

  Classification aims to organize and assign inventory input-output data to impact categories. Where inventory data falls into one category, the procedure is straight forward, however, some data may fall into two or more categories and therefore the effects of this output is counted twice. While double counting is acceptable if the effects are independent of one another, double counting can not occur where the effects are dependant on each other. For example, nitrogen dioxide can effect both acidification and ground level ozone formation at time the same time and therefore the effects this output has on each categories can be counted. However, sulphur dioxide can either stay at ground level and effect human health or it can travel into the atmosphere and contribute to acidification, but it can not contribute to both. In such cases, it would be feasible to allocate a representative portion of the results from the assessment for this output to each category, i.e. 50%.

- *Characterisation*

  Characterisation involves aggregating input and out data within an impact category. This typically involves using 'indicators' or 'equivalency factors' to convert and combine data into representative indicators for impacts to enable different inventory outputs to be directly compared. At this stage the implicit assumption that 'less is best' is linked to important considerations such as potency and environmental persistence to enable the impacts of different quantities of compounds to be assessed on an equal scale.

For some environmental impact categories there is a consensus about the equivalency factors to be used in the estimation of total impact (i.e. global warming potential is measured to the reference compound, carbon dioxide, with standard potency factors applied to other compounds and to it and expressed in tones CO2/year equivalents.) For impact categories such as land use however, no consensus has yet been reached and variations in how this is expressed exist.

- *Normalisation and weighting*
  While characterization groups inventory outputs into different impact categories, it is not possible to directly compare the different impact categories themselves. Normalisation and weighting aim to rank or aggregate the results of different categories into an order of relative importance. This is not a technical, scientific or objective process as impact categories and different environmental impacts are not directly comparable. It is a process which assigns weights or relative values to the different impact categories based on their perceived importance or relevance; this should also reflect the goals of the study and stakeholder values.

3.1.5 Interpreting the Results

This involves interpreting the results of the study, linking them to the objectives of the process, showing a clear understanding of the uncertainties and assumptions used to generate the results. The accuracy of the results must be verified and sufficient to support the purposes for performing the LCA as defined in the goals and scope of the survey. Study limitations should also be included; this may include a lack of spatial and temporal resolution, i.e. the size of river into which effluent is discharged; the effects will be greater in a small river than a large river and if all the effluent is released at once as opposed to small amounts over a longer period. Other limitations may include inventory speciation, where compounds are grouped together, i.e. VOC's and metals; this is not sufficient information to accurately assess the environmental impact of these compounds and threshold limits; 5 tonnes of contamination does not necessarily imply that the environmental effects are 5-times greater than 1 tonne of contamination.

LCA studies are useful tools as they encompass all process inputs and outputs which enables a realistic comparison of the environmental performance to be made between two or more products or processes encompassing all stages of the life cycle from raw material extract through the final disposal of the product. This can aid decision makers select those products or processes that produce the least impact on the environment and/or identify where environmental improvements can be made.

4.0 Goals and Scope of the Study

4.1 Goals of the Study

The objectives of the study were to assess the potential environmental impacts of four new process options for recovering electrical and electronic (E & E) plastic waste containing BFRs against landfill and traditional recovery options. The traditional recovery options include incineration with energy recovery (no bromine recovery), mechanical recycling and feedstock recycling.

Two of these new process options were high-lighted in the Interim Report published by Wrap in January 2005 titled 'Develop a process to separate brominated flame retardants from WEEE polymers' and included; Creasolv, and the Ionic Liquid processes. The other two additional processes detailed in the Interim Report were rejected from further analysis due to a lack of process data and perceived lack of commercial viability on conclusion of the report.

However, two additional processes were introduced for the purpose of this study; namely the Centrifuge and Evaporation and the Filtration and Anti-solvent processes.

The focus of the study was to compare the potential environmental impacts of recovering brominated flame retardant plastic waste using the identified waste treatment processes, from E & E sources, to those environmental impacts avoided by using the resulting recyclate to substitute other materials.

This study follows the principles and methods of the ISO 14040 Standard Environmental Management – Life Cycle Assessment – Principles and Framework (1997a).

4.2 Scope of the Study

The scope of the study considers the potential treatment options for waste plastics from E & E equipment. Small WEEE items such as mobile phones, MP3 players etc. were not considered in this project as alternative treatment methods, specifically the inclusions of these items into metal smelter furnaces was considered to be the most viable treatment method at present.

The interim WRAP report issued in January 2005 stated that the process options considered would be more commercially viable if they can be applied to polymers which have already been sorted into polymer type and where non-BFR-containing polymers have been removed. Therefore, it has been presumed that WEEE dismantling and pre-sorting of WEEE plastics from brown and white E & E goods has taken place to produce a mix of plastic material that is dominated by the styrenic polymers HIBS (High Impact Polystyrene), ABS (Acrylonitrile Butadiene Styrene) and PC (Polycarbonate) in equal proportions.

The main brominated flame retardants considered to be present in these polymers are: TBBPA (forming 7% in PC/ABS polymers and 5% in ABS polymers), Deca-BDE (forming 10% in HIPS polymers and 3% in ABS polymers), Octa-BDE (forming 5% in ABS polymers) and TBPE (forming 0.5% in ABS polymers).

For the purpose of this study, it is assumed that the substituted materials were crude oil in the case of feedstock recycling, virgin HIPS, PC and ABS polymers in the case of high-grade recycling.

The waste treatment process option considered by this study included the following:

a. **Landfill** – this is the reference system that is standard practice for WEEE plastics currently in the UK. The time span of the landfill site is considered to be 100 years. WEEE plastic waste is co-landfilled with other non-hazardous waste and no secondary products or recovered materials are gained from landfilling.
b. **Mechanical recycling with separated BFR WEEE plastics** – treatment and recycling of Low-BFR polymers and non-BFR WEEE polymers; presumes that the styrenic polymers PS, HIPS and ABS have been extracted in the dismantling, and pre-sorting phase outside the scope of the study. Presumed output is high-grade recyclate products, capable of substituting virgin polymers.
c. **Incineration (no energy recovery)** – using reject BFR polymers resulting from a mechanical sorting process. This material has been presumed to be incinerated with Municipal Solid Waste (MSW); a ratio of 3:97 BFR polymers to MSW has been presumed.
d. **Incineration with energy recovery –** using reject BFR polymers resulting from mechanical sorting process. This material has been presumed to be incinerated with Municipal Solid Waste (MSW); a ratio of 3:97 BFR polymer to MSW has been presumed. Energy only is recovered from this process at a presumed conversion efficiency of 26%.
e. **Feedstock recycling process RGS-90 –** This process has been developed for the treatment of PVC plastic waste but may be applied to brominated plastic wastes. Plastic polymers are mixed with caustic soda, pump through a heat exchanger and hydrolyser. The plastics hydrolyse to sodium bromide and denatured plastics. The plastic mix is filtered and the plastic waste discharged for further treatment; pyrolysis into an oil for further refining.
f. **Creasolv** – ground plastic material is dissolved in the creasolv solvent, which is filtered and passed through a second solvent through which the BFR's are extracted. The resulting solution is then passed through a solvent recovery process to produce a polymer that is suitable for re-use.
g. **Ionic Liquids** – This process uses a novel solvent which can be tailored to provide specific solvent properties. Plastic polymers are mixed with the ionic liquid into which the brominated compounds diffuse from the polymer matrix. The ionic liquid and solvent are processed and recycled.
h. **Centrevap** – This process uses solvents into which the plastic waste is dissolved at slightly elevated temperatures of 40°C – 60°C. The resulting slurry is then treated to remove the solid materials, including un-dissolved plastics, fillers and other additives, including un-dissolved BFR; these are collected and discharged as waste. The remaining slurry passes into a solvent recovery system to recycle the solvent and produce a pelletised clean polymer product.
i. **Anti-solvent** – This process uses a two solvents; the plastic waste is dissolved in one solvent at slightly elevated temperatures of 40°C – 60°C. The resulting slurry is then treated to remove the solid materials, including un-dissolved plastics, fillers and other additives, including un-dissolved BFR; these are collected and discharged as waste. A second solvent is then mixed with the polymer solution causing the polymer to precipitate; the solids are then removed using a centrifuge. The precipitated material is then melted and passed through a solvent recovery system prior to pelletisation of the material.

4.2.1 The Functional Unit

The functional unit of this study refers to the processing (input) of 1429kg of WEEE plastic polymer pre-sorted into brominated flame retarded styrenic polymers. This unit was defined by the mass balance throughput data available on the new process options and has been applied to other treatment options. With reference to incineration technologies, it has been assumed that this mass of plastic waste must be combined with municipal solid waste at a ratio of 3:97; the weight of total material entering this system has been multiplied up accordingly. It has also been presumed that 29kg of the input material is inert contaminants and 10% of the weight of plastic is accounted for by brominated flame retardant species.

In the case of mechanical recycling, it has been assumed that the functional unit is 1429kg of WEEE source plastics which have been pre-sorted to exclude brominated flame retardant styrenic polymers PS, HIPS and ABS; it has also been presumed that 29kg of the input material are inert contaminants.

4.2.2 System Boundaries

System boundaries were defined to incorporate the waste treatment options for separated E & E plastic waste; collection of this material originating from WEEE pre-sorting and dismantling plants is excluded as no study specific data was available and all transport related inputs and outputs would have been standardised for all process options. The defined system boundaries of this study can be seen in Figure 1.

The process of generating waste electrical and electronic equipment, the dismantling and pre-treatment of WEEE and polymer sorting of WEEE plastics from disposal collection points is specifically excluded. It was also assumed that the environmental impacts of final product manufacture using virgin compounds or recyclate were equal; this was also excluded from the scope of the survey.

As the study was conducted with a view to providing an broad overview of the potential environmental impact and comparable environmental performance of the different waste treatment processes, only those main consumables into each system were considered, i.e. primary energy, plastic polymer, inerts, solvents, water while output emissions inventories were restricted to the main species characterized in energy emission inventories; carbon dioxide, carbon monoxide, nitrogen oxides (NO_x), sulphur dioxide, Methane, non-methane Volatile Organic Hydrocarbons (NMVOC's). Emissions to water have been specifically excluded.

4.2.3 Data quality

Data available on the new recycling processes was obtained from practical studies and mass balance exercises undertaken by Axion Recycling. However, this information was only available at an aggregated level; only major material flows were detailed and no break down of energy consumption sources or measured emissions data was available. As such, realistic assumptions have been made where required; for example, solvent emissions during waste drum filling, and emission inventories for energy consumption have been derived from emission factors detailed in publicly available sources, such as NETCEN.

Avoided emissions and energy data relating to the production of virgin polymers was taken from the Eco-profile studies undertaken by the APME (Association of Plastic Manufacturers in Europe) during the late 1990s for the styrenic polymers included within this study. This information, although dated, has also been used as a base for deriving avoided energy and emissions data for the production and extraction of crude oils with regards to feedstock recycling processes.

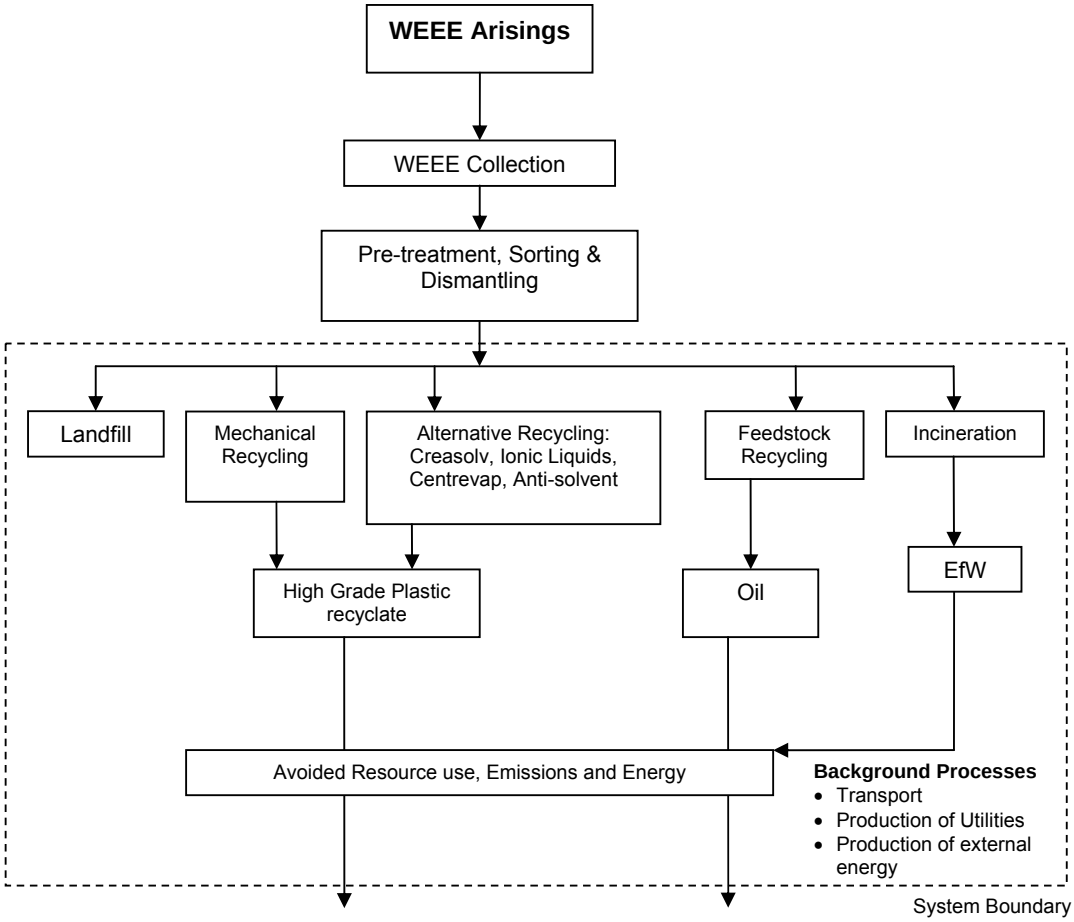

Figure 1 – System Boundaries of the Study

Publicly available data on mechanical recycling and incineration processes and emissions have been used and additional assumptions made where necessary; these are detailed in Appendix A; these include meeting the minimum emission requirements of the Incineration Directive. No specific practical trials using BFR plastics in these processes were undertaken for this study and therefore detailed inventory data is not available. Data used for the quantitative assessment is therefore generic to incineration and the mechanical recycling of plastic processes and not specific BFR WEEE plastic waste.

No input or output data for the RGS-90 process was publicly available and no practical trials were undertaken as part of this study to assess the feasibility or emissions inventories of using BFR plastics in a process specifically adapted for recovering PVC plastics. As such, no quantitative data additional to primary energy consumption could be derived for this process. Qualitative scores have been assigned to this process for the environmental impact categories selected for this assessment in a comparative evaluation of the overall environmental performance of the selected process options investigated in this study.

4.2.4 Critical Review

This study, as required by ISO 14040 has been reviewed by Axion Recycling.

5.0 Collecting Inventory Data

The first stage of the assessment involved quantifying all the inputs and outputs of each process by compiling an inventory of relevant energy and material inputs and associated environmental outputs. This data can be quantitative or qualitative in nature. To this effect, a qualitative pre-assessment of environmental impacts of each of the process options was undertaken to identify the potential environmental performance of each process. This was then supported by a quantitative assessment, using selected key environmental indicators.

Mass balance data provided from practical studies of waste treatment processes for BFR WEEE plastics has been used as a base for deriving more detailed inventory data where required. Assumptions have been made on the energy sources for these processes and emission inventories derived from nationally published UK data. Typically these have been sourced from NETCEN. All assumptions are detailed in Appendix C.

Inventory inputs and outputs relating to the avoided impacts of using recyclate in place of virgin styrenic polymers and crude oil have been taken from the Eco-profiles of the respective polymers published by APME; these have been derived from data provided to the APME from working plants across Europe and relate to specific production years. These are reported as inputs/ outputs per kg of polymer produced.

With regards to energy flows, fuels, electricity generation sources, energy efficiency conversion factors and emission factors, all these data are detailed in Appendix B and C. Allocation procedures for processes and systems that involve multiple products, i.e. petroleum refinery; materials, energy flows and releases have been considered and are detailed in Appendix B and C.

This data has been used to produce a simplified LCA to identify the potential inputs and outputs of these processes with regards to BFR plastic waste recovery options. Specific practical study data has been used where available in relation to the new process options evaluated. However, no specific inventory data was available relating to the processing of BFR plastics in mechanical recycling process, the feedstock recycling process or incineration processes. Generic, publicly available data has been used where available and the assumptions made in using this information are detailed in Appendix B and C.

6.0 Impact Assessment

6.1 Impact Assessment Categories

The following environmental impact categories were chosen and assessed for each waste treatment process;

- Global Warming
- Abiotic Resource Use
- Environmental toxicity
- Photo-oxidant formation

Other environmental indicators were considered for inclusion in this study, however, time constraints restricted the use of some additional indicators, while the use of other indicators were considered to be less relevant to the goals of the study. These are detailed below.

Global Warming
Global warming of the 'green-house effect' is the process whereby the lower atmosphere is heated by incoming radiation by the presence of gases, which prevents the release of this radiation into the outer atmosphere. The consequence of this process is elevated global temperatures, which may result in regional climate changes and lead to melting of the polar ice-caps and elevation of sea levels, causing global climate change.

The potential impact that greenhouse gases have on the environment is not only function of the volumes of gases released into the atmosphere, but also their ability to absorb or trap heat and their longevity in the environment. A co-efficient known as the Global Warming Potential (GWP) is a tool that has been used to quantify the potential global warming effect by qualifying the longevity and heat absorbing potentials of greenhouse gases relative to the reference specie, carbon dioxide, which is given a GWP of 1. GWP coefficients are rated on different time scales; usually on 20, 100 or 500 year periods as different greenhouse gases will effect global warming over different time scales.

The primary source of greenhouse gases for those waste treatment processes studied was expected to result from combustion processes; this is expected to be primarily linked to energy usage for all but incineration processes, where the embodied energy of the plastics themselves are released through combustion processes, resulting in the release of carbon dioxide and other emissions in excess of those expected from energy consumption. GWP was measured in terms of kg CO_2 equivalent (100 years) for CO_2 and CH_4.

Eco-toxicological Impacts
Eco-toxicology impacts are dependant on the actual emission and fate of these compounds when emitted to the environment. How these substances degrade and the rate at which they degrade will influence the nature of the toxicology effect that is produced, as will the rates of evaporation and degradation in particular environmental conditions and media. Where substances are not readily biodegradable the potential exists for these compounds to bio accumulate in the environment or biota to produce toxic effects.

The vast majority of literature publicly available relating to the environmental impact of BFR is concerned with the environmental and human toxicity of BFR species themselves, particularly in relation to the toxicology of sedimental organisms, their potential to bio accumulate and to form dioxins and furans on combustion and during other thermal processes.

The eco-toxicological impacts of those processes studied considered only the **potential** of those processes to release BFR species and to form dioxins and furans. This does not necessarily reflect the actual release of these compounds into the environmental from these processes.

No evaluation was undertaken with regard to other potential eco-toxicological impacts from these processes, such as the use of solvents or the creation of hazardous wastes.

Photo-oxidant formation

Ozone can be formed at ground level by a number of complex photochemical reactions between nitrogen oxides (NO_x) and organic compounds (VOC's (volatile organic compounds)). These are compounds that evaporate under ambient temperatures and pressures that are capable of creating ground-level ozone in the presence of sunlight, dependant on climatic conditions and relative concentrations of both VOC's and NO_x. The biological effects, in addition to local 'smog' formation and regional tropospheric ozone formation at a regional level, include damage to flora and humans exposed to ozone may suffer eye irritation and respiratory problems.

Photochemical ozone formation can be quantified by using photochemical oxidation potentials (POCP) for organic compounds. These are expressed as ethylene equivalents and are weighted against the reference compound ethylene (C_2H_4) which is given a value of 1. A negative POCP value is possible, implying that at ground level, the compound has the potential to destroy ozone.

VOCs species are produced by the combustion of fossil fuels; however, they are primarily associated with the use, discharge and storage of solvents. With the use of a number of solvents in the new BFR plastic recovery processes, there is the potential for photochemical ozone formation, dependant on the efficiency of solvent recovery and capture processes. Evaluating the POCP is therefore an environmental indicator for this study.

VOC's are not the only species that are linked to the formation of photochemical ozone; where individual VOC species can not be characterised in the emission inventories, NO_x, carbon monoxide and methane species should also be considered and associated POCP used.

Abiotic Resource Use

Abiotic resources include categories such as mineral deposits, fossil fuels, soil, groundwater, air etc. While resource use was incorporated as an environmental impact category in the qualitative assessment, complete and representative data was not available for all treatment options considered. Therefore, the quantitative assessment focused solely on primary energy consumption, which measures the depletion of non-renewable energy-providing resources, such as coal, crude oil and natural gas, expressed as Megajoules of energy.

Other Impact Categories:

Biotic Resources

This encompasses the harvesting of flora and fauna in non-sustainable and sustainable ways. Biotic resources are not believed to be a major inventory input to this study and therefore have not been considered further.

Land Use

Land use can be viewed from a number of different perspectives, including the impact that process activities have on bio-diversity, landscape fragmentation and degradation or food production. The timescales over which these changes are effected can range from short term to long term impacts. These are difficult to quantify and considered to effect the environment on a local scale.

Acidification Potential (AP)
Acidification is caused by the release of protons (H^+) into the environment. While the potential effect of these ions are dependant on the nature of the receiving environment, the emission of acid gases to the air can produce a number of detrimental environmental impacts including the acidification of soils and waters. There are four main gases that contribute to acidification (including sulphur dioxide, nitrogen oxides, hydrogen chloride and hydrogen fluoride), the major source of which is the combustion of fossil fuels and also waste. Acidification Potentials are expressed as SO_2 equivalents, weighted based on their acidic potential, expressed as acidification equivalents (moles H^+).

Linked with fuel combustion, AP indicators should follow the corresponding trend for GWPs where energy generation is the dominating source of greenhouse gases and there are no other significant sources of either greenhouse gases or acidic gases. Utilising the GWP indicator should therefore provide sufficient guide as to the relative trends for APs between the plastic waste treatment processes.

Eutrophication Potential
Eutrophication is defined as the over fertilization of soils and waters. The accumulation of nutritive compounds into these media's encourages the growth of certain algae, which in turn deplete the oxygen content of the media. As with acidification, the effect of emissions leading to eutrophication is dependant on the receiving environment.

The two most important eutrophicating substances are nitrates and phosphates, which are weighted in accordance to their potency and expressed as phosphate equivalents. The most important sources of these compounds are farming and industrial effluent. While ammonia originating from combustion processes is a potential source, deposition to waters and soils are not believed to be a significant source of eutrophication.

Industrial effluent with a COD (Chemical Oxygen Demand) is characterized as presenting an environmental burden and is represented with an eutrophication potency factor of 0.022. Plastic treatment processes which produce effluent to water may present a significant eutrophication potential, distorting the comparative trend with GWP that EP would otherwise be expected to follow. The adoption of EP as an environmental impact indicator in this study may need to be investigated further.

Stratospheric Ozone Depletion
The ozone layer is a layer of naturally occurring ozone molecules which forms a protective layer around the earth, filtering out incoming ultraviolet radiation. This layer exists at an altitude of 15 – 50km above the earth's surface. Decomposition of the ozone layer enables more UV radiation to reach the earth's surface, which can lead to skin cancer, cataracts, weaken the immune system and also lead to reduced crop yields and disrupt marine ecosystem. This has been observed particularly in the southern polar region where decomposition of the ozone layer is significant.

A number of man-made compounds, including chlorofluorocarbons (CFC's) are responsible for reducing the ozone layer. As with those gases that contribute to global warming, different ozone depleting compounds have differing potencies and residence times in the atmosphere; the potency of compounds to deplete the ozone layer are related to a reference compound. Ozone depleting potentials (ODP's) expressed as CFC-11 equivalents.

Prior to undertaking quantitative assessments on the environmental performance of the waste treatment options of BFR WEEE plastics, a qualitative environmental impact assessment was conducted using available published literature and process information.

6.2 Qualitative Assessment

6.2.1 Introduction

A qualitative pre-assessment of the chosen waste processing options was undertaken to assess and evaluate the potential and **perceived potential environmental burdens** of each process option weighed against the **perceived potential environmental benefits**. The result of this assessment is expressed as an overall potential environmental impact.

This assessment was undertaken prior to a quantitative assessment of process options in order to evaluate the relative environmental impacts of the different process options for treating bromine flame retarded plastics from waste electrical and electronic equipment.

6.2.2 Assessment Matrix

An assessment matrix was developed to evaluate the potential overall environmental impacts of the individual process options and the relative impacts of these processes against each other. This can be seen in Figure 2. These process options are placed into the matrix based on the relative assessed scores for a number of selected environmental benefit / burdens categorises, which are the summed and classified into low, low-medium, medium, medium-high and high impact bands.

Those processes which display low potential environmental burdens and high environmental benefits represent the lowest overall environmental impact and the best environmental situation; comparatively, where potential environmental burdens are high and the potential environmental benefits are low, a high overall environmental impact will result. This situation will make process the least suitable option, given the selected environmental categorises evaluated.

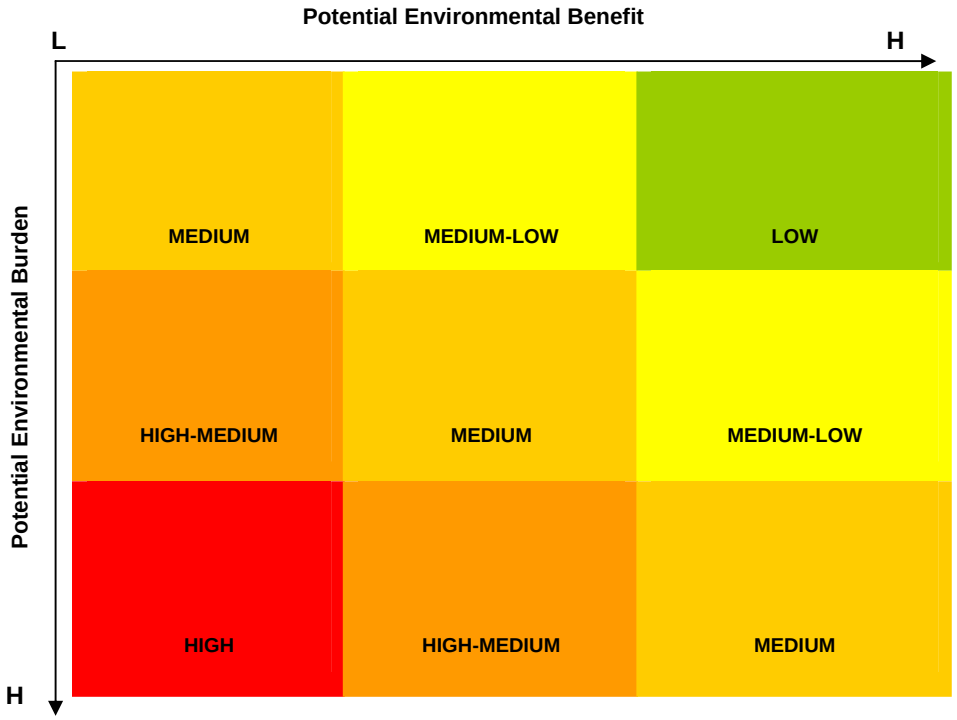

Figure 2: Environmental Impact Assessment Matrix

Details of the qualitative scoring process are provided in Appendix D.

6.2.3 Environmental Impact Categorises

Environmental impact categorises were selected based on literature research on the individual waste treatment options and the impact and fate of brominated flame retardants and their derivative(s) on the environment, and not on the potential availability of corresponding data. These categorises were deemed to reflect the most important detrimental and beneficial impacts that all processes might inflict on the global and local environment.

Environmental burden categorises include the environmental indicators Global Warming Potential (GWP) and Photochemical Oxidation Potential (PCOP), environmental toxicity and the consumption of raw materials and primary energy. Environmental benefit categorises were considered to include avoid emissions and resource use by the production and use of recyclate to substitute the use of virgin materials and the relative commercial value and quality of the resulting recyclate.

Arbitrary scores were appointed to each process for each category, summed to give total environmental benefit and burden scores and then allocated into a low, medium or high environmental impact band. The scoring system for this assessment can be seen in Appendix D. These were then placed into the corresponding areas of the environmental impact assessment matrix as seen in Figure 3.

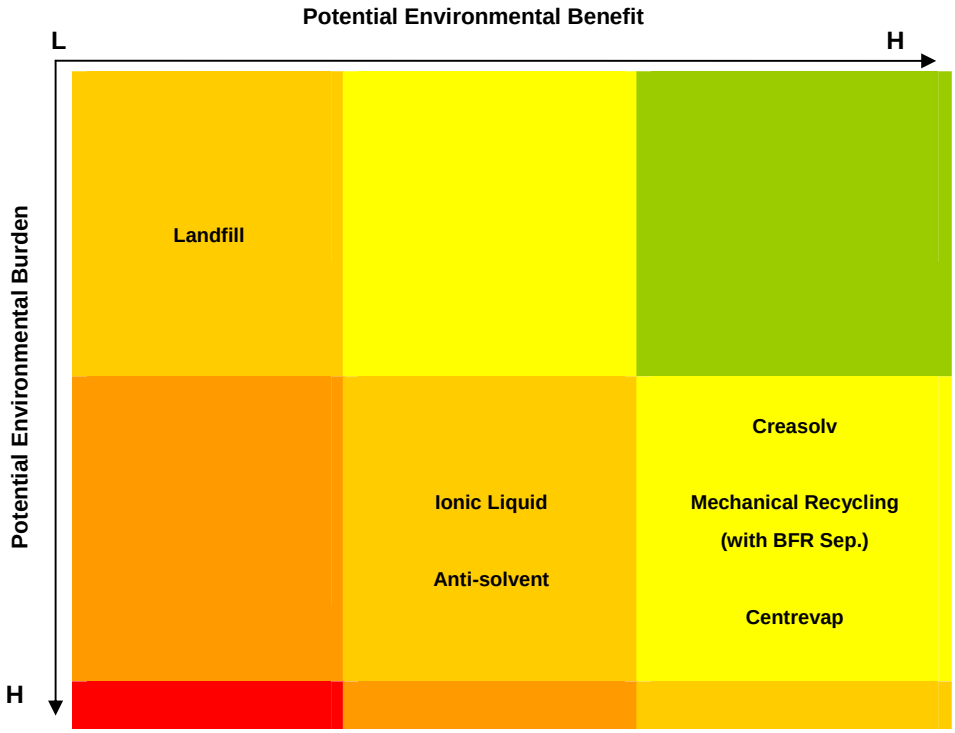

Figure 3: Results from the Qualitative Environmental Impact Assessment

6.2.4 Results from Qualitative Assessment

Results from the qualitative assessment suggest that Creasolv, mechanical recycling processes, Anti-solvent and Centrevap processes would demonstrate the smallest overall comparative environmental impact of those processes considered. A medium-low overall environmental burden was characterized, associated with a high potential environmental benefit, producing an overall medium-low environmental impact.

The assessment of Anti-solvent and Ionic liquid processes indicate that the overall environmental impact of these processes maybe higher than those of the previous solvent processes, producing a medium environmental impact. For the Ionic liquid process, scores for resource consumption and POCP are higher than those of the other solvent process, linked primarily to the higher solvent use and losses that are expected to be characterized by this process. In contrast, the Anti-solvent process has been scored higher for energy consumption and associated GWP than the other solvent processes, due to the perceived higher energy demands of the process.

The overall potential environmental performance for these new solvent processes is linked to the ability of these processes to produce a perceived high-grade plastic recyclate output which is able to substitute virgin plastic polymers (and therefore avoid the energy consumption and emissions that generated by these processes). In addition, these processes are not considered to be highly energy intensive nor do they involve high thermal processes which favour the release of environmental dioxins and furans, relative to some of the comparable processes.

Landfill processes have been categorised as presenting a medium overall environmental impact, despite presenting low environmental burdens, based on those assessment categories studied. This is due to the fact that the assessment reflects the lack of environmental benefits that can be derived from landfill processes. It should be mentioned at this point that this assessment does not take into account long-term eco-toxicity factors and land-use factors that are a particular concern in relation to landfill processes. The low environmental impact assessment relates to comparatively short-term impacts; this contrasts with the fact that many of the issues relating to landfill activities are long term impacts.

Feedstock recycling processes are characterized as presenting medium-high overall environmental impacts, along with incineration processes with energy recovery.

Feedstock recycling processes are characterized by high potentials to form dioxins and furans due to the high temperature that are required to process the plastic to oil which increase the environmental burden of this process. This is balanced by a perceived lower quality and value product output than mechanical and solvent recycling processes and the avoided the energy consumption and emissions that generated by these processes are less than for manufactured virgin polymers.

Incineration processes have been assessed as producing the highest potential overall impact on the environment. These processes release the embodied energy of the plastics, producing high GWP values and possess the high potential for furan and dioxin formation, producing a high environmental toxicological impact. Energy recovery processes off-set some of these burdens and therefore the environmental impacts of incineration with energy recovery fairs slightly better on the qualitative assessment.

6.3 Quantitative Assessment

6.3.1 Environmental Impact categories

Quantitative data was obtained for three of the four environmental impact categorises chosen for this study; primary energy consumption, Global warming potential (GWP) and Photochemical Oxidation Potential (POCP). However, no quantitative data could be obtained for the environmental toxicity indicator relating to the release of brominated flame retardant species during the new treatment process and the formation of dioxins and furans derived from these species through thermal processes. This was due to a lack of data available on the new processes and comparative process specific data for traditional process options. Given this, a review of currently available data and literature was undertaken and a qualitative assessment made of comparative environmental toxicity impacts of these processes.

6.3.2 Results from Quantitative Assessment – Environmental Indicators

The following Figures (4 to 6) show the environmental burdens and benefits calculated for each of the process options studied for three of the four environmental impact categories chosen. From these, the overall environmental impact for each process was determined and also displayed. Negative net impact values demonstrate that a process has an overall environmental benefit whilst positive net impact values reflect overall environmental burdens from a process.

While primary energy consumption data has been derived for the RGS-90 feedstock recycling process, no process emissions data was available. This is reflected in negligible environmental burden impacts for the GWP and POCP indicators being recorded in the emission inventories derived from energy consumption data, exclusive of additional process data. This does not reflect the true environmental impacts of this process for these indicators, only that no quantitative data is available to complete the analysis.

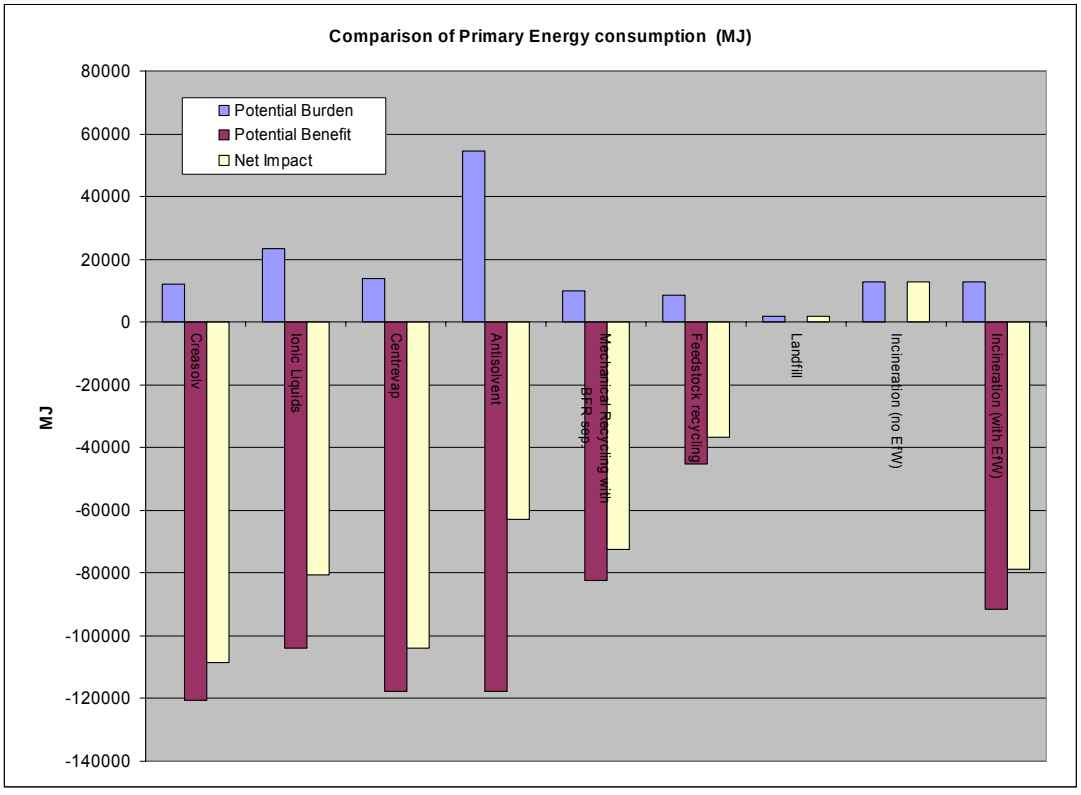

Figure 4 – Primary Energy Use (MJ) for each scenario

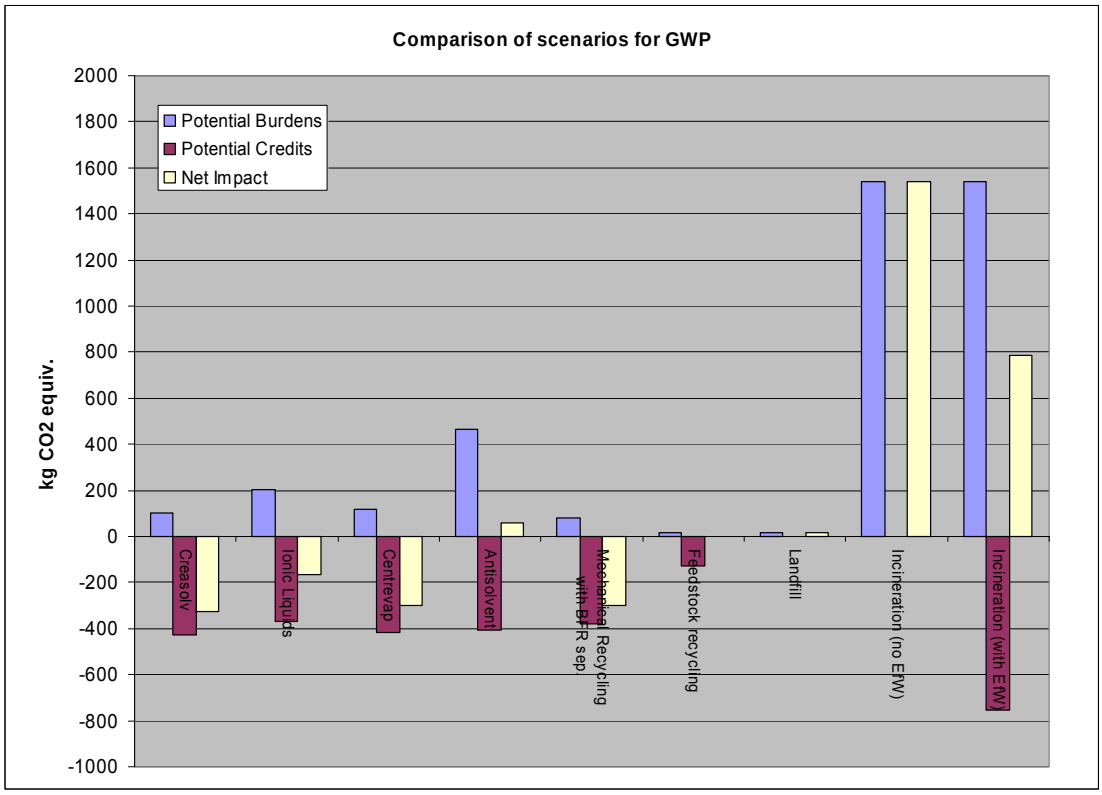

Figure 5 – Global Warming Potential (as kg CO_2 equivalents) for each scenario

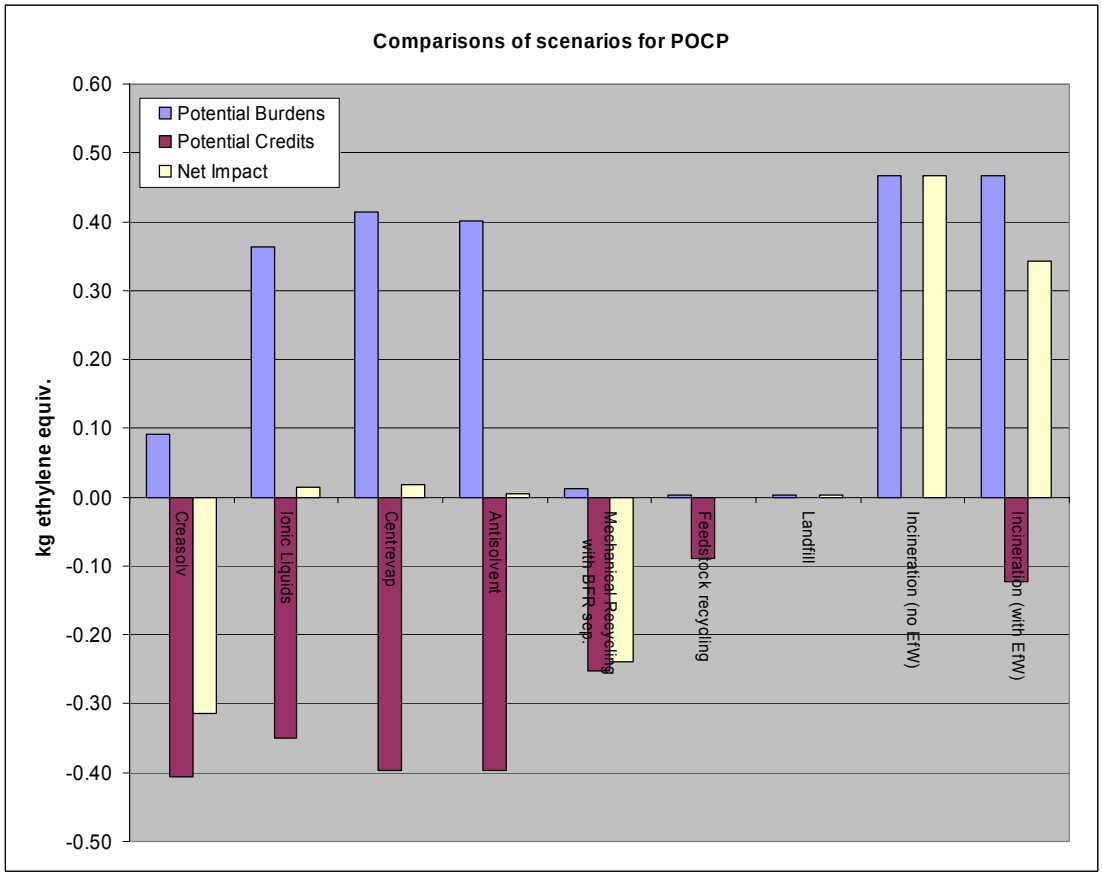

Figure 6 – Photochemical Oxidation Potential (as kg ethylene equivalents) for each scenario

6.3.3 Environmental Toxicology – Qualitative Assessment

Landfill Processes

Brominated flame retardants associated with plastic materials are likely to show little short-term volatisation from the plastic and leaching into the ground once landfilled. This is particularly relevant for reactive brominated flame retardants which are chemically bonded into the polymer matrix, rather than being added to the polymer prior to, during or following polymerisation. In the long term however, as the plastic starts to break down, which may take hundreds of years, the potential does exist for flame retardants to be released into the environment.

The potential for the formation of dibenzo-p-dioxins and furans from brominated flame retardants is associated with thermal processes, which do not typically exist at landfill sites. Therefore, the potential for these species to be formed is low. The exception to this is during landfill fires, which are generally accidental uncontrolled occurrences. Where landfill fires do occur, the potential for brominated dioxins and furans to be generated does exist, although the temperatures generated during such fires and the residence times of these compounds is likely to be longer than those used in experimental laboratory conditions, making predictions on the amounts of dioxins and furans that can be generated very difficult.

Mechanical Recycling Processes

A number of studies, including works undertaken by Riess et al. (1998), Meyer (1993), GfA (1999) and Hamm et al. (2001) suggest that dibenzo-p-dioxins and furans are not formed during normal extrusion and injection moulding processes. While the studies undertaken by Reiss et al (1998) and Meyer (1993) found that the levels of dioxins and furans in these recycled products exceeded the levels imposed by the German Dioxin Ordinance, the levels did not increase as a result of the recycling process. This is supported by work undertaken by GfA (1999) on Deca-BDE in HIPS plastics which related levels of dioxins and furans within the processed plastics to trace quantities found in the polymer prior to recycling.

The potential for dioxin / furan formation is associated with those processing stages which involve elevated temperatures, and for mechanical recycling processes, this is most applicable to the extrusion and moulding processes. These studies suggest that the dioxin / furan content of the recycled product is not influenced by the recycling processes itself, but by the dioxin / furan content of the input material; as such recycling of BFR plastics may only be feasible if mixed with other non-BFR plastics. However, dependant on material input and the use of suitable recycling conditions, the emissions of dioxins and furans and their concentrations in the recyclate can meet stringent levels imposed by the German Dioxin Ordinance.

It is less clear as to whether recycling processes result in a reduction of the higher brominated congeners to the lower brominated congeners which show greater environmental toxicity; work by Riess et al (1998) suggests that changes in the distribution of these congeners does occur during recycling processes, while works by GfA in 1999 using deca-BDE however found that there was no formation of the lower brominated diphenyl ethers. The potential for higher brominated congeners to reduce to the lower brominated congeners is dependant on the polymer and flame retardant composition of the recycled plastic material; this differs between studies or is not characterised making comparisons or analyses difficult. However, the plastic material considered for mechanical recycling within this study has undergone some polymer sorting to remove those stryenic polymers with which a high proportion of BFR species are associated and as such, the potential for the release of BFR species from mechanical recycling processes would be expected to be low and the resulting material of a quality to meet the minimum levels imposed by the German Dioxin Ordinance.

New Solvent-based Process Options

Brominated dibenzo-p-dioxins and furans may be present in small quantities as contaminants within brominated flame retardant species. The presence of these species following disposal and recycling activities does not therefore automatically ensure that they have been formed as a direct result of the process. However, no emissions analysis was conducted regarding dioxin and furan species formation or the release of BFR compounds, and, as novel processes, no comparable data is available from previous publicly available works from which an analysis can be made. Therefore, the potential for these processes to release BFR during the treatment process or the potential for the formation of dioxins and furans is unknown at present.

The formation of dioxins is greatest at temperatures approaching 250°C - 300°C, whilst the maximum temperature expected to be achieved during these solvent processes is 60°C. As such, it might be expected that the potential for dioxin and furan formation is lower than thermal processes such as feedstock recycling or incineration. However, the extrusion phase of these processes involves temperatures that are elevated above those expected during the extraction processes themselves, suggesting that the potential for new dioxin / furan formation exists at this stage.

It is unclear at present the potential of these processes to generate dioxins and furans during full-scale operations, particularly during plastic extrusion stages or how these processes compare to mechanical recycling in terms of dioxin and furan formation. However, it maybe expected that the potential for these compounds to be formed is lower than that of either incineration or feedstock recycling processes due to the lower temperatures generated and the lower-oxygen environments utilised by these processes.

There is also concern about the potential for dioxin / furans to build-up in the solvent recovery system of these processes, although this remains to be assessed (Axion, 2005). This concern should be investigated and addressed prior to commencement of full scale trials.

In contrast, the depolymerisation of the plastic during these processes may release reactive BFR species that are typically locked into the polymer structure of some BFR plastics and not available for release during traditional mechanical recycling processes. The release of BFR compounds may therefore be greater than mechanical recycling processes, particularly where the BFR waste is emptied into waste containers for disposal. Therefore, while not quantifiable at present it is possible to qualify them in relation to other processes considered in this study. While it might be expected that the emissions of these species exceeds those of mechanical recycling and landfill processes, it may also be expected that these emissions fall below those expected in thermal processes such as feedstock recycling and incineration.

While not a focus of the environmental toxicological assessment, the use of solvents in these processes may introduce additional environmental impact issues associated with their use and disposal, particularly as the waste generated through these processes are hazardous wastes.

RGS-90 Feedstock Recycling Process

The RGS-90 feedstock recycling process is designed to process PVC plastic waste through a hydrolysis process to produce oil, salt and minerals, for which end markets exist for all produced materials.

A review of the this process in the final report on; 'PVC Recovery Options Concept for Environmental and economic System Analysis' by PE Europe GmbH details that the formation of dioxins and furans is expected. This is a result of the process technology itself rather than the input material into the process. While the release of these compounds into the environment can be controlled through the use of primary and secondary scrubber systems and catalytic reactors, the potential for these compounds to be formed does exist, particularly downstream of the post combustion zone during the cool down phase in the boiler, through the so-called De-Novo-Synthesis process; this is optimal at temperature of 250°C – 300°C.

While is unclear what process changes would be required for this system to operate using brominated flame retardant plastic waste, the potential for dioxin and furan does exist, at levels approaching those expected through incineration processes and as such a similar environmental toxicological score would be expected. Specific emissions monitoring would be required to evaluate the true level of dioxin and furan formation from this process and those abatement measures that would be required in order for emission standards to be achieved.

Incineration Processes

Halogenated dibenzo-p-dioxins and furans are formed during thermal processes involving halogenated compounds. Optimal dioxin and furan formation is achieved at temperatures of 250°C – 300°C and at temperatures over 800°C the complete destruction of these species appears to occur. While proper incineration design can reduce the potential release to the environment, these species are formed during such processes. Several factors influence the formation of these furans including, temperature, residence time at that temperature, the presence of oxygen, the type of polymer matrix and the presence of other additives, particularly antimony trioxide.

While it is clear from a number of studies that polybrominated dioxins and furans are formed when heated, either alone or in mixed polymer matrices, quantification is difficult due the lack of analytical standards and experimental conditions. In a recent study by Söderström and Markland (2001), the ability of bromine and chlorine to form halogenated dibenzo-p-dioxins and furans during the co-combustion of Deca BDE or HBCD or TBBPA with municipal solid waste (MSW) was investigated. Results showed that under normal conditions, the flame retardants are completely destroyed and that there are no differences in the formation of dibenzo-p-dioxins or furans between the different flame retardants. However, co-combustion of BFR compounds with MSW is required in order to reduce the emissions of dibenzo-p-dioxins and furans to comply with current emissions standards.

In additional studies, no relationship between dioxin emissions from incinerators and the bromine level of the waste was found (Ten Berg, 1995), while Tange et al (2001) concluded that the formation of halogenated DBD and DBF was dependant on the products of incomplete combustion. Levels of halogenated dibenzo-p-dioxins and furans levels appeared to reach a constant level at bromine loads of 500 – 1,000mg/kg.

While proper incinerator design can reduce the release of dibenzo-p-dioxins and furans into the environment, incineration processes have the highest potential for the formation of dibenzo-p-dioxins and furans. It maybe expected that complex scrubber systems are required if BFR plastics are incinerated and studies suggest that high volumes of MSW are also required in order to dilute the concentrations of dibenzo-p-dioxins and furans emissions generated by BFR combustion to levels which will fall within current standards. In addition, while many incineration trials have been conducted using mixed WEEE plastic waste, the concentrates of BFR within these materials is not believed to be as great as those resulting from plastic pre-sorting stages of this study and the focus of our comparative processes.

As such, the emissions of these compounds may be expected to exceed those cited in other studies. In discussions with UK industry experts (Axion, 2005) concerns have been expressed that the combustion of the styrenic BFR-containing polymers resulting from the pre-sorting process, and used as a feedstock in comparable processes will substantially increase dibenzo-p-dioxins and furans formation. It is also anticipated that the consumption of material used in scrubber systems would also increase.

Due to this potential, incineration processes are considered to have the greatest potential environmental toxicity and has therefore been rated accordingly.

6.3.4 Results from Quantitative Assessment – Overall Environmental Impacts

The environmental burden / benefit of each process was scored for each environmental indicator, based on the comparative rank of these processes and summed to give a total environmental benefit and burden score (Table 1). These were then allocated into low, medium or high environmental impact bands and placed into the matrix developed through the qualitative assessment. The results of this quantitative environmental impact assessment can be seen in Figure 7. No weighting factors have been applied to these results.

With regards to the RGS-90 process, qualitative scores have been allocated for the GWP and POCP indicators based on the perceived ranking of these processes compared to those other processes studied.

	Primary Energy Consumption (MJ)		GWP (kg CO_2 equivalent)		POCP (kg ethylene equivalent)		Environmental Toxicity	**Overall Summed Score**	
	Burden	Benefit	Burden	Benefit	Burden	Benefit	Burden/ Benefit	**Burden**	**Benefit**
Creasolv	4	9	3	8	3	9	3	**13**	**26**
Ionic Liquids	8	6	5	5	4	6	6	**23**	**17**
Centrevap	7	8	4	7	6	8	5	**22**	**23**
Anti solvent	9	8	6	6	5	8	5	**25**	**22**
Mechanical Recycling	3	4	2	4	2	5	2	**9**	**13**
RGS-90 Feedstock recycling	2	3	7	3	7	3	8	**24**	**9**
Landfill	1	0	1	0	1	0	1	**4**	**0**
Incineration	6	0	9	0	9	0	9	**33**	**0**
Incineration (EfW)	6	5	9	9	9	4	9	**33**	**18**

	Qualitative score
High	25 – 36 (burden) 19 – 27 (benefit)
Medium	13 – 24 (burden) 10 – 18 (benefit)
Low	1 – 12 (burden) 1 – 9 (benefit)

Table 1: Environmental Performance Ranking Scores for each process

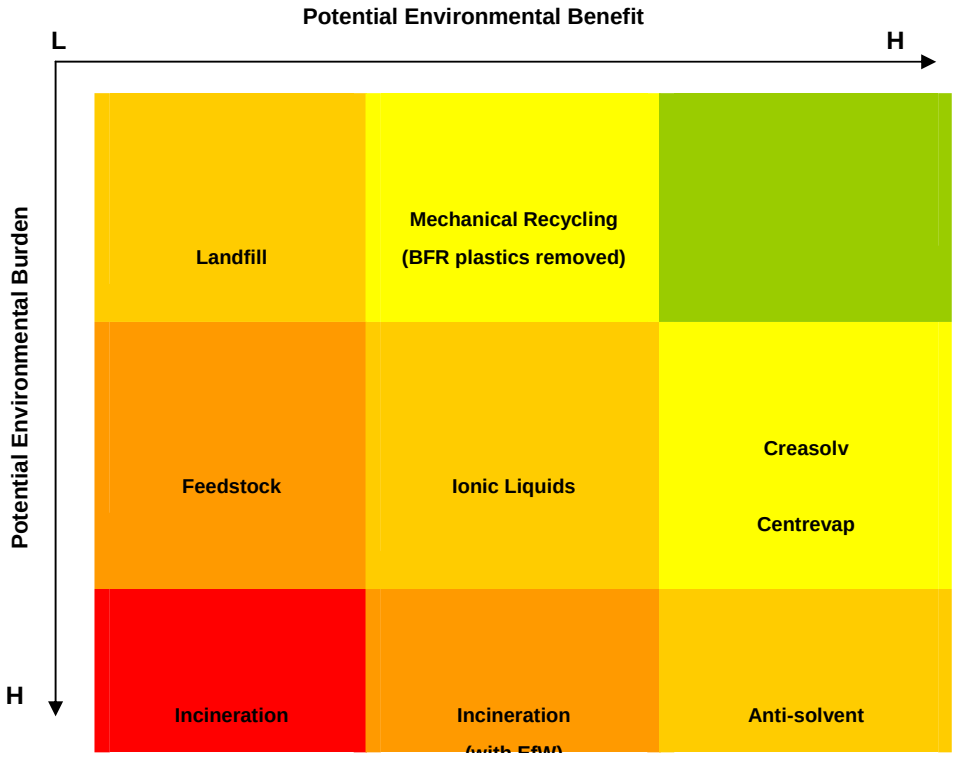

Figure 7: Results from the Quantitative Environmental Impact Assessment

Results from the quantitative analysis indicate that the environmental impacts of Landfill and Incineration (no EfW) processes follow those anticipated from the qualitative assessment. These processes (for those environmental indicators used) show no environmental benefits as no value is returned to the environment by treating BFR plastics through these processes.

The environmental burdens of landfill are primarily linked to the use of on-site compaction vehicles while those of incineration relate to the release of embodied energy and associated emissions from plastic combustion. As mentioned in the qualitative assessment, landfill activities are considered to have a medium overall environmental impact, based on those indicators used in this study. These do not take into account the long-term release of BFR to the environment as the plastic materials degrade or long-term land-use issues which impacting on the environmental burden of this process.

Comparatively, incineration (no Energy from Waste (EfW)) is categorised as having a high overall environmental impact, while incineration (with EfW) recovery has a medium-high overall environmental impact as expected. However, higher environmental burdens and benefits are resultant from this process than those predicted in the qualitative assessment. The difference between these two processes is reflected in the value of energy recovered in energy from waste processes, which substitutes for the combustion of non-renewable fossil fuels.

Data for the feedstock recycling process RGS-90 is absent in relation to the GWP and POCP indicators. Qualitative scores have been assigned to this process relating to the perceived overall rank of this process in relation those others studied and as a result, feedstock recycling processes have been assessed as resulting in an overall medium-high

environmental impact. Environmental toxicity has been scored as being high for this process, with process temperature generated being those approaching optimal for dioxin and furan formation.

The process also utilises a portion of the plastic material input as fuel to drive the process; the corresponding emissions have been allocated as falling between those of incineration processes and that of the Anti solvent process.

The results of the quantitative analysis indicates that the best environmentally performing processes involving the treatment of BFR plastics are the Creasolv and the Centrevap processes which demonstrate a low-medium overall environmental impact. Comparatively, the mechanical recycling of those plastics from which the styrenic BFR-containing polymers have been removed also produces a corresponding low-medium overall environmental impact, although the perceived environmental burdens of this process are lower than those of the best performing new solvent processes. This is primarily associated with the use of solvents in the new solvent processes.

Analysis of the comparative performance of the new processes, considering the four environmental indicators selected, are similar for all four of these processes. Primary energy consumption is seen to be greatest for the Anti-solvent and Ionic Liquid processes and this is reflected in the results for GWP, which are linked primarily to energy consumption for these processes. Comparative environmental benefits (through avoided virgin polymer production) for these and the Creasolv process are also similar.

However, the greatest variation between these processes is reflected in the results for the POCP. This is a direct result of the differences in the type of solvent used and the perceived solvent losses from these processes.

Mass balance data suggests that lowest solvent loss occurs from the Creasolv process; this is reflected in the overall potential environmental impact of this process for the POCP indicator and is the only solvent process for which an overall negative environmental impact was achieved. Comparative data for the Ionic Liquid process suggests that the greatest solvent losses occurs from this process, while the Anti-solvent process displays the greatest overall environmental impact in relation to this indicator. As a result, both these processes indicate an overall medium environmental impact, with the Anti-solvent process displaying high environment burdens and benefits compared to the medium environmental burdens and benefits of the Ionic Liquid process.

Creasolv and Centrevap process appear to offer the lowest environmental impacts of the new solvent processes investigated, for those environmental impact categories selected. These appear to compare favourably with those mechanical recycling processes from which the styrenic BFR containing plastic polymers have separated.

It should be high-lighted that the performance of all these solvent processes is dependant on the efficiencies of the solvent recovery systems in place. The Creasolv process in particular is distinguished as presenting low solvent losses and high solvent recovery efficiencies, however, if this efficiency is reduced, the environmental burden of the process will increase, along with results for the POCP environmental indicator. This would increase the overall environmental burden of the process.

Similar effects are expected for the other solvent processes, if the efficiencies of the solvent recovery systems are reduced.

7.0 Summary and Conclusions

Qualitative and a quantitative environmental impact assessment of the process options investigated in this study appear to show that Creasolv and Centrevap have the lowest potential environmental impacts, alongside mechanical recycling, for those environmental indicators used. These new solvent processes appear more favourable than the Ionic liquids and Anti-solvent processes, which have higher comparable solvent consumptions and/or energy demands per unit input/output of plastic material.

However, it should be high-lighted that the performance of all these solvent processes is particularly dependant on the efficiencies of the solvent recovery systems in place. If these efficiencies are reduced, the environmental burdens of these processes would be expected to increase resulting from higher POCP impacts and thereby increasing the overall environmental impact of the process.

No emissions or analysis data was available on the potential of these processes to form dibenzo-p-dioxins and furans during extrusion and concerns have been expressed that these compounds may have the potential to build up in the solvent recovery system. These should be assessed and quantified prior to commencement of any full scale trial. However, it may expected that the potential release of dibenzo-p-dioxin and furans by these processes is lower than those of feedstock recycling or incineration due to the significantly lower operating temperatures and low-oxygen environments used by these processes.

In contrast, both the qualitative and quantitative assessments show the greatest potential environmental impacts for the incineration processes. These have been assessed as producing high and medium-high potential environmental impacts based on the considerably higher GWP values to other treatment processes, and the perceived greater potential for dibenzo-p-dioxin and furan formation. In particular, industry experts have expressed concerns that the combustion of the styrenic BFR-containing polymers resulting from the pre-sorting process, and used as a feedstock in comparable processes will substantially increase dibenzo-p-dioxins and furans formation. It is also anticipated that the consumption of materials used in scrubber systems would also increase and that power generation efficiency would be compromised by the build-up of bromine and metal salts in the furnace super-heater.

While practical studies have been conducted that indicate that the formation of these compounds is not dependant on the bromine input into the process, but more on the process technology and that the release of these compounds into the environmental can be controlled by the installation of complex catalysts and scrubber systems, the environmental assessment has been conducted with a view to the potential of the waste processes to form these compounds.

Feedstock processes have been considered as providing similar potential to form these compounds. While a lack of quantitative data hinders the comparability of this process with those others studied, it is considered that this process may offer a medium environmental impact based on comparatively lower GWP and energy consumption values than incineration processes.

Landfill activities are considered to have a medium environmental impact, primarily based on low energy demands, however there are also low environmental benefits from the process. This is not necessarily a true reflection of the environmental impact of this process, as this waste ‘treatment’ option operates over a longer time scale than other processes considered, for example the potential release of BFR into the environment will operate over a period of hundreds of years as the plastic materials start to break down. In addition, land use indicators, which would be of particular importance to landfill sites, were not considered in this study.

8.0 Limitations of the Study

The quality of the analysis of the environmental impacts of waste treatment options for BFR plastic waste has been restricted by a lack of process specific emissions data, including dioxin, furan and BFR emissions for the new solvent processes and the feedstock recycling process RGS-90. Publicly available generic data has been utilised to fill in the data gaps, where possible, however, quantitative data gaps still exist with regards to BFR, dioxin and furan emissions.

In addition, concerns were also raised about the potential for dibenzo-p-dioxin and furans to build up in the solvent recovery systems of the new solvent processes.

Quantitative emissions data should be gathered to fill-in the data gaps in these processes and address those concerns raised about potential dibenzo-p-dioxin and furan build-up in solvent recovery systems which will affect the operating efficiency of large scale processes.

The study also did not consider the environmental impacts of the generation of hazardous waste as a consequence of the treatment process, the environmental impacts of solvent use nor did it consider emissions to water, on which some of the solvent process may have significant impact.

To complete a holistic assessment of the environmental impact for these processes, these environmental impacts should be investigated. It is also recommended that this study should be supported by process-specific emissions monitoring for the new solvent processes in order to validate the results of this investigation.

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10.0 Glossary

ABS	Acrylonitrile Butadiene Styrene
AP	Acidification Potential
APME	Association of Plastic Manufacturers in Europe
BFR	Brominated Flame Retardants
BDE	Diphenyl ethers
CFC	Chlorofluorocarbons
COD	Chemical Oxygen Demand
DBD	Dibenzo-dioxins
DBF	Dibenzo-furans
E & E	Electrical and Electronic
EfW	Energy from Waste
EP	Eutrophication Potential
GWP	Global Warming Potential
HBCD	Hexabromocyclododecane
HIP	High Impact Polystyrene
LCA	Life Cycle Assessment
MSW	Municipal Solid Waste
NETCEN	National Environment Technology Centre
NMVOC	Non-methane Volatile Organic Compounds
NOx	Nitrogen oxides
ODP	Ozone Depletion Potential
PBB	Polybrominated biphenyls
PBDE	Polybrominated Diphenyl ethers
PC	Polycarbonate
POCP	Photochemical Oxidation Potential
PVC	Polyvinyl Chloride
TBBPA	Tetrabromobisphenol-A
TBPE	1,2- (tribromophenoxy) ethane
VOC	Volatile Organic Compounds
WEEE	Waste Electrical and Electronic Equipment
WRAP	Waste and Resources Action Programme

APPENDIX A

REPORT CONDITIONS

WHITE YOUNG GREEN ENVIRONMENTAL

REPORT CONDITIONS

LIFE CYCLE ASSESSMENT:
SUMMARY REPORT OF

SELECTED TREATMENT PROCESSES FOR WEEE PLASTICS CONTAINING BROMINATED FLAME RETARDANTS

This Life Cycle Assessment summary report is produced solely for the benefit of Axion Recycling and no liability is accepted for any reliance placed on it by any other party unless specifically agreed in writing otherwise.

This report refers, within the limitations stated, to the operational processes as per the information supplied to WYGE. No warranty is given as to the possibility of future changes in the design of these processes.

This report is based on reference data provided by Axion Recycling, accessible referenced records and information supplied by those parties referenced in the text. Some of the opinions are based on unconfirmed data and information and are presented as the best that can be obtained without further extensive research.

Whilst confident in the findings detailed within this report because there are no exact UK definitions of these matters, being subject to risk analysis, we are unable to give categorical assurances that they will be accepted by authorities or funds etc. without question as such bodies often have unpublished, more stringent objectives. This report is prepared for the proposed uses stated in the report and should not be used in a different context without reference to WYGE. In time improved practices, data quality or amended legislation may necessitate a re-assessment.

APPENDIX B

ENERGY CONVERSION FACTORS

Energy conversion Factors

1.	1kWh	=	3.6 MJ
2.	1 MJ	=	0.2778 kWh
3.	1 therm	=	29.31 kWh
4.	1 kWh	=	0.03412 therms
5.	1 tonne coal	=	7583kWh
6.	1 tonne gas oil	=	12519 kWh
7.	1 litre heating oil	=	11.3kWh
8.	1 tonne heating oil	=	1238 litres heating oil
9.	1 litre heating oil	=	37.3 MJ
10.	$1m^3$ natural gas	=	39 MJ
11.	1 m^3 natural gas	=	0.0007 tonnes

APPENDIX C

ASSUMPTIONS

General

1. All data is based on the input of BFR WEEE polymers into the system. This equates to 1429kg WEEE plastic.
2. It is presumed that 1429kg WEEE plastic will be processed in an hour, for all processes.
3. It is assumed that all energy data provided for the new systems equals the amount of energy required to process 1429kg of WEEE plastic input, per hour.
4. An average draw of electricity of 500kWh has been presumed for the Ionic liquid, Creasolv, Anti-solvent, Centrevap, mechanical recycling and feedstock recycling processes, per hour. This is in addition to process specific energies.
5. Environmental burdens have been assessed based on primary energy consumption, fuel usage by on-site plant and solvent use for each process.
6. Emissions from processes such as plastic extrusion, pellet formation etc. have not been quantified and therefore not been assessed.
7. Environmental burden is calculated based on the burdens of processing 1429kg of WEEE plastic waste input into the system.
8. Environmental benefits are calculated based on the requirements of replacing virgin materials with the weight of the resulting product of the recovery process.
9. It is presumed that the new processes will produce high-grade plastic recyclate which will replace virgin plastic materials. A ration of 1kg recyclate to replace 1 tonne virgin plastic has been assumed.

Assumptions for Electricity Generation

1. That energy consumption, where not specified is split 60:40 between electricity and oil
2. That primary fuel sources for UK electricity generation are:
   a. Coal - 33%
   b. Gas – 41.5%
   c. Oil – 1.5%
   d. Nuclear 24%
   e. Hydro - 2%
3. No emissions arise from electricity production from nuclear and hydro / renewable energy sources
4. For electricity generation, the combustion efficiencies of the respective fuels are:
   a. Coal - 36.2%
   b. Gas - 46.6%
   c. Oil - 31%
5. Emission factors are taken from the national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei
6. Emission factors from electricity generation for electricity generation from Power Stations are taken from the national air emission inventory website. Emission factors for coal, natural gas and gas oil have been used.
7. Carbon dioxide emissions are based on a stoichiometric calculation, using the carbon emission factor provided from the National Air Emission Inventory website. (Carbon emission/mol. Wt carbon (12)) x mol. Wt. CO_2 (44)).

Environmental Impact Potency Factors

1. Two environmental impact factors have been chosen for this study; Global Warning Potential (GWP) and Photochemical Oxidation Potential (POCP).
2. These are reported as tonnes of CO_2 and tonnes of ethylene equivalents respectively per year.
3. All process data has been calculated based on input into the system over an hour period. The reported potency factors for these environmental indicators therefore require conversion to kg/hour.
4. Potency factors for GWP and POCP are taken from:
   www.icheme.org/sustainability/metrics.pdf

	GWP CO_2 equivalents		**POCP ethylene equivalents**	
	CO_2 t/y	**CO_2 kg/hr**	**Ethylene t/y**	**Ethylene kg/hr**
Carbon Dioxide	1	0.114	0	0
Carbon Monoxide	3	0.352	0.027	0.0031
NO_x	40	4.556	0.028	0.0032
N_2O				
Methane	21	2.397	0.0340	0.0039
NMVOC	11	1.256	0.596	0.0680
SO_2	0	0	0.048	0.0055
Toluene	11	1.256	0.771	0.088
Methanol	11	1.256	0	0
Creasolv 1st Solvent	11	1.256	0.596	0.068
Creasolv 2nd solvent	11	1.256	0	0
Ethyl Acetate	11	1.256	0.328	0.037
Hexyl pyridinium bromide	0	0	0	0

Assumptions for other On-site energy generation

1. That 40% of on-site energy generation for the new processes is generated from heating oil.
2. Combustion efficiency for this process is 81%. This figure is taken from the average UK oil fired steam boiler combustion efficiencies, which range from 70 - 92% (average = 81%. Source: www.actionenergy.org.uk
3. Emission factors for heating oil are taken from: national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei and those factors for fuel oil for 'other industry' have been used.
4. A gross calorific value of 45.6MJ has been used for diesel.
5. Emission factors available for diesel combustion, with the exception of carbon and sulphur dioxide, are characterised by the travel profile of the vehicle. No travel data was available for compactors.

Avoided Emissions: from virgin plastic production

1. Data is taken from the Eco-profiles for polymer plastics produced by APME. Eco-profiles for HIPS, ABS and PC have been used.
2. Data for gross primary fuels and feedstock have been used for energy consumption and feedstock process.
3. Energy consumption for fuel production and transport processes are specifically excluded.
4. Emissions include fuel use and process operations; emission from fuel production and transport are specifically excluded.
5. GWP weighting have been applied to the emission inventories where possible; a weighting of 11 has been given to all non-methane VOCs groupings, where individual values are not available.
6. POCP weighting have been applied to the emission inventories where possible; averaged values for the alkanes, alcohols, ketones and alkenes have been used as a representative weighting for the hydrocarbon group and 'other' organics; averaged values for aromatic species have been used fro the aromatic and polycyclic hydrocarbon groupings; the aldehyde grouping used average values for individual aldehyde species.

Process specific Assumptions: LANDFILL

1. There is no available data for energy consumption at landfill sites. An average electricity draw of 500kWh has been presumed.
2. There is no data available on transport emissions from compactor vehicles at landfill sites.
3. A fuel consumption figure of 0.6litres diesel per m^3 of landfill void filled is quoted in *'Integrated Solid Waste Management: A life-cycle Inventory'* (2001) by McDougall, F.R, White, P.R, Franke, M. and Hindle, P and has been used.
4. Emission factors have been taken from national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei relating to industrial off-road transport. These have been used as there is an absence of travel related data for this activity.

Process specific Assumptions: NEW PROCESSES

1. Emission factors from fuel use for plant have been taken from the national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei relating to industrial off-road transport.
2. Solvent emissions are presumed to amount to 2% of made-up solvent, minus those emissions to water.
3. A GWP of 11t/y CO_2 equivalent has been used for all solvents (equivalent to VOC emissions).
4. A POCP potency factor of 0.596 t/y ethylene equivalent has been used for paraffinic hydrocarbons; this is an averaged value from alkane, alkene, ketone and alcohol species.
5. The following plastic output from the New processes has been used (provided by Axion):
   a. Creasolv 1275kg
   b. Ionic Liquid 1100kg
   c. Centrevap 1245kg
   d. Anti-solvent 1245kg

Process specific Assumptions: INCINERATION

1. It is presumed that incineration plants recover power only, not heat; there is no Bromine recovery.
2. Combustion efficiency is calculated at 26%.
3. Assumes that ratio of MSW:BFR WEEE plastics is 97:3.
4. Assumes that BFR can only be incinerated alongside MSW.
5. Calorific value of WEEE plastic is 44.3MJ/kg. This is based on the average calorific values for ABS, HIPS and PC.
6. Assumes that the calorific value of MSW is 7.06MJ/kg. This figure is taken from 'Integrated Solid Waste Management: A life-cycle Inventory' (2001) by McDougall, F.R, White, P.R, Franke, M. and Hindle, P and is an averaged value for UK MSW.
7. Assumes 0.23m3/ tonne waste of natural gas is required to heat up the incinerator. This figure is taken from 'Integrated Solid Waste Management: A life-cycle Inventory' (2001) by McDougall, F.R, White, P.R, Franke, M. and Hindle, P.
8. Emission factors are taken from national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei relating to MSW incineration. Emissions are currently calculated on 100% MSW, not 97%; no information on emissions from plastic combustion is available at the present time.
9. Carbon dioxide emissions are based on a stoichiometric calculation, using the carbon emission factor provided from the National Air Emission Inventory website. (Carbon emission/mol. Wt carbon (12)) x mol. Wt. CO_2 (44)).
10. Assumes that power recovered generates electricity; this electricity replaces traditional means of electricity generation.
11. No allowance is made for additional or lower energy requirements of the system by incorporating a higher proportion of plastics into the stream.

Process specific Assumptions: MECHANICAL RECYCLING: separation of BFR plastics

1. Average energy draw of 500kWh is required
2. Energy consumption to process 1kg of plastic is 5632KJ. Taken from: MUNICIPAL PLASTIC WASTE: ALTERNATIVES FOR RECYCLING WITH PROFIT by *Ana C. Eulálio, Numa J. Capiati and Silvia E. Barbosa.*
3. Assumes that 100% energy consumption is obtained from electricity.
4. Assumes that input into the process is 1429kg of mixed plastic waste; when sorting efficiency and BFR plastics are discarded, it is presumed that the output of the process is 1143kg of plastic recyclate.
5. Assumes 100% of emission from the process is from energy consumption.
6. A sorting efficiency of 82% is achieved.
7. 29% of mixed plastic input is BFR plastics (mainly PS and ABS); these are discarded as waste (Wrap study): *'Recycling of WEEE plastic waste at PHB'* van Schijndel. P, van Kasteren, J. TU Eindhoven, Study for European Brominated Flame Retardant Industry Panel, April 2004.
8. Assumes 2% of material input is inerts / non-plastic material.
9. 100% of material is WEEE sourced plastic.
10. Assumes pre-sorting to produce a mixed plastic material.

APPENDIX D

QUALITIATIVE ASSESSMENT SCORES

Environmental Burdens

- Potential for Environmental Toxicity
  (based on potential to release BFR, dioxins & furans)
  0 – Negligible
  1 – Low
  2 – Medium
  3 – High (short term)
  4 – High (long-term)

- Global Warming Potential
  0 – Negligible
  1 – Low
  2 – Low - Medium
  3 – Medium - High
  5 – High

3. Energy Consumption
   0 – Negligible
   1 – Low
   2 – Medium
   3 – High

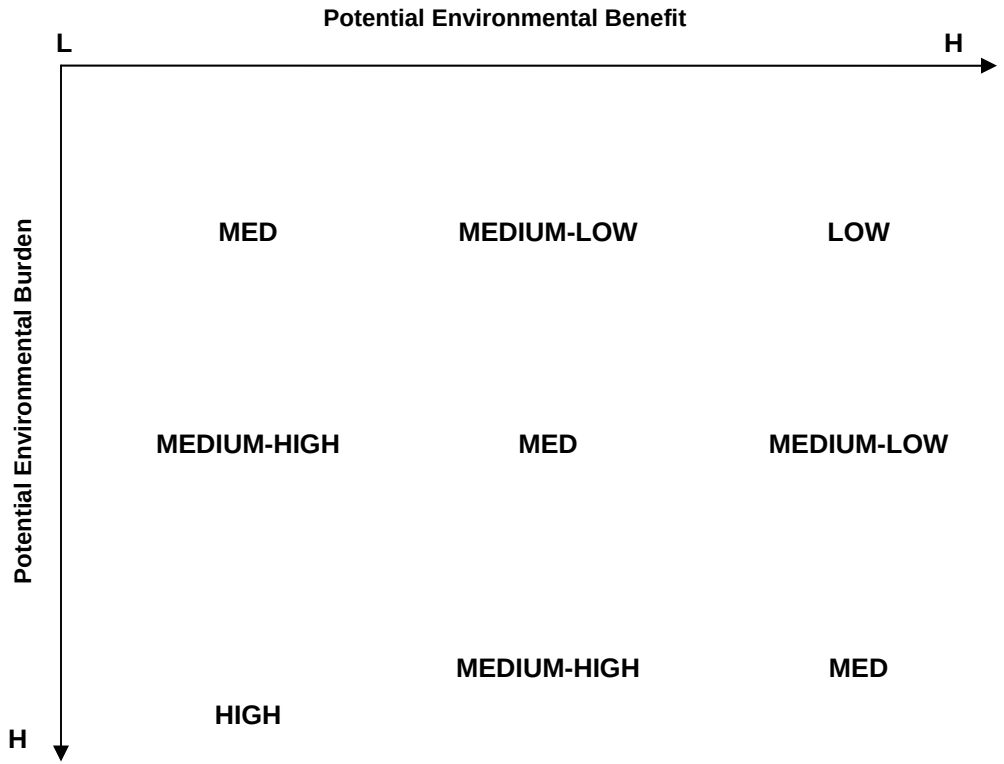
4. Resource Use
   (Resources consumed excl. E & E plastic)
   1 – Negligible
   2 – Low
   3 – Medium
   4 – High

5. POCP Potential
   1 – Negligible
   2 – Low
   3 – Medium
   4 – High

Environmental Benefits

1. Relative Value of Resource Recovered
   0 – none
   1 – Low (Energy / Bromide)
   3 – Medium (low grade recyclate / feedstock polymer)
   5 – High (high-grade recyclate)

2. Avoided Resource Use
   (primary resource & energy)
   0 – None
   2 – Fossil fuel for energy production
   3 – Oil (feedstock substitute)
   5 – Virgin plastic



The qualitative assessment has been made by evaluating the potential benefits that the individual processing options may have on the environment balanced against the potential burdens that these processes may have on the environment. The results of this evaluation have been expressed as an overall potential environmental benefit.

The matrix set out above has been score based on the overall potential benefits that the processing systems may bring to the environment. The scoring bands, based on the qualitative scoring system detailed above are set out below.

Lowest potential environment impact score = +10
Highest potential environmental benefit score = -20

Score Bands:

High Environmental Impact –	(-15 to -20)	Medium – High Environmental Impact -	(-8 to -14)
Medium Environmental Impact -	(-2 to -7)	Low - Medium Environmental Impact -	(+4 to -1)
Low Environmental Impact -	(+10 to +5)		

Scoring for WEEE Plastic Recovery and Recycling Processes

Process	Environmental Burden Score		Environmental Benefit Score	Overall Environmental Impact Score
Incineration (no EfW)	(1)= 4	(2)= 5	(1)= 0	0 – 17 = -17
	(3)= 2	(4)= 2	(2)= 0	
	(5)= 4	**Total = 17**	**Total = 0**	**HIGH**
Incineration (with EfW)	(1)= 4	(2)= 5	(1)= 1	3 – 17 = -14
	(3)= 2	(4)= 2	(2)= 2	
	(5)= 4	**Total = 16**	**Total = 3**	**MEDIUM-HIGH**
Feedstock Plastic Recycling	(1)= 3	(2)= 3	(1)= 3	6 – 14 = -8
	(3)= 3	(4)= 2	(2)= 3	
	(5)= 3	**Total = 14**	**Total = 6**	**MEDIUM-HIGH**
Landfill	(1)= 1	(2)= 0	(1)= 0	0 – 3 = -3
	(3)= 0	(4)= 1	(2)= 0	
	(5)= 1	**Total = 3**	**Total = 0**	**MEDIUM**

Creasolv	(1)=	1	(2)=	2	(1)=	5	10 – 7 = +3
	(3)=	2	(4)=	1	(2)=	5	
	(5)=	1	**Total = 7**		**Total = 10**		**MEDIUM - LOW**
Ionic Liquid	(1)=	2	(2)=	2	(1)=	5	10 – 12 = -2
	(3)=	2	(4)=	4	(2)=	5	
	(5)=	2	**Total = 12**		**Total = 10**		**MEDIUM**

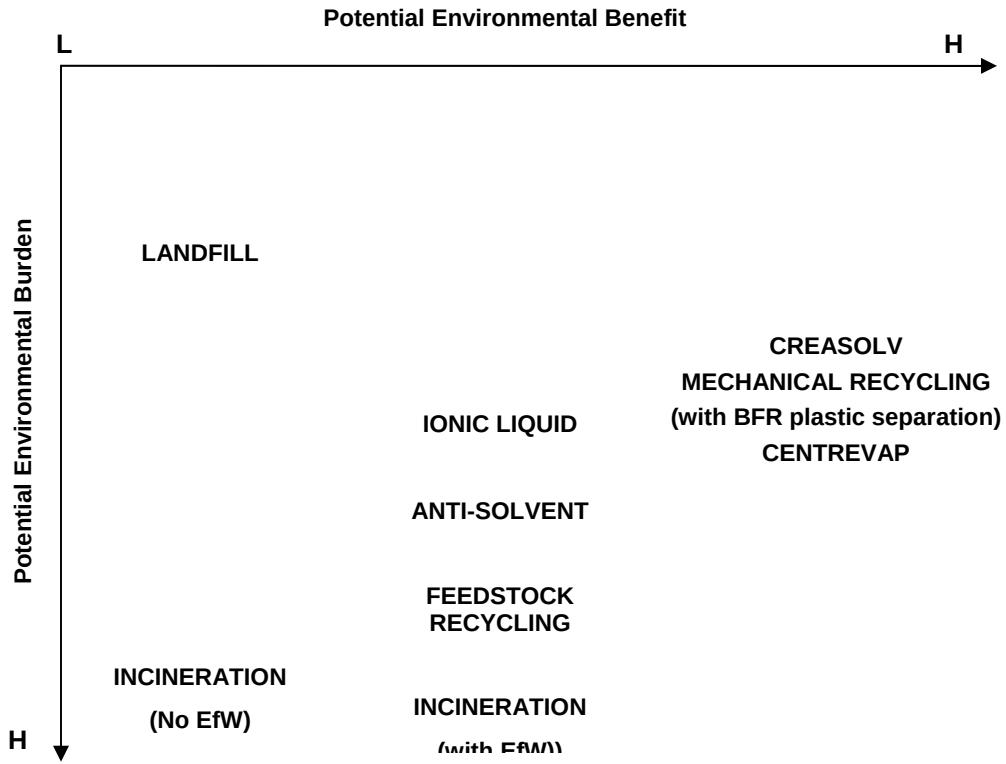
Process	**Environmental Burden Score**				**Environmental Benefit Score**		**Overall Environmental Impact Score**
Centrevap	(1)=	2	(2)=	2	(1)=	5	10 – 8 = +2
	(3)=	2	(4)=	1	(2)=	5	
	(5)=	1	**Total = 8**		**Total = 10**		**MEDIUM - LOW**
Anti-solvent	(1)=	2	(2)=	3	(1)=	5	10 – 12 = -2
	(3)=	3	(4)=	2	(2)=	5	
	(5)=	2	**Total = 12**		**Total = 10**		**MEDIUM**
Mechanical Recycling (with BFR separation)	(1)=	1	(2)=	3	(1)=	5	10 – 10 = 0
	(3)=	3	(4)=	2	(2)=	5	
	(5)=	1	**Total = 10**		**Total = 10**		**MEDIUM - LOW**

Low –	(0 - 6)
Medium	(7 to 14)
High -	(15 to 20)

<u>Score Bands: Environmental Benefit:</u>

Low –	(1 - 3)
Medium	(4 to 7)
High -	(8 to 10)

<u>Score Bands: Environmental Burden:</u>


Potential Environmental Benefit
L
H
Potential Environmental Burden
H
LANDFILL
INCINERATION
(No EfW)
IONIC LIQUID
ANTI-SOLVENT
FEEDSTOCK
RECYCLING
INCINERATION
(with EfW))
CREASOLV
MECHANICAL RECYCLING
(with BFR plastic separation)
CENTREVAP

Justification for Process Scores:

1. Potential for Environmental Toxicity

   These scores were based on the potential of the system, primarily, to release BFR or furans. The highest scores were allocated to incineration technologies, as without the use of sophisticated scrubber systems, the potential to create furan and dioxins is high. Heating and extrusion processes in feedstock and mechanical recycling of plastics with a BFR content are presumed to release some BRFs, although mechanical recycling of WEEE plastics from which BFR plastics have already been separated are presumed to release negligible volumes of BFR or dioxins.

   Ionic Liquid, Centrevap and Anti-solvent processes are also presumed to release BFRs. In addition to this, some weighting has also been given to the use of toluene in these processes, which has a potential toxicology effect. Creasolv does not use toluene and is therefore weighted accordingly. It is also presumed that some BRF will be released from WEEE sent to landfill, although over a longer time scale than other processes.

2. Global Warming Potential and Energy Consumption

   Global warming potentials for these processes has been evaluated as being primarily linked to energy consumption for all processes but incineration processes, for which higher values are expected associated with the combustion of the WEEE plastic. These scores were weighted primarily on the amounts of energy consumed in each process and therefore the potential release of CO2 into the atmosphere. Again, incineration technologies that require the direct combustion of the material through the process are scored the highest, followed by feedstock recycling process. Energy consumption for feedstock processes is expected to be largely met by the processes itself; it is able to generate the major of it's energy consumption needs, however, CO2 emissions will be associated with these thermal processes and as such, it has been weighted below incineration processes, but above mechanical processes and the new solvent processes.

   Initial data on energy consumption data from the new solvent processes indicates that the Anti-solvent process consumes more energy than the other solvents processes and this has been weighted according and comparable to mechanical recycling processes.

   Centrevap, Ionic Liquid and Creasolv processes all use comparable amounts of energy and been assessed comparatively. Landfill is presumed to have a negligible GWP associated only with compaction vehicles operating on site. Background energy consumption processes are excluded from the system boundary.

3. Resource Use

   This is presumed to include resources such as solvents, scrubbers, filters, etc. that are lost from the system as waste and /or emissions. The use of comparatively more complex scrubber systems in incineration processes with EfW is perceived to be a higher potential resource use than other incineration processes and has been scored accordingly. Feedstock recycling processes have been rated similar to incineration processes although insufficient information is available at the present time to justify this rating.

   Similarly, treatment processes in mechanical recycling that separate out BFR-containing plastics prior to recycling may require more resources than non-separating processes and this is reflected accordingly. Ionic liquid has the greatest solvent loss for the system of any of the new treatment processes considered and this is reflected in the higher scores given to this process; creasolv and centrifuge / evaporate are perceived to produce similar

volumes of waste are rated as showing the lowest resource use between the new recycling processes.

Landfill is presumed to utilise negligible additional resources, excluding landfill linings and capping materials.

4. POCP Potential

This indicator has been linked primarily to the use of solvents in the treatment processes and release of VOC species through thermal treatment processes. Landfill and mechanical recycling processes are presumed to have a negligible POCP value and are scored the lowest.

Incineration and feedstock processes, while not utilising solvents do utilise thermal processes and it is presumed that these will be responsible for the release of some VOC species.

The potential for release of VOC's from new plastic processes have been rated based on sources of release identified; waste drum filling, extraction, evaporation and vacuum stripping, the remediation measures put in place to minimise these emissions and the volumes of solvents used. The Ionic liquid process uses the largest volume of solvents and has been weighted with the highest POCP score of the new processes alongside Anti-solvent, which demonstrated the highest energy consumption of the solvent processes and therefore has a high potential for VOC formation. Solvent reclamation processes are visible in the process flow sheets for Creasolv and Centrevap processes and it is considered that these are effective in recovering solvent throughput and minimising the release of VOC emissions to the environment. These have been scored as presenting minimal POCP's.

Appendix 5B – Explanation of QWERTY life cycle analysis

o Starting point

This Chapter is written in order to provide some background information on the ideas and reasons behind QWERTY analysis and to illustrate the way of working:

Product recyclability has mostly been calculated on a weight basis only, which is a poor yardstick from an environmental perspective and scientifically very inaccurate. It can lead to incorrect conclusions regarding initial environmental goals of take-back legislation. Calculations based on weight-based recyclability are likely to lead to incorrect decisions, especially when materials are present in low amounts, but with high environmental and economic values like precious metals in cellular phones. This notion has led to the development of the QWERTY concept for calculating product recyclability on a real environmental basis. The European take-back legislation for the electronics industry, the so-called WEEE Directive is primarily set up out of environmental motives[13]. The description of treatment performance and evaluation of recyclability targets, should therefore also take place in environmental terms. Currently this is only the case in a very limited way.

In contrast to traditional Life-Cycle Assessment (LCA)[14] [15], QWERTY analysis starts at the point of disposal. From here, the key question is to find out which end-of-life scenarios are preferable. As a consequence of this reasoning, usually environmental burdens appear for incineration and landfill scenarios and environmental gains appear, due to preventing new material extraction for recycling scenarios. In more detail, QWERTY calculations are based on three values as illustrated in Figure 1.

[13] Commission of the European Communities, Directive 2002/96/EC of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE), Official Journal of the European Union, Brussels, February 13, 2003

[14] M. Goedkoop, R. Spriensma, The Eco Indicator '99, a damage-oriented method for Life Cycle Impact Assessment. Final Report, National Reuse of Waste Research Program. Pré Consultants, Amersfoort, The Netherlands

[15] R. Spriensma, C. Alvarado, M. Goedkoop, LCA soldering materials, Report for Philips and Alpha Fry Technology, Amersfoort, February 2002

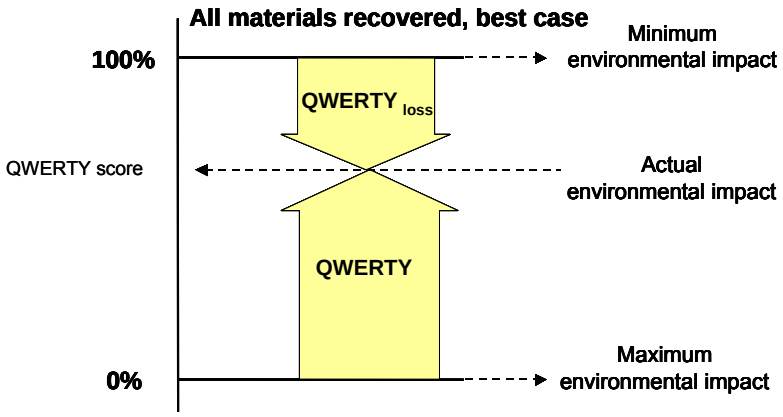


Figure 1. Calculating QWERTY values

1. The minimum environmental impact is defined as all materials being recovered completely without any environmental impact of end-of-life treatment steps, thus representing an environmental substitution value for newly extracted and produced materials. (Usually a negative value, maximum environmental gain as negative environmental impacts).
2. The maximum environmental impact for end-of-life treatment are defined as every material ending up in the worst possible (realistic) end-of-life route, including the environmental burden of pre-treatment: collection, transport and storage. The 'realistic' end-of-life scenarios under consideration are controlled landfill, incineration with or without energy recovery and all subsequent treatment steps for material fractions in case of material recycling like a plastic recycler.
3. The actual environmental impacts based on the actual environmental performance of the end-of-life scenario under consideration are compared with the two boundary conditions and expressed as percentages.

All detailed backgrounds and formulas to calculate QWERTY values have been published in the open literature.[16] [17] [18]. One important remark here, in this analysis, the pre-treatment of WEEE including shredding and separation, transport, etc., will be disregarded. The starting point here is having BFR and mixed BFR plus non-BFR plastics available for further treatment or disposal independent from previous treatment steps.

[16] J. Huisman, The QWERTY/EE concept, Quantifying recyclability and eco-efficiency for end-of-life treatment of consumer electronic products, Ph.D. thesis, ISBN 90-5155-017-0, Delft University of Technology, May 2003, Delft, The Netherlands

[17] J. Huisman, C.B. Boks, A.L.N. Stevels, Quotes for Environmentally Weighted Recyclability (QWERTY), The concept of describing product recyclability in terms of environmental value, accepted for the International Journal of Production Research, Special Issue on Product Recovery, 41 (16): pp 3649-3665

[18] J. Huisman, A.L.N. Stevels, I. Stobbe, "Eco-efficiency considerations on the end-of-life of consumer electronic products", accepted for the IEEE Transactions on Electronics Packaging Manufacturing, to be published in 2004.

o QWERTY: Environmental values

The QWERTY calculations require 'environmental values'. These values can be derived from any comprehensive environmental assessment model that provides such scores, but also from methods focusing on a single environmental effect, like for instance, eco-toxicity or resource depletion, can be used. The default method applied for this research is the Eco-Indicator '99 method, a damage oriented LCA-method[19]. The approach is also called a top-down LCA-method since all contributions to all environmental effects are translated to actual damage inflicted to eco-system quality, human health and resource depletion. Results will be checked by presenting the results also under grouped individual environmental themes rather than single indicators to determine to influence of the choice of the environmental assessment model. In addition to the default choice, also other methods are integrated in the QWERTY calculations to evaluate the environmental outcomes. It is also possible to evaluate on single environmental themes, like for instance on climate change effect. With this the disadvantages of applying a final weighting step as enumerated below are reduced, but it limits the transparency and relevance of results to single environmental themes only. In this report the results will also be displayed under these individual impact categories. Further considerations with respect to the use of LCA methods and methodologies for providing environmental values are:

1. In LCA there is always a 'subjective' evaluation step involved to weigh different environmental themes and to produce a single end-point score. This is inherent to aggregated environmental scores of any kind. One reason for choosing the Eco-Indicator '99 is that, compared to other LCA methods, it is the most transparent one regarding influence of different environmental perspectives and opinions of all factors that influence the final end-point score (and not only the final weighting step).
2. Again, the starting point of the QWERTY concept is not the same compared to LCA. The QWERTY analysis starts at the point of disposal till the 'end of the end-of-life' phase, while LCA methods regard the full life-cycle of products, hence different system boundaries and allocation rules apply. Due to this different starting point, the QWERTY concept regards materials that are recycled as preventing extra environmental load (so negative values appear for recycled materials) due to new raw material extraction or energy production. Due to this choice, many problems with allocation and the definition of system boundaries are prevented.
3. An important requirement is an environmental database providing environmental values for all relevant end-of-life processing steps and materials. For all relevant processing of materials, the mass and energy balances must be transferred to corresponding environmental values. Especially for the end-of-life phase of products, there are usually many data gaps within current LCA-databases. However, with the existing QWERTY calculations all relevant materials and processing steps have good quality inventories as the background data.

[19] M. Goedkoop, R. Spriensma, The Eco Indicator '99, a damage-oriented method for Life Cycle Impact Assessment. Final Report, National Reuse of Waste Research Program. Pré Consultants, Amersfoort, The Netherlands

o Eco-efficiency: Connecting with economic values

In order to enhance the 'eco-efficiency over the total end-of-life chain', the outcomes of eco-efficiency calculations can support the stakeholders and enablers of take-back and recycling. These stakeholders are: authorities by helping formulating criteria for collection of disposed products and monitoring end-of-life performance of take-back systems; it enables producers to calculate economical and environmental values on forehand; it supports recyclers in finding the right avenues of future technology application and investments; from a consumer or society point of view it helps getting insights in the environmental impacts per amount of money being spent, directly or indirectly, whereas the consumers pay the environmental and economic bill in the end.

In Figure 2, the four main eco-efficiency directions are shown in a two-dimensional eco-efficiency graph. The Y-axis represents the absolute environmental outcomes of the QWERTY calculations (in environmental millipoints), the X-axis represents the economic outcomes. The points in the graph are representing various end-of-life scenarios for one and the same product (or an individual component, assembly, fraction or product stream). The scenarios are based on changes in technology, design or system organization. Examples of such changes are for instance saving more products from the landfill (increasing collection rates), increasing plastic recycling and glass recycling, the effects of Design for End-of-Life activities or logistics changes.

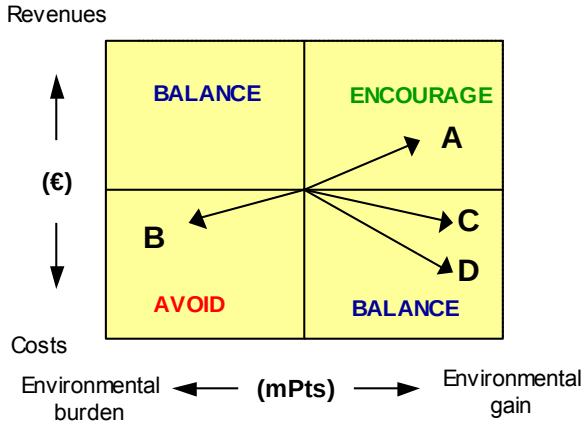


Figure 2. The four eco-efficiency directions

In order to achieve a higher eco-efficiency compared to an existing recycling scenario, one should move into the direction of the upper right part of Figure 2 (a 'plus' for environment and a 'plus' for economy). Besides this direction, the opposite direction (minus, minus) should be avoided and the (minus, plus) and (plus, minus) should be balanced or ranked.

Based on Figure 2, application of the eco-efficiency method to analyze take-back and recycling includes two important steps:
Step 1 is application of a 'vector approach' as sketched above. This means that in first instance four quadrants are selected. A 'positive eco-efficiency' is realised when for example the resulting vector is directed to the first quadrant (e.g. point A) of Figure 2 compared to the original situation (reference point). The opposite counts for the third quadrant. Options and directions is this case should be avoided from both an environmental as an economic point of view.
Step 2 includes calculation of environmental gain over costs ratios and ranking of the 'quotient' for the second and fourth quadrant. This is applied when an environmental improvement is realised and financial investments are needed to obtain this or in reverse. In general, when multiple options are

appearing in the fourth quadrant, the 'quotient approach' can be applied to determine how much absolute environmental improvement (mPts) is realised per amount of money invested (€).

It should be noted that the vertical axis represents the total societal costs for take-back and recycling, the actual costs or direction found per stakeholder can differ from this. For some parts of the recycling chain there always has to be paid: like for the transport and collection stage. In general, with setting up and financing take-back systems, there is a costs shift from public to private. The costs or vertical directions presented later on this report represent this societal perspective. In addition, the individual costs per stage can be calculated as well.

o Comprehensive modelling of take-back and recycling

For this analysis, all data, results and graphs presented in this section are based on the following general assumptions:

1. Economies of scale are realised for all examples and improvement options.
2. Accurate Life Cycle Inventories for metals are obtained from TU Delft, Department of Applied Earth Sciences.
3. The Eco-Indicator '99, Philips Best-Estimate, Hierarchic Perspective, Average Weighting set is used as a default environmental assessment model.
4. All fractions sent to a subsequent process fall under the acceptance criteria applicable for this process or operation. The environmental effects of final waste disposal are obtained from research published by Forschungzentrum Karlsruhe[20]. All further underlying data for all process steps and stages and the environmental validation methods are published in previous work already referenced earlier in this chapter.

[20] J. Vehlow, B. Bergfeldt, K. Jay, H. Seifert, T. Wanke, F.E. Mark, Thermal Treatment of E+E Waste Plastics, Waste Management & Research, 18 (2000) 131 – 140, Forschungszentrum Karlsruhe GmbH, Institute for Technical Chemistry, Karlsruhe, Germany; Dow Europe, Horgen, Switzerland

Appendix 5C – QWERTY analysis method for this project

- **Introduction**

Background

This report is requested by Axion Recycling Ltd acting as project manager for The Waste and Resources Action Programme – WRAP Project on developing processes to extract brominated flame retardants from WEEE Polymers. As part of this project an environmental impact assessment and eco-efficiency evaluation is needed. It is decided not to apply a classic LCA study (Life Cycle Assessment) on BFR plastics but rather a streamlined description on what happens from an environmental and economic point of view when these plastics are obtained at processing WEEE by recyclers. The QWERTY/EE approach (Quotes for environmentally WEighted RecyclabiliTY and Eco-Efficiency)[21] , is built for this purpose and quantifies the environmental and economic performance throughout the WEEE recycling chain. The approach, developed at TU Delft, resulted in comprehensive descriptions and data collection on all actors of the recycling chain of waste electronic products. As can be seen in Figure 3, the stages include product compositions, characteristics on collection and treatment including modelling of shredding and separation, final waste routes and closing material cycles through upgrading, refining. The approach applied for this report describes the environmental and economic effects of BFR and non-BFR plastics with the starting point that these plastic fractions already have become available at collection and treatment by means of shredding and separation and dismantling. In the analysis, these previous stages of the WEEE recycling chain are left out of the scope of the analysis. Therefore, the material recycling arrow and incineration/ landfill arrows of Figure 3 plus all further treatment steps are quantified.

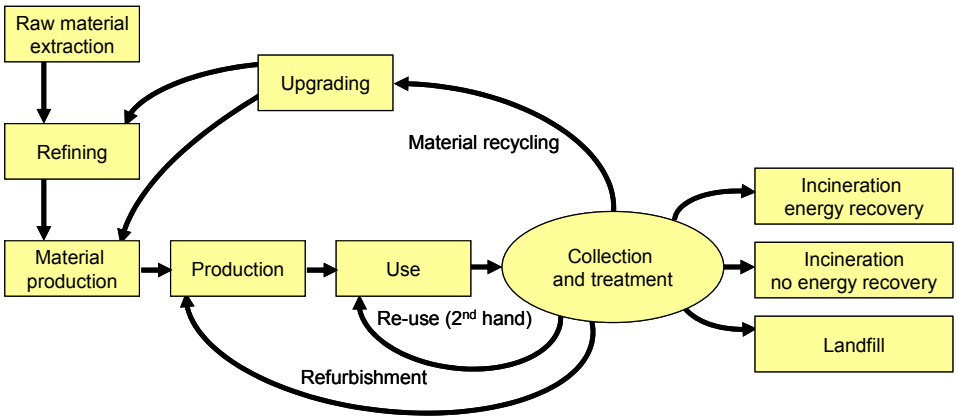


Figure 3. The end-of-life chain

[21] J. Huisman, C.B. Boks, A.L.N. Stevels, Quotes for Environmentally Weighted Recyclability (QWERTY), The concept of describing product recyclability in terms of environmental value, accepted for the International Journal of Production Research, Special Issue on Product Recovery, 41 (16): pp 3649-3665

With the chosen approach, two scenarios are investigated:

1. Treatment of the sorted and separated BFR fraction from the larger WEEE-plastics fraction in dedicated BFR removal processes (plus a few reference scenarios).
2. The position of BFR treatment processes related to the total effect of treatment of WEEE plastic fractions, containing both brominated flame retardant polymers (BFR, 10% on weight and non-BFR plastics (90%).

The processes to be evaluated are selected by Axion Recycling and summarised in Table 1. In all scenarios, 1 kg of plastics input is used. The first scenario is the actual evaluation of the BFR plastics already sorted from the non-BFR plastics processed by the various options. The second scenario is to demonstrate the outcomes of the BFR treatment in the total of plastics recycling. The scenarios 1A – 1D and 2A – 2D are included as reference scenarios. Scenario 1D and 2D are theoretical options based on direct mechanical recycling without having the brominated flame retardants being removed. This is in practice not desirable in light of the RoHS Directive and the general trend of phasing out brominated flame retardants.

Table 1. End-of-life scenarios investigated

Scenario 1	***BFR plastics (10%) to:***	***Scenario 2***	***Non BFR (90%)+ BFR (10%) plastics separated to:***
1A	*Incineration (no energy recovery)*	*2A*	*Incineration (no energy recovery)*
1B	*Incineration (energy recovery)*	*2B*	*Incineration (energy recovery)*
1C	*Controlled landfill*	*2C*	*Controlled landfill*
1D	Mechanical Recycling (incl. BFR)	2D	Mechanical Recycling incl. BFR)
1E	*Creasolv*	*2E*	*Plastic rec. 90% + Creasolv 10%*
1F	*Centrevap*	*2F*	*Plastic rec. 90% + Centrevap 10%*
1G	*Antisolv*	*2G*	*Plastic rec. 90% + Antisolv 10%*
1H	*Ionic Liquid*	*2H*	*Plastic rec. 90% + Ionic Liquid 10%*
1I	*RGS90*	*2I*	*Plastic rec. 90% + RSG90 10%*
		2J	*Plastic rec. 90% + Incineration 10%*
		2K	*Plastic rec. 90% + Landfill 10%*

(The technical descriptions of the above processes are available in the full WRAP report)

For the scenarios 1D – 1I, a gate fee is assumed while final waste disposal is replaced for which otherwise has to be paid. Sorting costs are also excluded as the input fraction is assumed to be obtained from 'normal' mechanical recycling operations already. However, for the scenarios 2E – 2K the sorting and separation costs are included as here the non separated stream of BFR and non-BFR plastics is taken and additional sorting and separation is needed for the BFR routes in order to separate also other not dissolving plastic types..

o Goal

The goal of this screening environmental and eco-efficiency assessment is to compare and rank the different treatment options for BFR plastics (scenario 1) and BFR/non-BFR plastics (scenario 2). The results will be used to further develop the most promising treatment technologies considered from both an environmental and economic perspective and to address the weak-points found at the moment.

o Scope and approach

The scope of the analysis is treatment (excluding plastics separation itself) in the UK. The final waste processes (A-C,J,K) are already present in the QWERTY/EE calculations and are updated to reflect current UK conditions[22]. The technical descriptions, mass balances and business models for the scenarios E - I, are obtained from Axion Recycling.

Before discussing the actual data collection (Chapter 3) and the results (Chapter 4), the QWERTY concept will be introduced in more detail (Chapter 2). In Chapter 5, Discussion, the robustness and reliability of the results will be highlighted regarding the various choices and assumptions made.

• Inventory

o Fraction compositions, assumptions

In Table 2, the fraction compositions used for the scenarios 1 and 2 are mentioned. The compositions of the separated styrene based plastics fraction including BFR's, is given at the left side of the table. The Bromine content of the flame retardant fraction is assumed to be 8,2%. The other materials present are estimated as: 1% coarse fraction of the total input consists of PVC (50%) and copper (50%); 1% of fine fraction consists of antimony (50%), lead (10%), cadmium (0,1%) and filling materials (Calcium Carbonate, 39,9%).
The composition of the mixed BFR plus non BFR fraction for scenario 2 is assumed to consist of 10% of the BFR plastics of scenario 1 plus 90% of non BFR-plastics of the same types. In addition to the two scenarios, also the case of sorting a single plastic type out of the BFR stream or otherwise will be evaluated.

Table 2. Fraction compositions

Scenario 1	Plastic type	Material	weight (g)	Scenario 2	Plastic type	Material	weight (g)
1A-1I	ABS/PC	ABS/PC	299,33	2A-2G	ABS/PC	ABS/PC	29,93
1A-1I	FR	Br	27,33	2A-2G	FR	Br	2,73
1A-1I	ABS - FR	ABS	299,33	2A-2G	ABS - FR	ABS	29,93
1A-1I		Br	27,33	2A-2G		Br	2,73
1A-1I	HIPS - FR	HIPS	299,33	2A-2G	HIPS - FR	HIPS	29,93
1A-1I		Br	27,33	2A-2G		Br	2,73
1A-1I	Other	PVC	5,00	2A-2G	Other	PVC	0,50
1A-1I		Copper	5,00	2A-2G		Copper	0,50
1A-1I		Sb	5,00	2A-2G		Sb	0,50
1A-1I		Pb	1,00	2A-2G		Pb	0,10
1A-1I		Cd	0,01	2A-2G		Cd	0,00
1A-1I		Other	3,99	2A-2G		Other	0,40
				+ Plastic recycling		ABS/PC	300,00
						ABS	300,00
						HIPS	300,00
		Total	1000,00			Total	1000,00

[22] Personal communications with Roger Morton and Stuart Corns, Axion Recycling Ltd. UK settings for incineration and landfill, June 2003.

o Environmental data

The most important environmental settings for all BFR solvent processes (excluding mechanical recycling, RSG90, Incineration and landfill) are presented in Table 3. It is assumed that the recovered polymers are Bromine-free when the concentration is less then 0,1%. The modelling of the processes by Axion is based on 1,429 ton input per hour, which corresponds with 1,000 ton polymer content and 0,429 other materials (inerts + BFR). The values in Table 3 - Table 6 are based on this input per hour.

Table 3. General environmental settings*

General settings for BFR routes		
Input/hr (1 ton polymer)	*1429*	*kg incl. inerts*
Transport distance to facility	*100*	*km*
Energy consumption electric	*350*	*kWh/ton*
Grade (environmentally)	*100%*	
Grade (economically)	*47%*	

(*except for mechanical recycling, landfill, incineration)

The key environmental data per process option is summarised in Table 4.

Table 4. Key environmental data per process

Incineration			**Creasolv**		
Lime (neutralize HBr)	28,3	kg per ton	Steam	1041	kg/ton input
Lower Heating Value	40%	MJ/kg	Recovery polymers	99%	
Energy efficiency	26%	electricity	Solvent: Creasolv	14,4	kg/ ton input
Energy efficiency	75%	thermal	Solvent: G-PS-F	6	kg/ ton input
			Solvent Isopropanol	0	kg/ ton input
Mechanical recycling			**Ionic Liquid**		
Transport distance	100	km	Steam	3037	kg/ton input
Energy used elect.	500	kWh/ ton	Recovery polymers	99%	
Recovery polymers	77%		Solvent: Ethylacetate	423	kg/ ton input
Br free' when Br	<0,1%		Solvent: Hexane	1,25	kg/ ton input
Individual plastics	>80%	of one type	Solvent Ionic Liquid	10	kg/ ton input
RGS90			**Centrevap**		
Produced: Cokes	105,7	kg/ ton input	Steam	2217	kg/ton input
Heating value Cokes	59,8	MJ/kg	Solvent: Toluene	11	kg/ ton input
NaOH	40,6	kg/ ton input	**Antisolv**		
Water	46,2	kg/ ton input	Steam	8150	kg/ton input
Produced: NaBr	105,0	kg/ ton input	Solvent: Toluene	14	kg/ ton input
Produced: Fuel Oil	46,2	kg/ ton input	Solvent: Methanol	19	kg/ ton input

1. For incineration and landfill, the existing landfill and incineration model within the QWERTY calculation schemes is applied. This includes average first and second order emissions for metals as well as all other relevant environmental impacts. For incineration, the model is based on average behaviour of materials in MSW incineration plants with wet flue gas cleaning systems. The landfill settings are for controlled landfill with cleaning of the effluent. More details can be found in.
2. The mechanical recycling settings are also provided by the existing QWERTY calculation model and updated and checked by Axion Recycling. Here it is assumed, that recovered plastics are regarded Bromine free under 0,1 % Br content. When more than 80% of the input is of a

single plastic type, the recovered plastics are assumed to replace primary plastic production of the same type.

3. Also in Table 4, the main environmental effects: transport, energy consumption, solvent make-up and recovery of polymers are highlighted. The remaining BFR/ inerts fraction of these solvent routes is assumed to be send to controlled landfill.
4. For some of the solvents consumed, standard Life-Cycle Inventories are available in the Simapro LCA database used: This is the case for Ethylacetate, Hexane, Toluene, Methanol; However for the Creasolv solvent no production inventory is available and therefore a substitute inventory is applied. The same counts for the Ionic Liquid (the double inventory of Bisphenol-A, as production will require two similar production steps compared to Bisphenol-A).
5. Not included in the environmental evaluation are the Global Warming Potentials (GWP's) and Ecotoxicity values for the solvents applied and the potential (but in the current modelling very limited) VOC emissions.
6. No dioxin emissions are incorporated for all processes, as in the modelling sufficient measures are taken to minimize this. For incineration, the additional lime consumption due to the higher Bromine content is included to neutralize the HBr formed. Also at mechanical recycling by means of granulating and re-extruding, no dioxin emissions are assumed.

o Economic data

The most relevant economic data applicable for all processes are demonstrated in Table 5. It includes the sorting costs for splitting BFR and non-BFR plastics which is relevant for scenario 2 as well as the revenues for the different plastics. For evaluation of scenario 1, the BFR routes only, it is assumed that the BFR polymer will be a by-product or waste stream from a profitable plastic separation operation that sells BFR-free polymer. So, for scenario 1, the BFR polymer fraction will attract a gate fee because it would otherwise go to landfill or incineration. The values are given for mixed plastics fractions from mechanical separation. Manual dismantling and direct sorting in different plastics types is left out of scope of this evaluation.

Table 5. General economic settings

General settings		
Currency conversion: 1 £= € 1,4610		
Sorting costs BFR vs. non BFR (scenario 2)	164	€/ ton
Revenues BFR plastics	300	€/ ton
Revenues non BFR plastics	643	€/ ton
Primary HIPS, ABS, ABS/PC	1370	€/ ton
Grade polymers (economically) from BFR routes:	47%	
Gate fee BFR routes (scenario 1)	51	€/ton

The key economic parameters for each processing option are presented in Table 6.

Table 6. Key economic data per process

Incineration			**Ionic Liquid**		
Total costs	190	€/ton	Capital costs	11.110	x € 1000
Br penalty in % per ton, threshold 1%	40	€/ton	Operational costs	5.930	x € 1000/ yr
Revenue (energy rec.)	70	€/ton	Management, overhead	1.543	x € 1000/ yr
Mechanical recycling			**Centrevap**		
Total costs	51	€ per ton	Capital costs	9.991	x € 1000
RGS90			Operational costs	2.720	x € 1000/ yr
Total costs	113	€ per ton	Management, overhead	1.379	x € 1000/ yr
Creasolv			**Antisolv**		
Capital costs	9.027	x € 1000	Capital costs	15.695	x € 1000
Operational costs	2.233	x € 1000/ yr	Operational costs	4.233	x € 1000/ yr
Management, overhead	1.543	x € 1000/ yr	Management, overhead	1.543	x € 1000/ yr
			Landfill		
			Total costs	90	€/ton

1. For incineration with energy recovery, the total costs per ton are estimated at € 190 per ton. In addition to this, the higher Bromine content will result in extra costs for quicklime and active carbon consumption in order to neutralize HBr and dioxin formation. The energy recovery will yield in revenues for electricity and heat produced. See Table 4 for the efficiencies assumed.
2. For the RGS90 process a relatively limited business model is available in comparison with the other processes. It is only addressing aggregated costs and revenues. The total costs and revenues are based on the values in Table 4. For the other solvent routes, a more extensive business model is developed. The aggregated values for capital costs, operational costs and management plus overhead are presented in Table 6.
3. The sorting and separation of the different plastics types from each other is assumed to be efficient and without technical limitations. The potential loss of other plastics present (besides the small PVC content) is not taken into account. When in practice other for instance nylon types are present, these would be lost to the inerts/ BFR fraction to landfill and reduce overall polymer recovery.

- # Results

Main results scenario 1

The main results of scenario 1 for the routes for treatment of the BFR plastics are summarised in Table 7. The third column shows the mPts (millipoints) outcomes as single indicator values based on the Eco-Indicator'99 LCA methodology. A negative sign means avoided environmental burden (environmental gain) and/ or costs (revenues).

Table 7. Main results BFR plastics routes

Scenario	*QWERTY*	*mPts*	*€*
1A. Incineration (no energy recovery)	*26,6%*	*24,1*	*0,17*
1B. Incineration (energy recovery)	*38,3%*	*-9,0*	*0,16*
1C. Controlled landfill	*31,6%*	*1,4*	*0,12*
1D. Mechanical Recycling (100%, incl. BFR)	*87,3%*	*-251,9*	*-0,21*
1E. Creasolv	*93,2%*	*-278,9*	*-0,29*
1F. Centrevap	*87,1%*	*-251,0*	*-0,26*
1G. Antisolv	*68,8%*	*-167,9*	*-0,11*
1H. Ionic Liquid	*73,7%*	*-190,3*	*0,04*
1I. RGS90	*45,9%*	*-63,4*	*0,04*

From the table is can be concluded that the 1E. Creasolv and 1F. Centrevap options are the most preferable from an environmental perspective. Again note that the 1D. Mechanical Recycling scenario is added as a reference. With this scenario, the BFR is not removed but remains within the polymer product. The 1G. Antisolv and 1H. Ionic Liquid options seem to have a lower scoring followed by the two thermal scenarios 1I. RGS90 and 1B. Incineration with energy recovery. The least preferable options are 1C. Controlled Landfill and 1A. Incineration without energy recovery.

QWERTY scores: environmental ranking scenario 1

The absolute environmental values (mPts) of Table 7 can also be displayed as relative values with QWERTY scores. Note that the QWERTY scores are based on the two boundary conditions of recovery of all materials without any environmental burden (100%) and the maximum burden per materials over all relevant processes, including energy consumption, transport and loss of materials (0%). Also, the environmental impacts of the collection, transport and shredding and separation steps prior to the BFR treatment options are **not included.** These choices make that the some of the actual scenarios of Table 4 are 100% best case condition. It should be noticed that all environmental burden of previous processing steps are not included here.

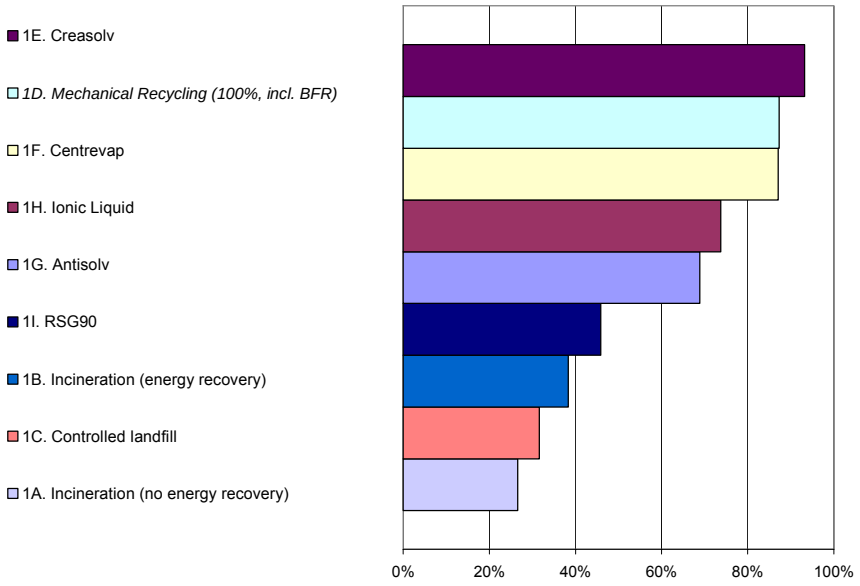


Figure 4 QWERTY scores for BFR plastics processing routes - scenario 1

Again, in line with Table 7, the graph shows the distinction between the 1E. Creasolv and 1F. Centrevap processes versus 1H. Ionic Liquid and 1F. Antisolv versus the thermal processes 1I. RSG90 and 1B. Incineration with energy recovery. Obviously, the lower solvent and energy consumption of 1E. Creasolv and 1F. Centrevap from Table 4 compared to the other solvent routes leads to the much higher environmental performance. The same effect is visible in the economic outcomes. Whereas the recoveries are comparable, the lower energy and solvent consumption also leads to less costs and higher overall performance:

o Eco-efficiency diagram scenario 1

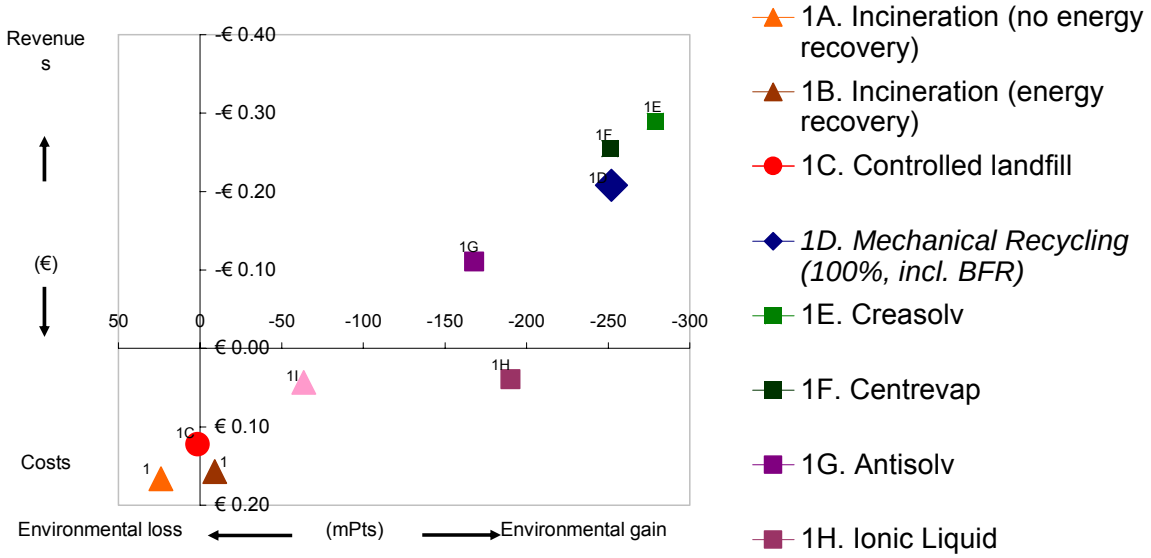


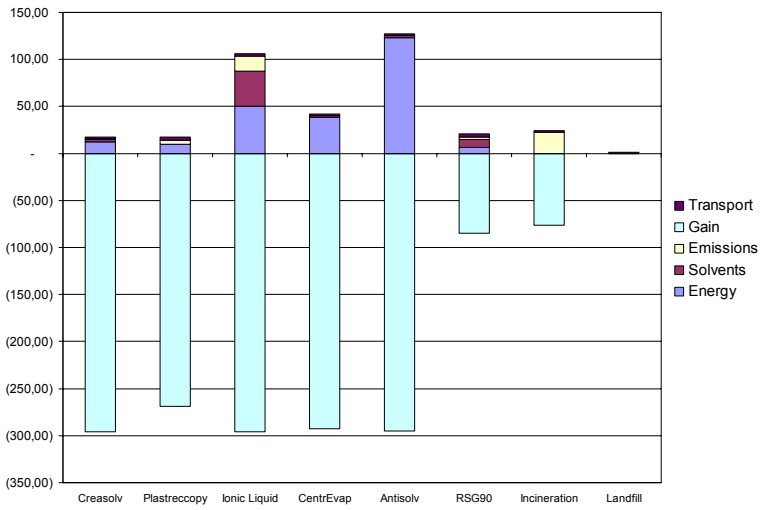
Figure 5 Eco-efficiency diagram for Scenario 1 (based on Table 7)

The eco-efficiency graph also shows the 1E. Creasolv and 1F. Centrevap process in the preferred upper right part of the graph. This is due to the lowest energy and solvent consumption, the gate fee, the recovery and production of new plastics and the connected avoided environmental burden of this. It also indicates that the material recycling demonstrated with the solvent routes are to be preferred above the thermal routes 1I. RGS90 and 1B. Incineration with energy recovery. One remaining question is of course how the sorting costs for separating the BFR plastics for the main plastics fraction would influence this and what the environmental effect is of enabling the 1D. scenario of Mechanical Recycling for the other 90% of the WEEE plastics. This will be illustrated for scenario 2, but first the contribution of the various BFR treatment stages is highlighted.

o Contribution of stages

In Figure 6, the contribution of transport, emissions, solvent and energy consumption to the environmental burden (on top) and the environmental gain due to replaced material or energy production is displayed. The bars represent the weighted single indicator according to Eco-Indicator'99. The same environmental results are demonstrated for all grouped environmental impacts (HH, Human Health, EQ, Ecosystem Quality, RD, Resource Depletion) and all individual environmental impact categories. In this graph, environmental burden is directed above, environmental gain below.

Figure 6 Contribution of stages, scenario 1



Note the relatively large environmental gain (below 0) of replacing primary materials for the solvent routes, the solvent effect of Ionic Liquid in particular and the substantial effect of the high energy consumption of the Antisolv process. For the thermal processes it can be observed that the emissions of incineration play a role as well as the connected energy recovery effect to the environmental gain. The energy recovery effect is less compared to the materials recovered for the solvent routes. The emissions of the RGS90 process are lower compared to incineration, as a result of the oil and coke production and the fact that the further thermal use of these intermediate products is outside the system boundaries as only the replacement effect of oil respectively the coal cakes production and extraction are taken into account and the excluded emissions of later thermal use.

o Main results scenario 2

Table 8 shows the outcomes of scenario 2 on the position of the BFR removal processes in the total picture for WEEE plastics recycling. Again the reference scenario 2D is only hypothetical as the Mechanical Recycling is leading to plastics still containing BFR.

Table 8. Main results BFR + non BFR plastics routes

Scenario	*QWERTY%*	*mPts/ kg*	*€ /kg*
2A. Incineration (no energy recovery)	*23,0%*	*23,7*	*0,14*
2B. Incineration (energy recovery)	*41,0%*	*-59,5*	*0,12*
2C. Controlled landfill	*27,8%*	*1,4*	*0,09*
2D. Mechanical Recycling (100%, incl. BFR)	*89,4%*	*-246,2*	*-0,18*
2E. Plastic recycling 90% + Creasolv 10%	*88,8%*	*-280,8*	*-0,26*
2F. Plastic recycling 90% + Centrevap 10%	*88,1%*	*-278,0*	*-0,26*
2G. Plastic recycling 90% + Antisolv 10%	*86,4%*	*-269,7*	*-0,24*
2H. Plastic recycling 90% + Ionic Liquid 10%	*86,8%*	*-272,0*	*-0,23*
2I. Plastic recycling 90% + RGS90 10%	*84,1%*	*-259,3*	*-0,23*
2J. Plastic recycling 90% + Incineration 10%	*83,8%*	*-257,7*	*-0,22*
2K. Plastic recycling 90% + Landfill 10%	*82,7%*	*-252,8*	*-0,23*

The table clearly shows the environmental benefits of separating the BFR from the other polymers which also enables plastic recycling of the other 90%. The third column again shows the mPts (millipoints) outcomes as single indicator values based on the Eco-Indicator'99 LCA methodology. A negative sign means avoided environmental burden (environmental gain) and/ or costs (revenues).

o QWERTY scores: environmental ranking scenario 2

Similar to scenario 1, the absolute environmental values (mPts) of Table 8 can are displayed as relative values with QWERTY scores.

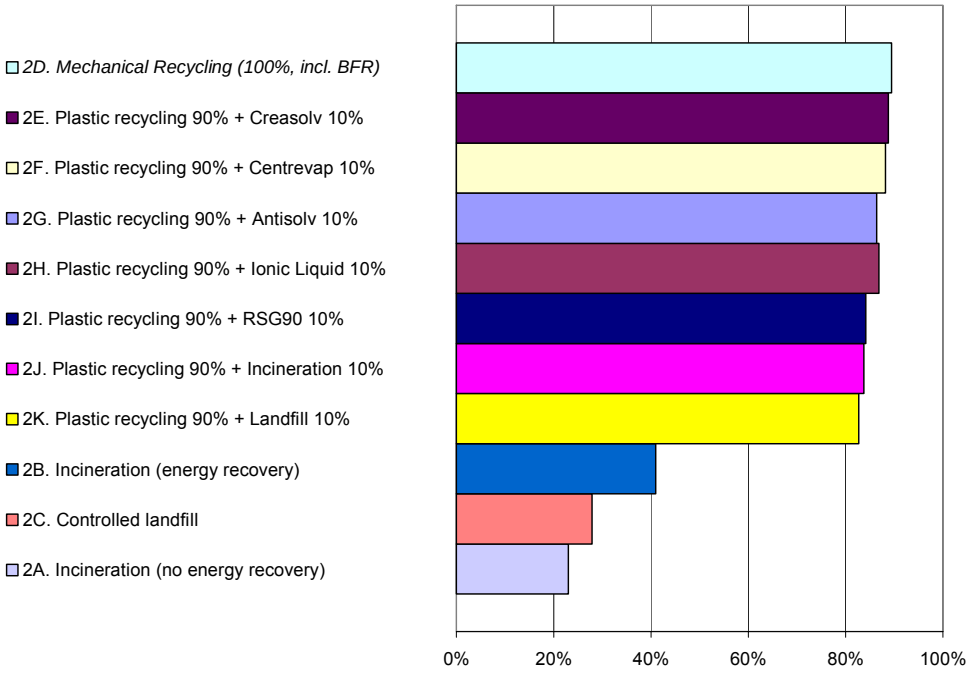


Figure 7 QWERTY scores BFR plastics routes scenario 2

In 0 the distinction between the BFR routes is less clear due to the ‘diluting effect’ of the added 90% of other polymers. It basically demonstrates the high relevance of being able to separate BFR and non-BFR plastics with a substantial increase of environmental value recovered compared to the final waste options. Also here, the same effect is visible in the economic outcomes dominated by the revenues of the plastic recycling of the 90% of the non-BFR plastics.

o Eco-efficiency diagram scenario 2

This outcome is displayed in the overall eco-efficiency graph of Figure 8. Apparently, here the eco-efficiency graph shows the BFR routes for the 10% BFR plastics around the same position. It also demonstrates a better performance than the direct Mechanical Recycling including the BFR content of reference scenario 2D. Furthermore, it demonstrates the basic outcome that all plastic recycling scenarios are having a positive eco-efficiency compared to the final waste option of landfill and incineration of the total BFR plus non-BFR fractions.

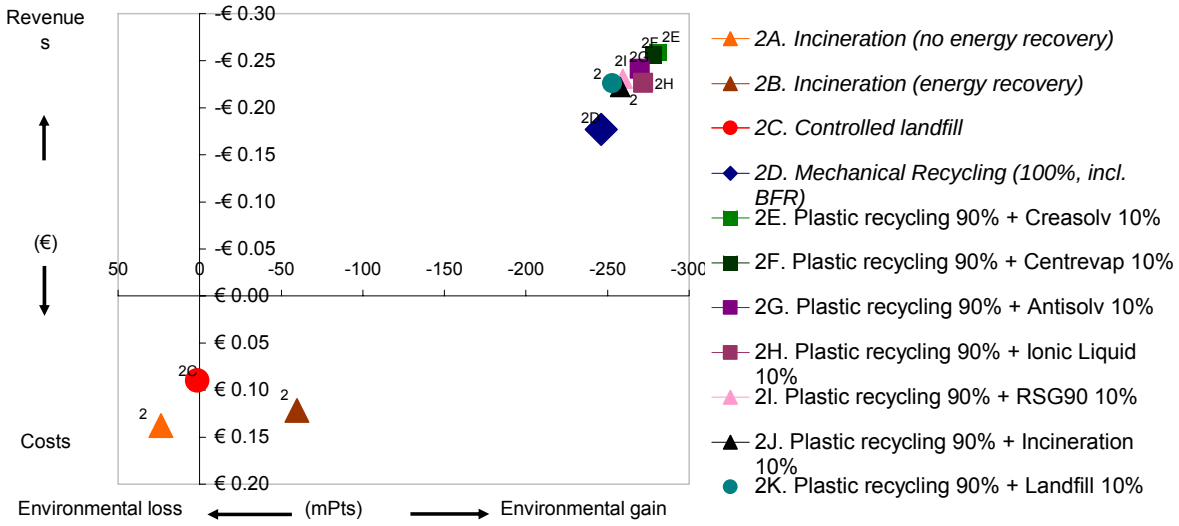


Figure 8 Eco-efficiency graph scenario 2

- # Discussion

o Reflection on the assumptions

The robustness and reliability of the results is related to two general aspects. At first, the various assumptions and data quality and availability is discussed here by qualitative means. Secondly, the choice for the environmental impact assessment methodology and the single environmental indicators as discussed in the next section.

The influence of the most important assumptions is discussed in a qualitative way:

1. Plastics sorting and separation efficiency: The current settings for sorting of plastics is assumed to have a 100% efficiency. The potential negative of other plastics present in the BFR fraction is left out of scope and might decrease the recovery percentages. This also includes possible metal and other materials present ending-up in the inerts/BFR residue to landfill. On the other hand, the solvent routes make a separation of such additives or contaminations possible.
2. Market prices for both BFR and non-BFR mixed styrene based plastics are obtained from Axion recycling and presented in Table 5. When applicable, deviating prices per kg will change the eco-efficiency graphs with a similar amount per kg.
3. Gate fees are assumed for the BFR routes of scenario 1 in relation to final waste disposal routes. Included is also the economic effect of replacing the caloric value of Municipal Solid Waste by material with a much higher caloric value which has its effect of the limited 'thermal capacity' of incinerators at the moment. However, in the future it might be possible that the current caloric value of MSW in the UK will decrease due to more separation of certain streams (other plastics). As a consequence, the calculated gate fee could decrease at the incinerator in the future.
4. The calculations for both incineration and RGS90, assumingly, no additional dioxins are emitted compared to current emissions from MSW. For incineration with a wet flue gas cleaning this effect is realistic as no higher influence of the Bromine content on the dioxin levels is found. However, in practice this needs to be checked for UK incinerators with a dry cleaning system. The expected effect of a higher activated carbon consumption in order to prevent this is not included in the calculations.
5. No VOC emissions are taken into account for solvent recovery steps and extruding of the produced polymer with remaining solvent present. This might have a slight effect on the emissions.
6. The modelling of the thermodynamics of the RGS90 process and more specific of the internal oil consumption for the energy supply, is rather uncertain. Currently, 10% of the produced oil is assumed to be used in the pyrolyser internally. A higher or lower amount would influence the environmental gains of the process.

The last remark on the assumptions and data reliability is the perhaps the most important one: The solvent routes in particular are based on process modelling and lab-scale testing. The estimates on the actual mass and energy balances are expected to be realistic values. However, the quality of this screening eco-efficiency analysis can be improved by checking the outcomes of the future processes with real-life data from full scale operations.

o Environmental ranking for grouped impact categories

Another important discussion aspect is the choice for using single environmental indicators. The stability of the results is checked for scenario 1 by calculating the three grouped environmental themes of Human Health, Ecosystem Quality and Resource Depletion as well as all individual impact categories. See also the Table in this Appendix for all abbreviations used.

In Table 9, the environmental ranking under the three grouped themes as well as the often used category of global warming (in CO2 equivalents), is summarised. The table provides important guidance on the often debated stability of environmental outcomes under single indicator calculations. Here the ranking of the best performing options (1E. Creasolv and 1F. Centrevap) remains above the other options, followed by 1H. Ionic Liquid and 1G. Antisolv, followed by the thermal options 1B. Incineration and 1I. RSG90 and finally by 1C. Controlled Landfill. The same conclusion can be drawn from the individual impact categories, with one surprising exception: For Human Health – Toxicity the thermal options 1I. RGS90 and 1B. Incineration are preferable above the other options. The reason is the toxicity effect related to the avoided energy production compared to the other options where the replacement of primary materials is adding less to the environmental gain.

Table 9. Environmental ranking of scenario 1 for grouped environmental themes

	EI99 overall	**HH**	**EQ**	**RD**	**CO2**
1E. Creasolv	1	2	1	2	1
1D. Mechanical Recycling (100%, incl. BFR)	2	1	3	1	2
1F. Centrevap	3	3	2	3	3
1H. Ionic Liquid	4	6	4	4	4
1G. Antisolv	5	5	5	5	7
1I. RGS90	6	7	6	6	5
1B. Incineration (energy recovery)	7	4	8	8	6
1C. Controlled landfill	8	8	7	7	8

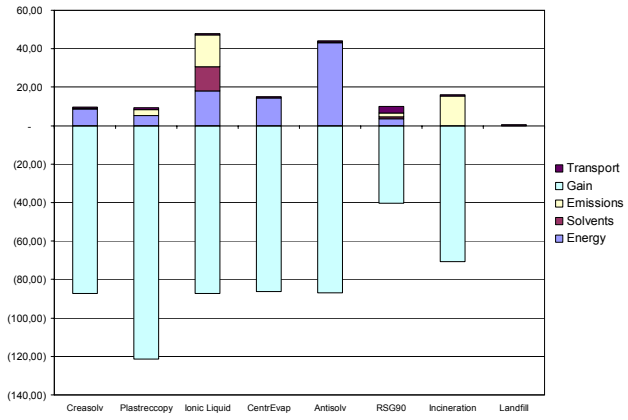
Appendix 5D – Detailed results for QWERTY analysis

Abbreviation and short explanation environmental impact categories

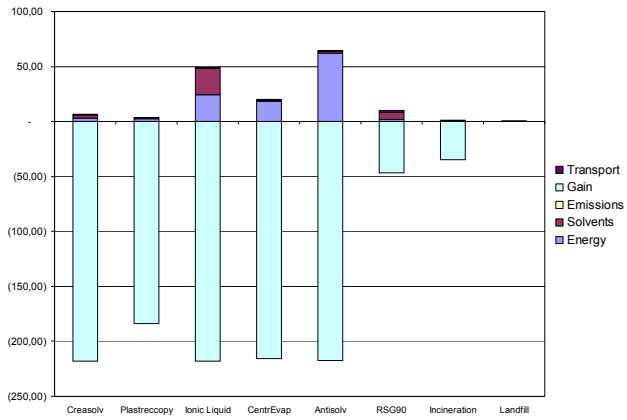
Abbreviation	*Impact Category/ Group Name*	*Comment*
EI99 default	*Eco-Indicator'99, default weighting set*	
HH	*Human Health, grouped*	
EQ	*Ecosystem Quality, grouped*	
RD	*Resource Depletion, grouped*	
HH carc	*Human Health, carcinogenic effects*	
HH resporg	*Human Health, respiratory organics*	
HH respinorg	*Human Health, respiratory inorganics*	
HH clim	*Human Health, climate change (in CO2 equiv.)*	
HH rad	*Human Health, radiation*	*Not applicable/ relevant*
HH ozone	*Human Health, ozone layer depletion*	
HH tox	*Human Health, toxicity*	
EQ ecotox	*Ecosystem Quality, ecotoxicity*	
EQ acid	*Ecosystem Quality, acidification, eutrophication*	
EQ land	*Ecosystem Quality, land-use*	*Not applicable/ relevant*
RD min	*Resource Depletion, minerals*	
RD fossil	*Resource Depletion, fossil fuels*	

In the next graphs environmental burden is directed above, environmental gain below.

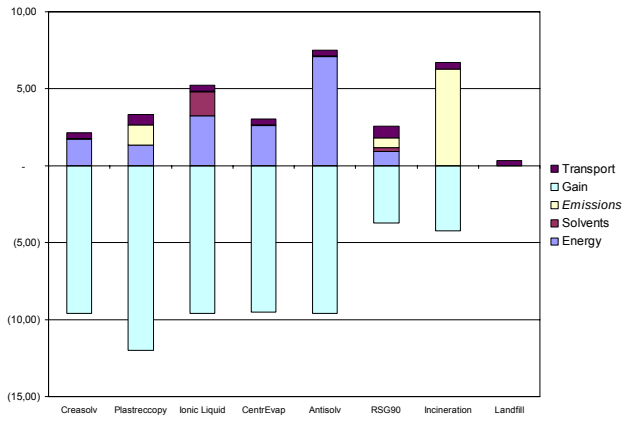
HH grouped



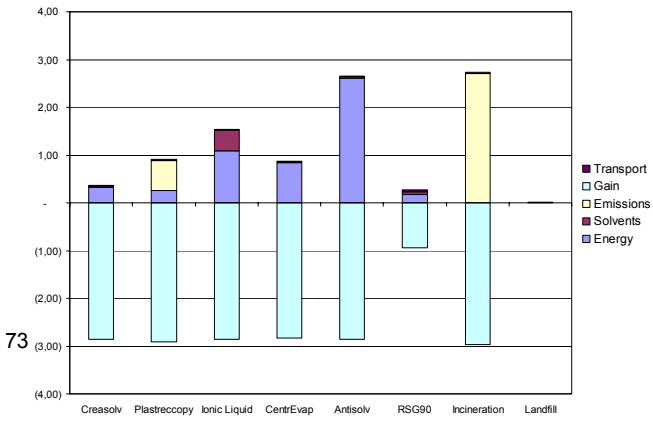
EQ grouped

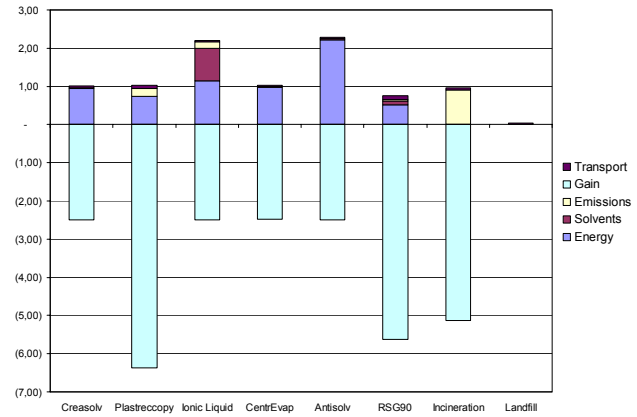


RD grouped

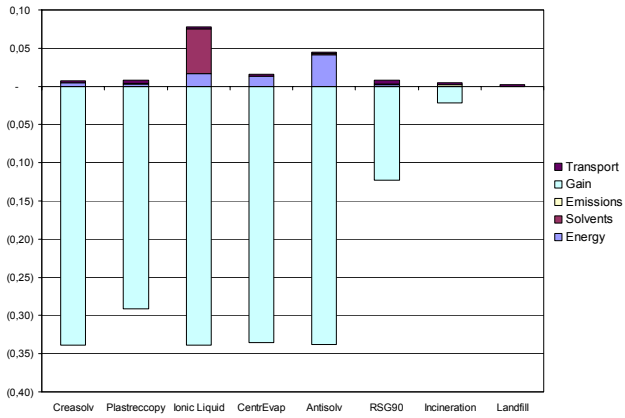


HH clim (in kg CO2 equivalent)



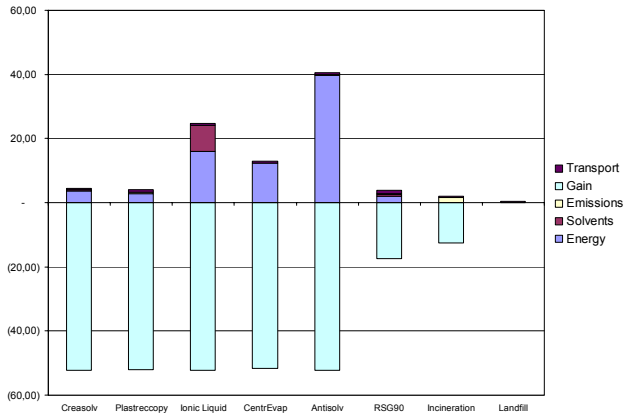


HH carc

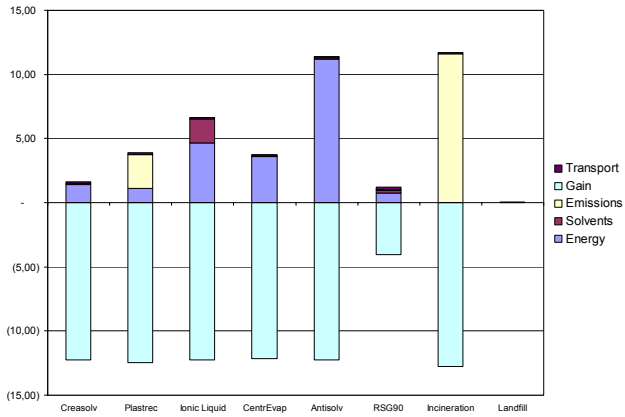


HH resporg

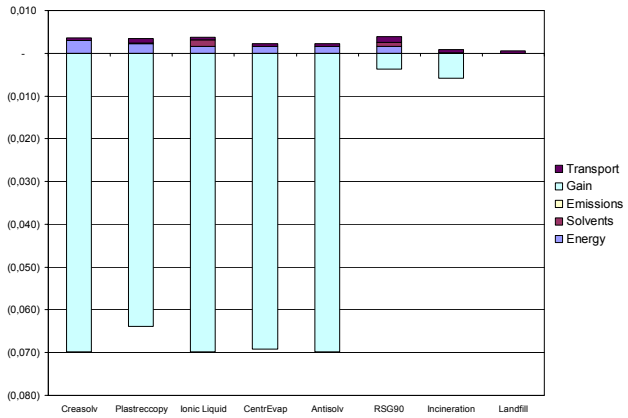
HH respinorg



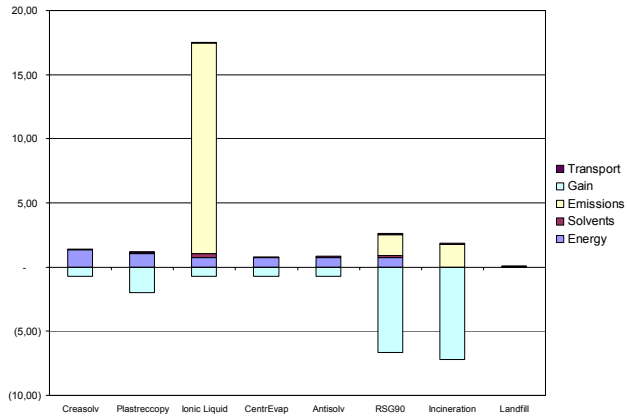
HH clim



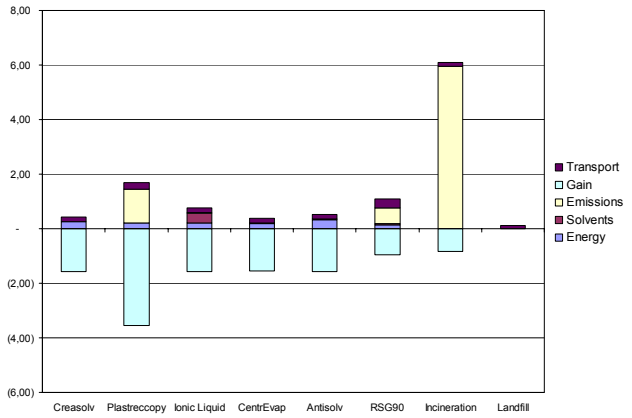
HH ozone



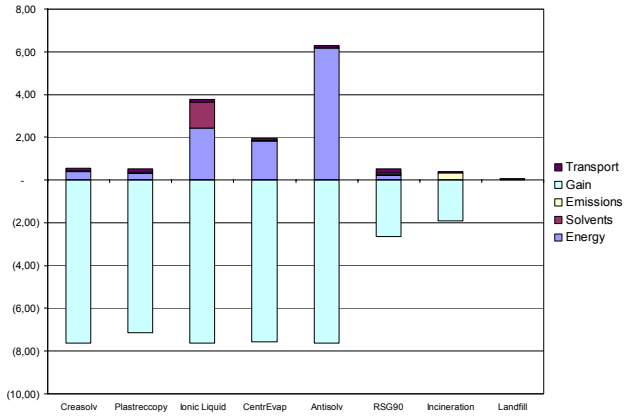
HH tox



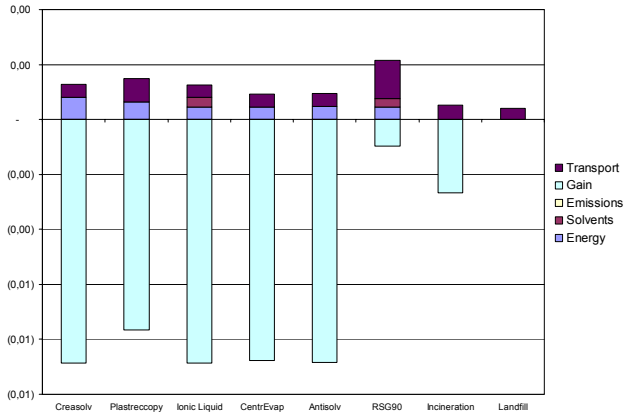
EQ ecotox



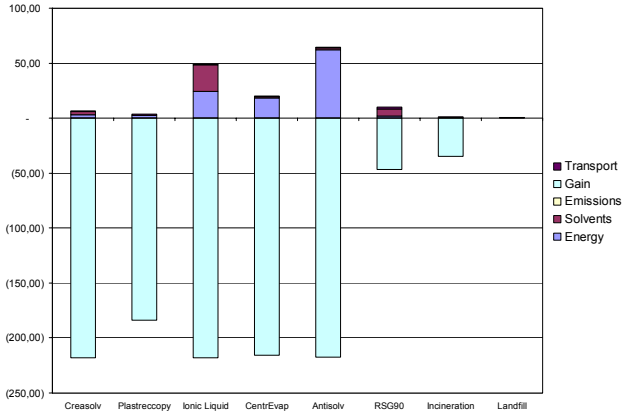
EQ acid



RD min



RD fossil



Appendix 5E - Update of White Young Green environmental impact assessment for Phase 3 results

LIFE CYCLE ASSESSMENT STUDY:

ADDENDUM REPORT

Selected Treatment Processes for WEEE Plastics Containing Brominated Flame Retardants

Reference: **Life Cycle Assessment Addendum Report to WYGE project ref. E4833 – July 2006**				
Issue		**Prepared by**	Checked by	**Verified by**
1	July 2006			
				HALL
		Consultant	**Associate**	**tor**
File Ref: N:\Projects\E9001-E9500\E009397\reports\2006 update				

White Young Green Environmental Limited, Arndale Court, Headingley, Leeds. LS6 2UJ.
Telephone: 0113 278 7111 Facsimile: 0113 275 0623 E-Mail: enviro.leeds@wyg.com

TABLE OF CONTENTS

Life-cycle Assessment of Waste Treatment Options for Waste Electrical and Electronic Plastic containing Brominated Flame Retardant Compounds

4.0 Background

In 2005, White Young Green Environmental (WYGE) were commissioned by Axion Recycling to undertake a Life Cycle Assessment (LCA) study of designated processing options for plastics containing brominated flame retardants as part of the Waste and Resources Action Programme (WRAP) funded project 'Develop a process to separate brominated flame retardants from WEEE polymers.'

This study was based on mass balance data available from preliminary practical trials and process design work undertaken in Phase 2 of the project and generic, publicly available data. Following the principals detailed in ISO 14040, the potential environmental impacts of four new process options identified in Phase 1 of the study were compared to the traditional waste disposal and recovery options of incineration, feedstock recycling and landfill. The results of this study were included within Interim Report 2 for the project, published by WRAP in August 2005 (WYGE project ref. no. E4833).

5.0 Aims

Following the completion of Phase 3 of this study, WYGE have been commissioned by Axion Recycling to update the quantitative Life Cycle Assessment (LCA) study for those two processes for which practical trials were undertaken in Phase 3, the Creasolv and Centrevap processes, using updated mass balance data collected during the practical trials undertaken in Phase 3. The potential environmental impacts from these processes were compared to those traditional waste disposal and recovery processes of landfill and incineration using those environmental indicators adopted in the original study.

This report forms an addendum to the original WYGE project report no. E4833, as detailed in the Interim 2 Report: 'Develop a process to separate brominated flame retardants from WEEE polymers' and summarises the additional work which has been undertaken, based on the original study. Background information, detailed methodology, including the results of the qualitative and quantitative assessments and discussions from the original LCA study are not included within this report. As such this addendum report should be read in conjunction with the original study report (WYGE Ref. E4833) included within the Interim 2 Report for the project published in August 2005 by WRAP.

6.0 Introduction

Brominated flame retardants (BFR's) are compounds containing bromine which are added to materials such as plastics to inhibit or suppress the ability of materials to burn and are widely found in electronic and electrical equipment, furniture, paints and textiles.

Despite the importance these compounds have on enhancing the safety of items such as electronic and electrical equipment, the production and use of some BFR compounds is now prohibited due to the potentially hazardous nature and toxicological effects of these compounds, (i.e. DeBB, Penta-PDE, Octa-BDE) and there is continuing concerns about the safety of others, i.e. Deca-BDE and its potential to degrade into lower brominated PBDE's. In addition, the longevity of some electrical and electronic equipment (E&E) units will ensure that plastics containing these compounds and in particular those which are currently banned, will continue to find their way into the waste stream for a number of years.

In an effort to prevent and reduce the disposal of waste electrical and electronic equipment (WEEE) and promote and encourage the recovery and closed-loop recycling of these items, the Waste Electrical and Electronic Equipment (WEEE) Directive (2002/96/EC) was introduced. Under this Directive, the selective treatment of a number of materials and components commonly found within WEEE is required in order to avoid the dispersal of pollutants and encourage the recovery and recycling of WEEE components. Amongst those materials which are required to be treated prior to disposal / recovery are plastics containing brominated flame retardants. The aims of this Directive are further supported by the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) (02/95/EC) Directive, which requires that from 1st July 2006, new E & E equipment placed onto the market contains less than 0.1% PBB and PBDE's.

In the face of these legislative drivers, the Waste and Resource Action Programme (WRAP) has identified that one of the barriers to the closed-loop recycling of plastic polymers from WEEE in the UK is the need to remove unwanted additives from the plastic polymers before they can be reused, and these include BFR's. To address this technical barrier, WRAP have funded a study to investigate potential commercially viable techniques for extracting BFR's from WEEE polymers in order to create better opportunities for the closed–loop recycling of WEEE polymers back into new electronic and electrical equipment.

Axion Recycling Ltd. has been appointed to lead a project to develop a process to separate brominated flame retardants from WEEE polymers. This study has been phased to enable the issues concerning separating BFRs from WEEE polymers to be qualified, current technologies to be reviewed, practical trials and process design works to be undertaken and assessments made to determine which of these technologies have the potential to be commercially viable in the UK.

6.1 Summary of Phase 2 Life Cycle Assessment Analysis

The potential environmental impacts of the four selected potential new process options Creasolv, Centrevap Ionic Liquids and Antisolvent processes, were assessed using the four environmental indicators chosen and as detailed in the Phase 2 report for the project and compared to those anticipated from traditional recovery options, such as incineration with energy recovery, landfill and feedstock recycling.

Of those four new processes investigated for separating BRF from plastic polymers, the results of the quantitative analysis suggested that the best environmentally performing processes were the Creasolv and Centrevap processes, presenting low – medium overall potential environmental impacts (figure 1). The potential environmental impacts resultant from these processes appears to compare favourably with those perceived impacts for landfill and incineration (with and without energy recovery).

The potential environmental impacts of the Anti-solvent and Ionic Liquids processes were perceived to be greater than Centrevap and Creasolv processes (presenting a medium overall environmental impact) due to a number of factors. These include increased energy consumption, decreased polymer recovery efficiencies, variations in the types of solvent used and variations in solvent loss and recovery efficiencies of the process design.

While landfill processes are typically associated with low environmental impacts, this study categorised landfill processes as presenting medium overall environmental impacts. Based on those environmental indicators used, the quantifiable environmental burdens of landfill were primarily linked to the use of on-site compaction vehicles and therefore found to be low compared to the more energy intensive processes studied. However, this is contrasted by the lack of environmental benefits, using those indicators detailed in the study, perceived to result from this process.

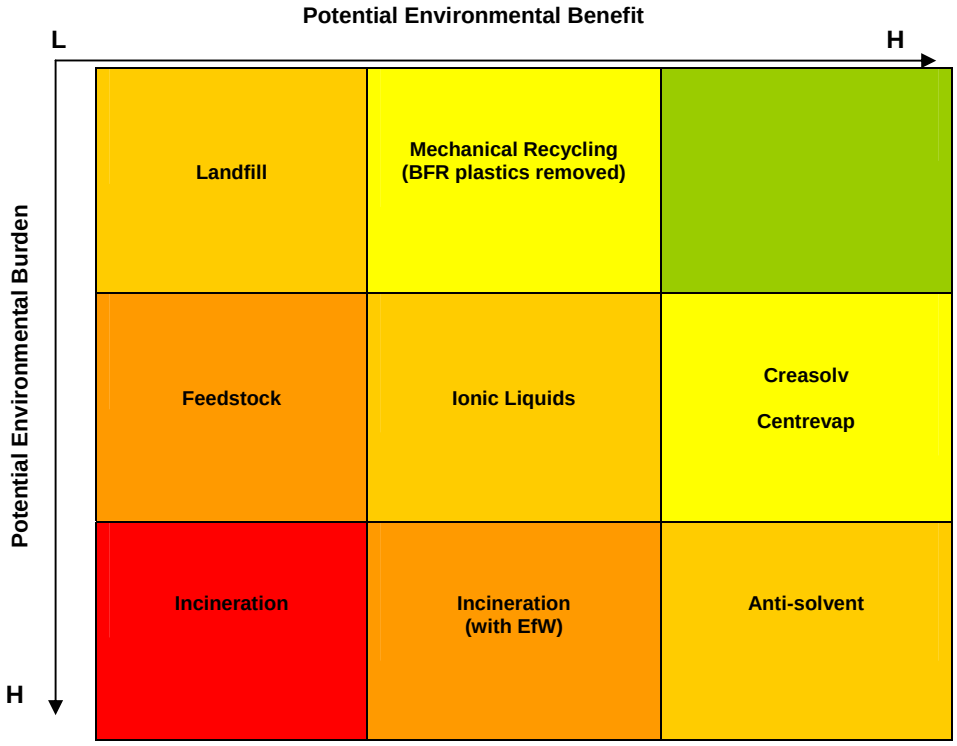


Figure 1: Results of the Phase 2 Quantitative Environmental Impact Assessment

In contrast, incineration processes were categorised as presenting medium-high to high overall environmental impacts, largely as a direct result of incineration processes releasing the embodied energy of the plastics, producing comparatively high GWP and POCP values to those other processes studied.

The results of this analysis appeared to compare favourably with the supporting 'QWERTY' eco-efficiency analysis undertaken for this phase of the study by Huisman Research Recycling in parallel to this study. Both studies suggest that the new BRF separation processes, Creasolv and Centrevap, operating alongside traditional mechanical recycling processes have the lowest overall impact of those processes studied and may present a better environmental option than landfill and incineration (with energy recovery) processes.

6.2 Summary of Phase 3 Process Trials

Phase 3 of the project involved practical technical scale testing of those processes highlighted in Phase 2 which were recommended for further development and evaluation based on laboratory trials and environmental and economic assessments. These processes were identified as being the Creasolv and Centrevap processes.

The results of these practical trials indicate that the Creasolv process has the potential to be commercially viable in the UK context and demonstrates the most potential for separating BRF species from WEEE polymers. Given the results of theses trials, the outcome of the Phase 3 study recommended that the Creasolv process should be developed and assessed further through larger scale trials.

In contrast, the Centrevap process was shown not to be able to achieve significant reductions in the BFR content of the polymer and is therefore not a suitable process for separating BFR species from WEEE polymers. However, the results of the practical trials indicate that the process may be a good, robust alternative treatment process for removing insoluble impurities for a wide range of polymers.

Based on these results, the Centrevap processes can not be considered as a comparable, alternative treatment process to Creasolv, however, it could be a commercially viable solvent process capable of removing other impurities to the sub-micron level from none BFR-containing polymers. As such, further practical trials will be undertaken on the Centrevap process to evaluate this potential alongside the Creasolv process.

4.0 Goals and Scope of the Study

4.3 Goals of the Study

The objective of the study was to update the original environmental impact assessment work undertaken in Phase 2 using new updated mass balance data provided by Axion Recycling Ltd, resulting from Phase 3 practical trials for the Centrevap and Creasolv processes.

The results of Phase 3 practical trials demonstrate that the Centrevap process can not reduce the BFR content of WEEE polymers to set target levels and therefore can no longer be directly assessed against the Creasolv process, which can. However, the project team indicate that the Centrevap process could be a viable process for removing insoluble impurities from none BFR-containing polymers and is therefore being considered in further trials. Therefore the original environmental impact assessment work for the Centrevap process will be updated to provide an indication as to the potential environmental impacts from this process as a treatment option for non-BFR WEEE plastic polymers.

While it is understood that the process itself will not be affected by replacing a BFR-containing feedstock with a non-BFR-containing polymer throughput, it is unclear as to whether factors such as solvent loss or energy consumption will be impacted. As such, this assessment should be considered as an *indicative assessment* only as to the potential environmental impacts of this process as practical trials using non-BFR containing polymers have yet to be undertaken. .

The environmental impacts for each of the new solvent processes will be compared to the potential environmental impacts resulting from the traditional disposal options of landfill and incineration (with and without energy recovery).

This study is based on the background data and assumptions used in the original study and should be read in conjunction with the original report. This study also follows the principles and methods of the ISO 14040 Standard Environmental Management – Life Cycle Assessment – Principles and Framework (1997a).

4.4 Scope of the Study

While the Creasolv process was identified as the only suitable and commercially viable process for separating BRF species from WEEE polymers, it is understood that both processes will undergo further large scale testing in order to asses their potential as a future solvent based recycling process. The results of the assessment for each of the novel processes will therefore not be directly comparable as the throughput material is different.

It is understood that the source of input material has not changed between Phase 2 and Phase 3 practical trials and therefore this study is based on those material input assumptions made in the original study, including;

- Small WEEE items such as mobile phones, MP3 players etc. are excluded;
- WEEE dismantling and pre-sorting of WEEE plastics has taken place to produce a mix of plastic material that is dominated by the styrenic polymers HIBS (High Impact Polystyrene), ABS (Acrylonitrile Butadiene Styrene) and PC (Polycarbonate) in equal proportions;
- That substituted materials resulting from the separation processes are virgin HIPS, PC and ABS polymers.
- That feedstock material comprises 10% BFR, 0.8% Antimony and 10% inert materials.
- The main brominated flame retardants considered to be present in these polymers are: TBBPA (forming 7% in PC/ABS polymers and 5% in ABS polymers), Deca-BDE (forming 10% in HIPS polymers and 3% in ABS polymers), Octa-BDE (forming 5% in ABS polymers) and TBPE (forming 0.5% in ABS polymers).

The waste treatment process options considered by this study included the following as detailed in the original study. Further details on refinements and changes to the process design for the Creasolv and Centrevap processes between Phases 2 and 3 of the study can be found in Interim Report 3 for the project. Five process options were evaluated:

j. Landfill
k. Incineration (no energy recovery)
l. Incineration (with energy recovery)
m. Creasolv process
n. Centrevap process

4.2.1 The Functional Unit

The functional unit of this study refers to the processing (input) of 1500kg of WEEE plastic polymer pre-sorted into brominated flame retarded styrenic polymers. This unit was defined by the mass balance throughput data available on the new process options and has been applied to other treatment options. With reference to incineration technologies, it has been assumed that this mass of plastic waste must be combined with municipal solid waste at a ratio of 3:97; the weight of total material entering this system has been multiplied up accordingly.

4.2.2 System Boundaries

System boundaries used are the same as those defined in the original study and can be seen in Figure 2.

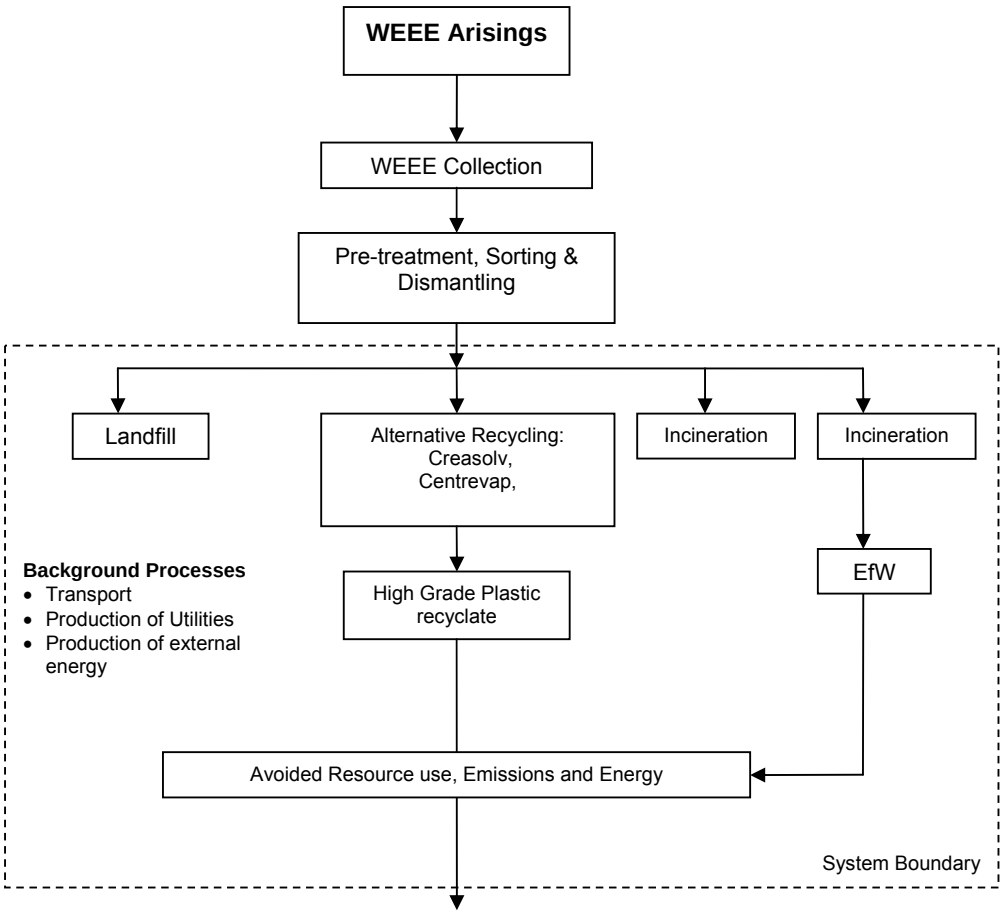


Figure 2 – System Boundaries of the Study

As the study was conducted with a view to providing a broad overview of the potential environmental impact and comparable environmental performance of the different waste treatment processes, only those main consumables into each system were considered, i.e. primary energy, plastic polymer, inerts, solvents, water while output emissions inventories were restricted to the main species characterized in energy emission inventories; carbon dioxide, carbon monoxide, nitrogen oxides (NO_x), sulphur dioxide, Methane, non-methane Volatile Organic Hydrocarbons (NMVOC's). Emissions to water have been specifically excluded.

4.2.3 Data quality

Data available on the new recycling processes was obtained from practical trials undertaken during Phase 3 of the project and compiled mass balance data produced by Axion Recycling. As with previous data, this information was only available at an aggregated level with only major material flows detailed and no break down of energy consumption sources or measured emissions data available. As such, realistic assumptions have been made where required and publicly available data used with regards to emissions and energy data as detailed in the original study to fill in data gaps.

Following Phase 3, process specific emissions data for the Creasolv and Centrevap processes, with regards to dioxin, furan and BFR emissions have yet to be collated and therefore detailed inventory data remains unavailable.

6.0 Methodology

The methodology followed for the update of this LCA is based on the methodology detailed in the original report (WYGE project ref. E4833), as found in Interim Report 2 for this project.

The environmental impact categories used as the same as those detailed in the original study. These are;

- Global Warming
- Abiotic Resource Use
- Environmental toxicity
- Photo-oxidant formation

Please refer to the original study for information regarding the choice and background of environmental indicators. Quantitative data was obtained for three of the four environmental impact categorises chosen for this study; primary energy consumption, Global warming potential (GWP) and Photochemical Ozone Creation Potential (POCP).

Quantitative data remains unavailable for dioxin / furan and BRF emissions resulting from the Creasolv and Centrevap processes; therefore a qualitative assessment has again been used to evaluate the potential environmental toxicity of the Creasolv and the Centrevap process to the potential environmental toxicity of landfill and incineration processes. This assessment has not changed from the original study and therefore has not been detailed in this addendum report. For information on the qualitative assessment on potential environmental toxicity, please refer to the original study.

7.0 Impact Assessment

6.1 Impact Assessment: Creasolv

6.1.1 Results from Quantitative Assessment – Environmental Indicators

The following Figures (3 to 5) show the environmental burdens and benefits calculated for each of the process options studied for three of the four environmental impact categories chosen. From these, the overall environmental impact for each process was determined and also displayed. Negative net impact values demonstrate that a process has an overall environmental benefit whilst positive net impact values reflect overall environmental burdens from a process.

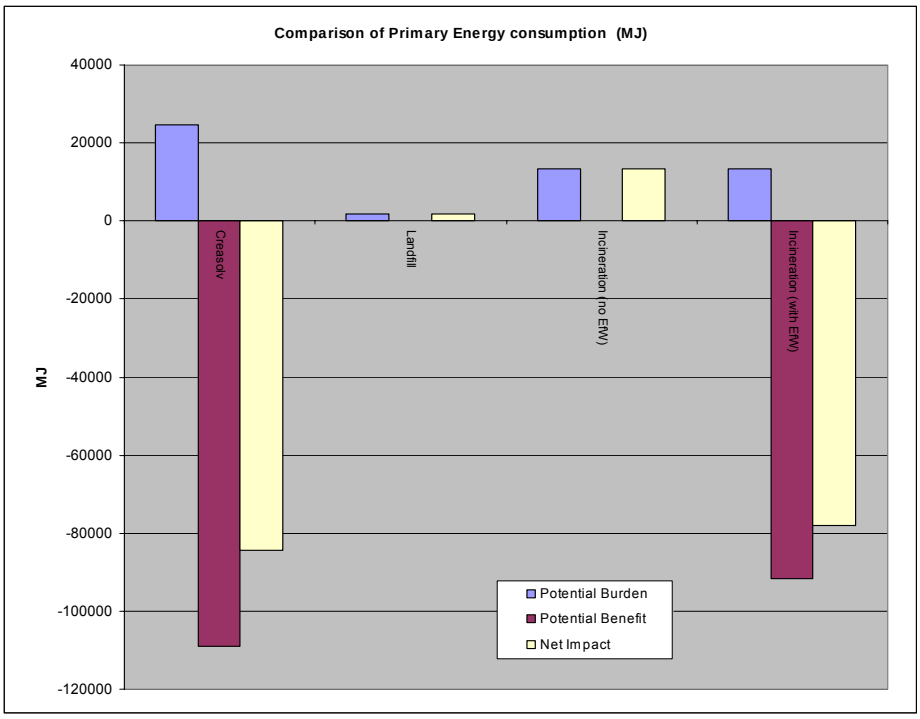


Figure 3 – Primary Energy Use (MJ) for each scenario

The throughput of materials into the incineration and landfill processes has increased slightly to reflect the additional material passing through the Creasolv process, therefore providing a direct comparison between the processes. However, the overall potential environmental impacts of these processes remains unaltered as the environmental impacts per unit of throughput material remains unaltered.

The results for all of the three quantitative indicators show that the Creasolv process offers lower potential environmental impacts than landfill or incineration processes. Changes to the design process have resulted in an increase in primary energy consumption, due to the lengthening of the process cycle, when compared to the results of the original assessment. This has increased the environmental burden for the process and reduced the overall environmental impact margin between this process and that of incineration with energy recovery for this indicator.

The impacts on the GWP indicator, which for the Creasolv process is closely linked to primary energy use, also shows an increase in overall impact when compared to the original assessment, however the margin between this and incineration processes with energy recovery remains high, as the GWP for incineration processes is also associated with the combustion and the release of the embodied energy of the material into the atmosphere.

For the Creasolv process, the results of the POCP indicator are largely reflective of solvent use and loss through the system. While the volume of solvent has increased since the original study as a result of the increased process cycle, solvent losses through the system have reduced slightly. While a small increase in the impacts of the POCP indicator are seen, the environmental impacts for this indicator appear to be significantly lower than for comparable incineration processes.

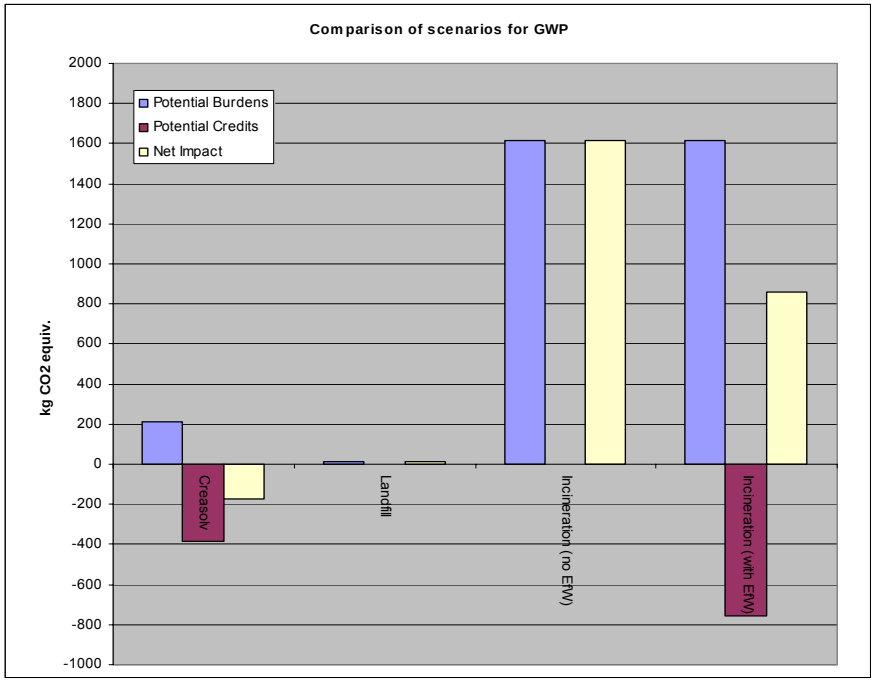


Figure 4 – Global Warming Potential (as kg CO_2 equivalents) for each scenario - Creasolv

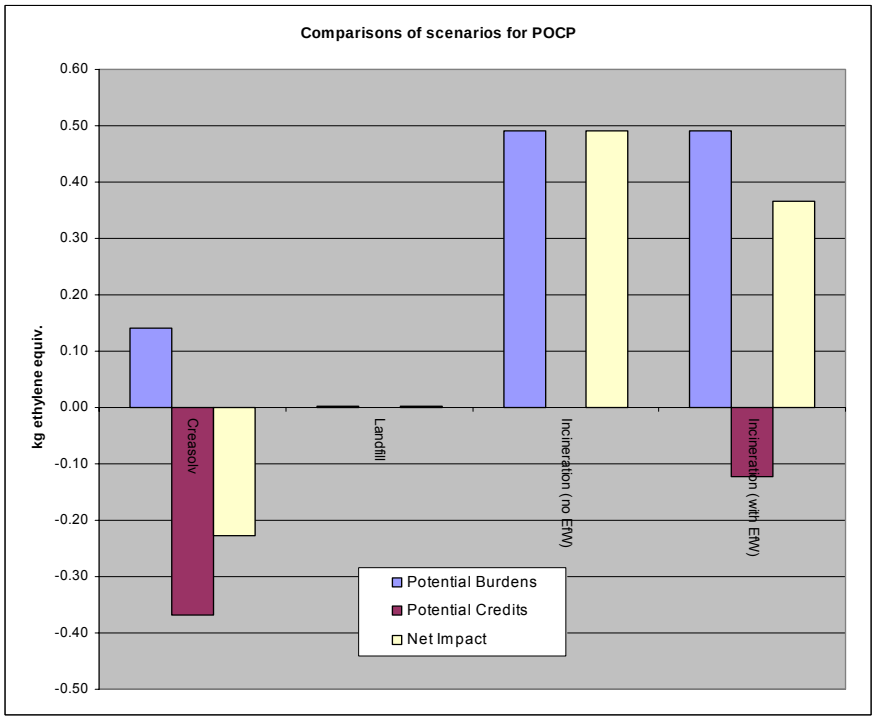


Figure 5 – Photochemical Oxidation Potential (as kg ethylene equivalents) for each scenario - Creasolv

6.1.2 Results from Quantitative Assessment – Overall Environmental Impacts

The environmental burden / benefit for the Creasolv process was scored for each environmental indicator, based on the comparative rank of those processes studied and summed to give a total environmental benefit and burden score as detailed in the original study. This was then allocated into a low, medium or high environmental impact band and placed into the matrix developed through the qualitative and quantitative assessments undertaken in the original study. The results of this quantitative environmental impact assessment can be seen in Figure 6. No weighting factors have been applied to these results.

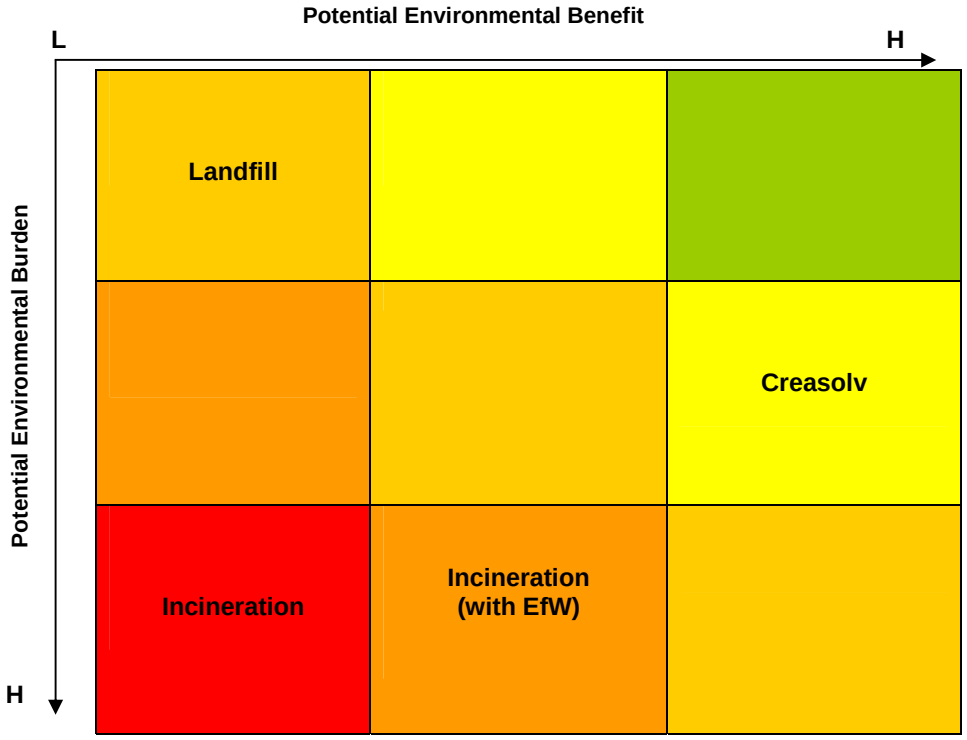


Figure 6: Results from the Quantitative Environmental Impact Assessment - Creasolv

The overall potential environmental impacts of the traditional process options of landfill, incineration and incineration (with energy recovery) processes remains unaltered as the environmental impacts per unit of throughput material remains the same.

Despite increases in energy consumption and changes in process design, the potential environmental impacts of the Creasolv process appears to remain unaltered, based on those environmental indicators used. As detailed in the original report, based on the data and environmental indicators used, the Creasolv process appears to offer lower potential overall environmental impacts compared to traditional waste disposal and treatment processes.

Data quality issues and data gaps highlighted in the original report remain valid for the update of the original study; only major material throughputs have be quantified and quantitative data gaps still exist with regards to BFR, dioxin and furan emissions from the Creasolv process. Concerns raised about the potential for dibenzo-p-dioxin and furans to build up in solvent recovery systems have not yet been addressed and the environmental impacts of hazardous waste generation has not been considered.

As recommended in the original study, to complete a holistic assessment of the environmental impact for these processes, these environmental impacts should be investigated and supported by process-specific emissions monitoring in order to validate the results of this study.

6.2 Impact Assessment: Centrevap

6.2.1 Results from Quantitative Assessment – Environmental Indicators

The following Figures (7 to 9) show the environmental burdens and benefits calculated for each of the process options studied for three of the four environmental impact categories chosen. From these, the overall environmental impact for each process was determined and also displayed. Negative net impact values demonstrate that a process has an overall environmental benefit whilst positive net impact values reflect overall environmental burdens from a process.

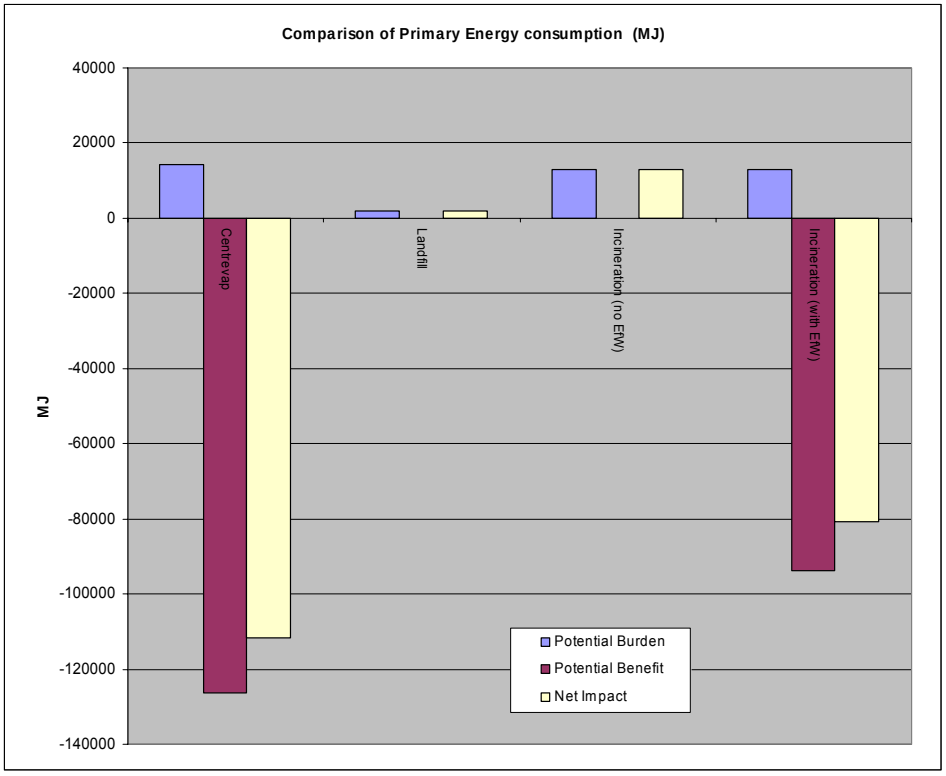


Figure 7 – Primary Energy Use (MJ) for each scenario - Centrevap

The throughput of materials into the incineration and landfill processes has increased slightly to reflect the additional material passing through the Centrevap process, therefore providing a direct comparison between the processes. However, the overall potential environmental impacts of these processes remains unaltered as the environmental impacts per unit of throughput material remains unaltered.

The results for all of the three quantitative indicators suggest that the Centrevap process offers lower potential environmental impacts than landfill or incineration processes. Changes to the design process have resulted in a small increase in primary energy consumption when compared to the results of the original assessment. This has increased the environmental burden for the process slightly, resulting in slightly highly environmental burdens for the primary energy use and GWP indicators.

Results for the POCP indicator are largely reflective of solvent use and loss through the Centrevap system and in contrast to the original study, there is a significant reduction in solvent loss through the process. As a result, the environmental impact for the POCP indicator has reduced significantly and the process now displays a net environmental benefit in contrast to the original net environmental burden with regards to this indicator.

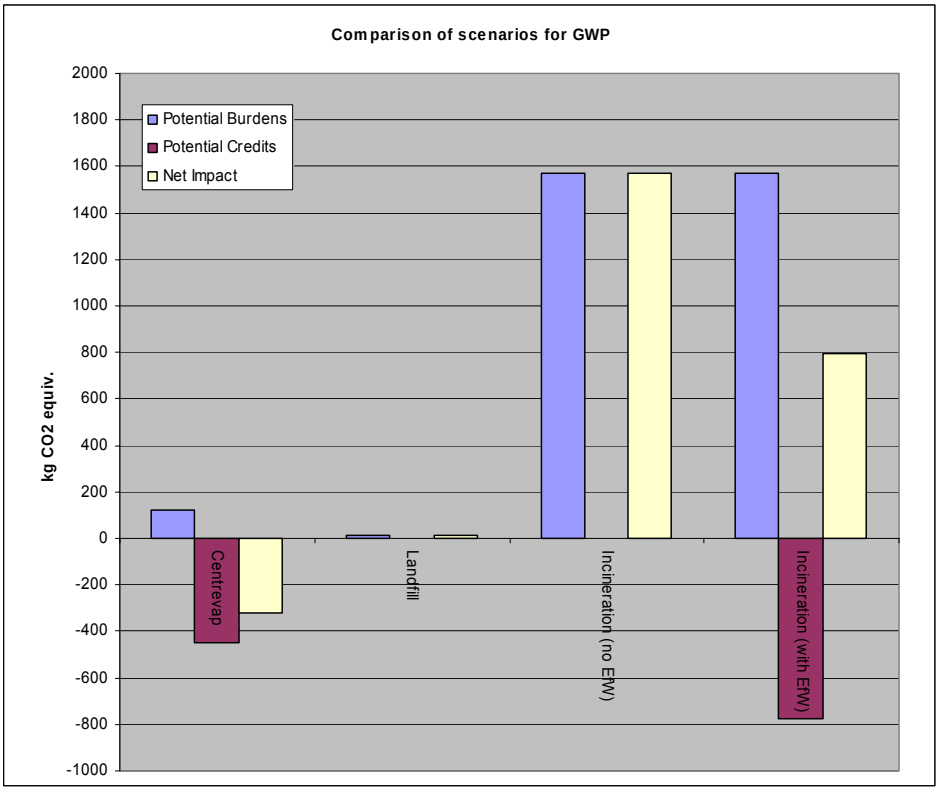


Figure 8 – Global Warming Potential (as kg CO_2 equivalents) for each scenario - Centrevap

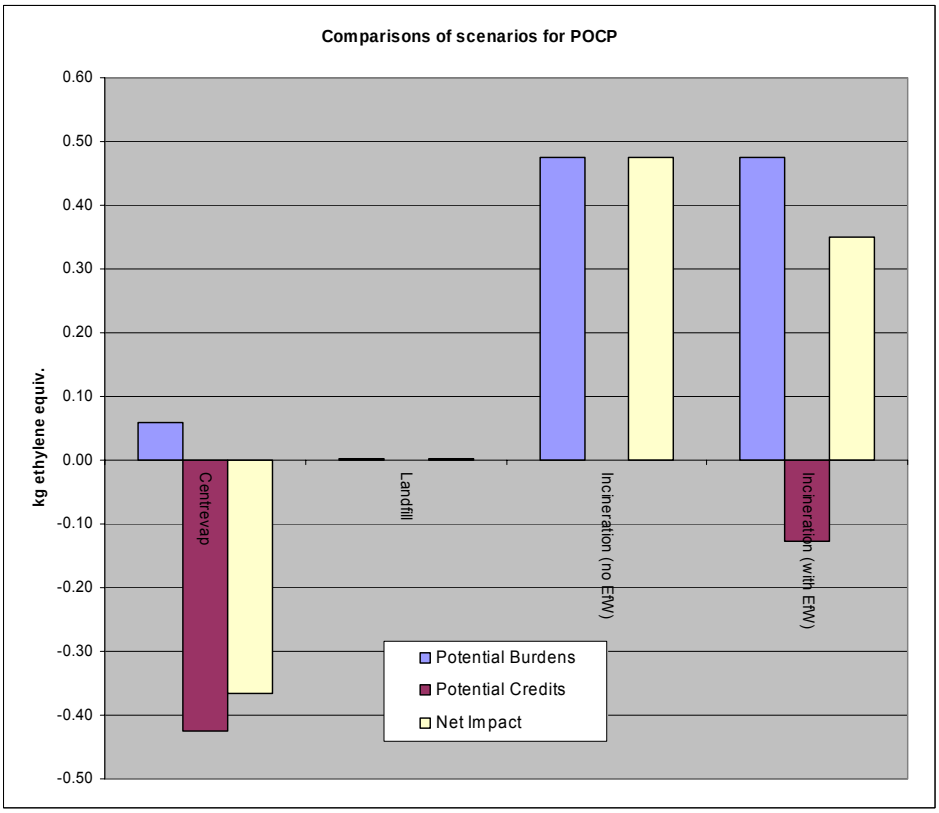


Figure 9 – Photochemical Oxidation Potential (as kg ethylene equivalents) for each scenario - Centrevap

6.2.2 Results from Quantitative Assessment – Overall Environmental Impacts

The environmental burden / benefit for the Centrevap process was scored for each environmental indicator, based on the comparative rank of those processes studied and summed to give a total environmental benefit and burden score as detailed in the original study. This was then allocated into a low, medium or high environmental impact band and placed into the matrix developed through the qualitative and quantitative assessments undertaken in the original study. The results of this quantitative environmental impact assessment can be seen in Figure 10. No weighting factors have been applied to these results.

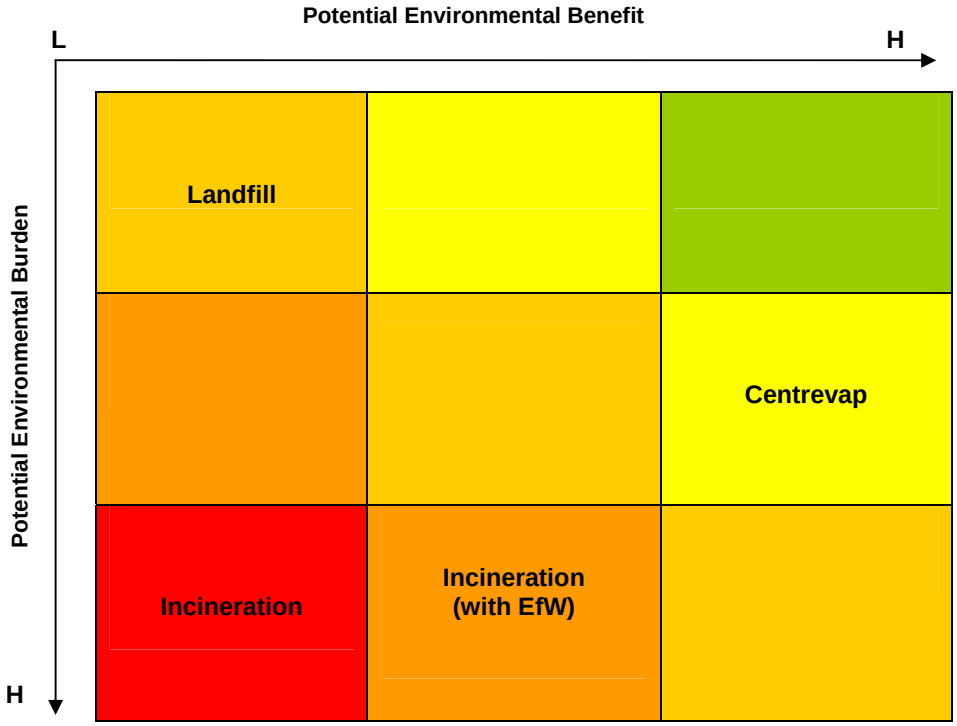


Figure 10: Results from the Quantitative Environmental Impact Assessment - Centrevap

The overall potential environmental impacts of the traditional process options of landfill, incineration and incineration (with energy recovery) processes remains unaltered as the environmental impacts per unit of throughput material remains the same.

Despite small increase in energy consumption as a result of changes to process design and the significant reductions in solvent use and loss through the process, the overall potential environmental impacts of the Centrevap process appears to remain unaltered, based on those environmental indicators used. As detailed in the original report, based on the data environmental indicators used, the Centrevap process appears to offer a lower overall environmental impacts compared to traditional waste disposal and treatment processes.

However, it should be highlighted that this is an indicative assessment only based on Phase 3 process trial data, which involves a throughput of BFR-containing plastic polymers into a process which can not effectively remove BFR from plastics polymers. However, it is anticipated that this process could prove to be a viable alternative treatment process for non-BRF polymers. In order to determine the potential environmental impacts of this process for treating non-BFR polymers and to quantify any changes in the process required to treat a different throughput material, a further study should be conducted looking at mass balance data resulting from a throughput of non-BFR polymers.

8.0 Conclusions

Despite the increase in energy consumption required by the Creasolv process as a result of changes in process design, the study appears to demonstrate that the overall environmental impacts of the process have not changed significantly from the results of the original study. As a result, the Creasolv process continues to demonstrates a medium-low overall environmental impact and still appears to be a more favourable process option for the treatment of BFR-containing plastic wastes compared to traditional incineration and landfill processes in terms of those environmental indicators used.

With regards to the Centrevap process, small increases in energy consumption as a result of changes to the design process have not significantly influenced the potential environmental impacts of this process. Changes in the solvent recovery process has significantly improved the performance of the process with regards to the POCP indicator, however, again this does not appear to have a significant impact on the overall performance of the process.

However, due to the different potentials of the Centrevap and the Creasolv processes to extract BFR's from WEEE polymers the potential environmental impacts of these two processes can not be directly compared as they could potentially be utilised to process difference materials.

Like the Creasolv process, the Centrevap process appears to be a potentially more favourable process option to both landfill and incineration process for non-BFR containing polymers. However, this assessment can be no more than an indicative as all mass balance data relates to process trials undertaken using BFR-containing polymers yet conclusions from the Phase 3 process trials state that this process will only be viable for non-BRF containing plastic polymer wastes. As such, a further assessment of the process should be undertaken using process data which utilises a non-BFR-containing throughput material. This will enable any changes in energy requirements, solvent recovery and polymer recovery efficiency to be fully characterised and related to potential environmental impacts.

8.0 Limitations

Data quality issues and data gaps highlighted in the original report remain valid for the update of the original study; only major material throughputs have be quantified and quantitative data gaps still exist with regards to BFR, dioxin and furan emissions from the Creasolv and Centrevap processes.

Concerns raised about the potential for dibenzo-p-dioxin and furans to build up in solvent recovery systems have not yet been addressed and the potential environmental impacts of hazardous waste generation has also not been considered.

As recommended in the original study, to complete a holistic assessment of the environmental impact for these processes, these environmental impacts should be investigated and supported by process-specific emissions monitoring for the new solvent processes in order to validate the results of this investigation.

In addition, a further assessment of the Centrevap process should be undertaken once additional process trials have been completed using a non-BFR-containing plastic polymer throughput material. This is necessary in order to adequately characterise any process changes which may result from the removal of BFR's from the process design and which may impact on those environmental indicators assessed.

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10.0 Glossary

ABS	Acrylonitrile Butadiene Styrene
AP	Acidification Potential
APME	Association of Plastic Manufacturers in Europe
BFR	Brominated Flame Retardants
BDE	Diphenyl ethers
CFC	Chlorofluorocarbons
COD	Chemical Oxygen Demand
DBD	Dibenzo-dioxins
DBF	Dibenzo-furans
E & E	Electrical and Electronic
EfW	Energy from Waste
EP	Eutrophication Potential
GWP	Global Warming Potential
HBCD	Hexabromocyclododecane
HIP	High Impact Polystyrene
LCA	Life Cycle Assessment
MSW	Municipal Solid Waste
NETCEN	National Environment Technology Centre
NMVOC	Non-methane Volatile Organic Compounds
NOx	Nitrogen oxides
ODP	Ozone Depletion Potential
PBB	Polybrominated biphenyls
PBDE	Polybrominated Diphenyl ethers
PC	Polycarbonate
POCP	Photochemical Oxidation Potential
PVC	Polyvinyl Chloride
TBBPA	Tetrabromobisphenol-A
TBPE	1,2- (tribromophenoxy) ethane
VOC	Volatile Organic Compounds
WEEE	Waste Electrical and Electronic Equipment
WRAP	Waste and Resources Action Programme

APPENDIX A

REPORT CONDITIONS

WHITE YOUNG GREEN ENVIRONMENTAL

REPORT CONDITIONS

UPDATE TO THE LIFE CYCLE ASSESSMENT: SUMMARY REPORT OF

SELECTED TREATMENT PROCESSES FOR WEEE PLASTICS CONTAINING BROMINATED FLAME RETARDANTS

*This Life Cycle Assessment summary report is produced solely for the benefit of **Axion Recycling Ltd.** and no liability is accepted for any reliance placed on it by any other party unless specifically agreed in writing otherwise.*

This report refers, within the limitations stated, to the operational processes as per the information supplied to WYGE. No warranty is given as to the possibility of future changes in the design of these processes.

This report is based on reference data provided by Axion Recycling, accessible referenced records and information supplied by those parties referenced in the text. Some of the opinions are based on unconfirmed data and information and are presented as the best that can be obtained without further extensive research.

Whilst confident in the findings detailed within this report because there are no exact UK definitions of these matters, being subject to risk analysis, we are unable to give categorical assurances that they will be accepted by authorities or funds etc. without question as such bodies often have unpublished, more stringent objectives. This report is prepared for the proposed uses stated in the report and should not be used in a different context without reference to WYGE. In time improved practices, data quality or amended legislation may necessitate a re-assessment.

APPENDIX B

ENERGY CONVERSION FACTORS

Energy conversion Factors

12.	1kWh	=	3.6 MJ
13.	1 MJ	=	0.2778 kWh
14.	1 therm	=	29.31 kWh
15.	1 kWh	=	0.03412 therms
16.	1 tonne coal	=	7583kWh
17.	1 tonne gas oil	=	12519 kWh
18.	1 litre heating oil	=	11.3kWh
19.	1 tonne heating oil	=	1238 litres heating oil
20.	1 litre heating oil	=	37.3 MJ
21.	$1m^3$ natural gas	=	39 MJ
22.	1 m^3 natural gas	=	0.0007 tonnes

APPENDIX C

ASSUMPTIONS

General

10. All data is based on the input of BFR WEEE polymers into the system. This equates to 1500kg WEEE plastic.
11. It is assumed that 10% of the throughput material is accounted for by brominated flame retardant species, 0.8% Antimony and that 10% of the throughput material is accounted for by inert contaminant materials.
12. It is assumed that the polymer composition of the throughput material is primarily Acrylonitrile Butadiene Styrene (ABS), High Impact Polystyrene (HIPS) and Polycarbonate (PC) in equal proportions.
13. It is assumed that 1500kg WEEE plastic will be processed in an hour, for all processes.
14. It is assumed that all energy data provided for the new systems equals the amount of energy required to process 1500kg of WEEE plastic input, unless where stated.
15. An average draw of electricity of 500kWh has been presumed for the landfill processes. This is in addition to process specific energies.
16. Environmental burdens have been assessed based on primary energy consumption, fuel usage by on-site plant and solvent use for each process.
17. Emissions from processes such as plastic extrusion, pellet formation etc. have not been quantified and therefore not been assessed.
18. Environmental burden is calculated based on the burdens of processing 1500kg of WEEE plastic waste input into the system.
19. Environmental benefits are calculated based on the requirements of replacing virgin materials with the weight of the resulting product of the recovery process.
20. It is presumed that the new process will produce high-grade plastic recyclate which will replace virgin plastic materials. A ratio of 1tonne recyclate to replace 1 tonne virgin plastic has been assumed.

Assumptions for Electricity Generation

8. That energy consumption, where not specified is split 60:40 between electricity and oil
9. That primary fuel sources for UK electricity generation are:
    a. Coal - 33%
    b. Gas – 41.5%
    c. Oil – 1.5%
    d. Nuclear 24%
    e. Hydro - 2%
10. No emissions arise from electricity production from nuclear and hydro / renewable energy sources
11. For electricity generation, the combustion efficiencies of the respective fuels are:
    a. Coal - 36.2%
    b. Gas - 46.6%
    c. Oil - 31%
12. Emission factors are taken from the national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei
13. Emission factors from electricity generation for electricity generation from Power Stations are taken from the national air emission inventory website. Emission factors for coal, natural gas and gas oil have been used.
14. Carbon dioxide emissions are based on a stoichiometric calculation, using the carbon emission factor provided from the National Air Emission Inventory website. (Carbon emission/mol. Wt carbon (12)) x mol. Wt. CO_2 (44)).

Environmental Impact Potency Factors

5. Two environmental impact factors have been chosen for this study; Global Warning Potential (GWP) and Photochemical Oxidation Potential (POCP).
6. These are reported as tonnes of CO_2 and tonnes of ethylene equivalents respectively per year.
7. All process data has been calculated based on input into the system over an hour period. The reported potency factors for these environmental indicators therefore require conversion to kg/hour.
8. Potency factors for GWP and POCP are taken from:

www.icheme.org/sustainability/metrics.pdf

	GWP CO_2 equivalents		POCP ethylene equivalents	
	CO_2 t/y	CO_2 kg/hr		CO_2 t/y
Carbon Dioxide	1	0.114	Carbon Dioxide	1
Carbon Monoxide	3	0.352	Carbon Monoxide	3
NO_x	40	4.556	NO_x	40
N_2O			N_2O	
Methane	21	2.397	Methane	21
NMVOC	11	1.256	NMVOC	11
SO_2	0	0	SO_2	0
Toluene	11	1.256	Toluene	11
Methanol	11	1.256	Methanol	11
Creasolv 1st Solvent	11	1.256	Creasolv 1st Solvent	11
Creasolv 2nd solvent	11	1.256	Creasolv 2nd solvent	11
Ethyl Acetate	11	1.256	Ethyl Acetate	11
Hexyl pyridinium bromide	0	0	Hexyl pyridinium bromide	0

Assumptions for other On-site energy generation

6. That 40% of on-site energy generation for the new processes is generated from heating oil.
7. Combustion efficiency for this process is 81%. This figure is taken from the average UK oil fired steam boiler combustion efficiencies, which range from 70 - 92% (average = 81%. Source: www.actionenergy.org.uk
8. Emission factors for heating oil are taken from: national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei and those factors for fuel oil for 'other industry' have been used.
9. A gross calorific value of 45.6MJ has been used for diesel.
10. Emission factors available for diesel combustion, with the exception of carbon and sulphur dioxide, are characterised by the travel profile of the vehicle. No travel data was available for compactors.

Avoided Emissions: from virgin plastic production

7. Data is taken from the Eco-profiles for polymer plastics produced by APME. Eco-profiles for HIPS, ABS and PC have been used.
8. It is assumed that the resulting recyclate substitutes these virgin polymers in equal proportions.
9. Data for gross primary fuels and feedstock have been used for energy consumption and feedstock process.
10. Energy consumption for fuel production and transport processes are specifically excluded.
11. Emissions include fuel use and process operations; emissions from fuel production and transport are specifically excluded.
12. GWP weighting have been applied to the emission inventories where possible; a weighting of 11 has been given to all non-methane VOCs groupings, where individual values are not available.
13. POCP weighting have been applied to the emission inventories where possible; averaged values for the alkanes, alcohols, ketones and alkenes have been used as a representative weighting for the hydrocarbon group and 'other' organics; averaged values for aromatic species have been used fro the

aromatic and polycyclic hydrocarbon groupings; the aldehyde grouping used average values for individual aldehyde species.

Process specific Assumptions: LANDFILL

5. There is no available data for energy consumption at landfill sites. An average electricity draw of 500kWh has been presumed.
6. There is no data available on transport emissions from compactor vehicles at landfill sites.
7. A fuel consumption figure of 0.6litres diesel per m^3 of landfill void filled is quoted in *'Integrated Solid Waste Management: A life-cycle Inventory'* (2001) by McDougall, F.R, White, P.R, Franke, M. and Hindle, P and has been used.
8. Emission factors have been taken from national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei relating to industrial off-road transport. These have been used as there is an absence of travel related data for this activity.

Process specific Assumptions: NEW PROCESSES

6. Emission factors from fuel use for plant have been taken from the national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei relating to industrial off-road transport.
7. Solvent emissions are presumed to amount to 2% of made-up solvent, minus those emissions to water.
8. A GWP of 11t/y CO_2 equivalent has been used for all solvents (equivalent to VOC emissions).
9. A POCP potency factor of 0.596 t/y ethylene equivalent has been used for paraffinic hydrocarbons; this is an averaged value from alkane, alkene, ketone and alcohol species.

Process specific Assumptions: INCINERATION

12. It is presumed that incineration plants recover power only, not heat; there is no Bromine recovery.
13. Combustion efficiency is calculated at 26%.
14. Assumes that ratio of MSW:BFR WEEE plastics is 97:3.
15. Assumes that BFR can only be incinerated alongside MSW.
16. Calorific value of WEEE plastic is 44.3MJ/kg. This is based on the average calorific values for ABS, HIPS and PC.
17. Assumes that the calorific value of MSW is 7.06MJ/kg. This figure is taken from 'Integrated Solid Waste Management: A life-cycle Inventory' (2001) by McDougall, F.R, White, P.R, Franke, M. and Hindle, P and is an averaged value for UK MSW.
18. Assumes 0.23m3/ tonne waste of natural gas is required to heat up the incinerator. This figure is taken from 'Integrated Solid Waste Management: A life-cycle Inventory' (2001) by McDougall, F.R, White, P.R, Franke, M. and Hindle, P.
19. Emission factors are taken from national air emissions inventory web-site: www.aeat.co.uk/netcen/airqual/naei relating to MSW incineration. Emissions are currently calculated on 100% MSW, not 97%; no information on emissions from plastic combustion is available at the present time.
20. Carbon dioxide emissions are based on a stoichiometric calculation, using the carbon emission factor provided from the National Air Emission Inventory website. (Carbon emission/mol. Wt carbon (12)) x mol. Wt. CO_2 (44)).
21. Assumes that power recovered generates electricity; this electricity replaces traditional means of electricity generation.
22. No allowance is made for additional or lower energy requirements of the system by incorporating a higher proportion of plastics into the stream.

Appendix 5F – Huisman update of QWERTY analysis for Phase 3 results

Screening Eco-Efficiency Study on Treatment of BFR Plastics

Eco-efficiency and QWERTY analysis on treatment of plastics with brominated flame-retardants in the United Kingdom

Short update report

Date: June 8, 2006
Commissioned by:
Roger Morton
Axion Recycling Ltd
Project manager for the WRAP (The Waste and Resources Action Programme)
PLA00037 – Develop a Process to Extract Brominated Flame Retardants from WEEE Polymers

Written by:
Dr. Ir. Jaco Huisman

TU Delft
Industrial Design Engineering,
Design for Sustainability Program
Landbergstraat 15, 2628 CE
Delft, The Netherlands
J.Huisman@io.tudelft.nl

Huisman Recycling Research
Boschdijk 466,
5622 PD, Eindhoven
The Netherlands
HRR@chello.nl

Introduction

In the June 2005 the report "Screening Eco-Efficiency Study on Treatment of BFR Plastics" was written. This report contains an update of this work as part of the WRAP project PLA00037 – Develop a Process to Extract Brominated Flame Retardants from WEEE Polymers.

Objective

Objective is to specifically update the 2005 eco-efficiency calculations for the Creasolv and Centrifuge – Evaporate processes as more detailed data is derived in the meantime.

Main changes and relevant parameters

Compared to the 2005 calculations, the following changes and relevant parameters are presented in the following Table:

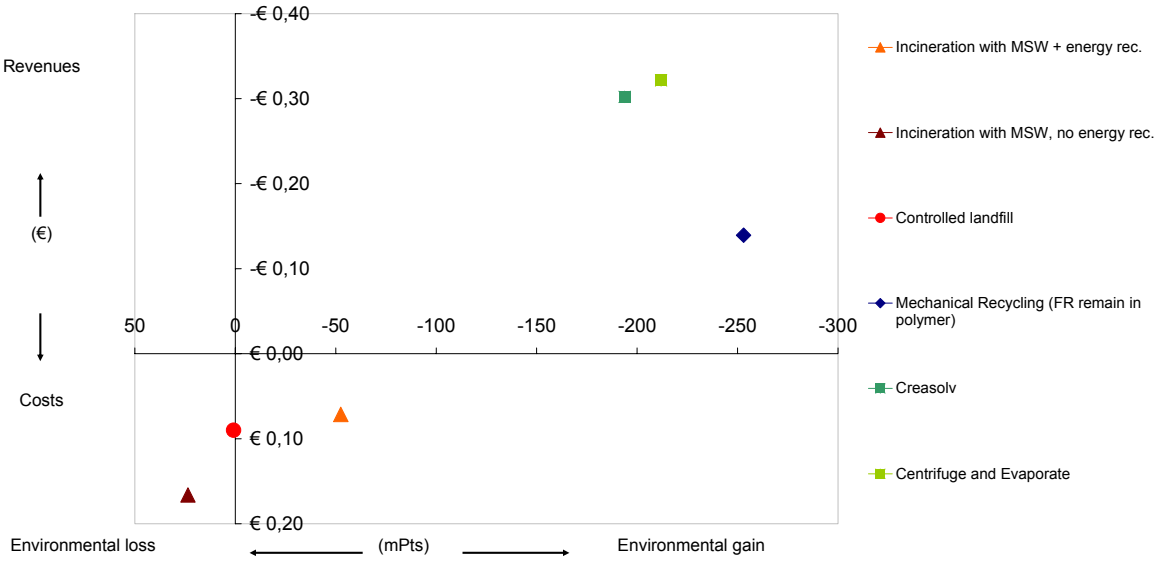
General parameters	**Old**	**New**
1. 1 £ =	€ 1,4610 (at 2006-06-07)	€ 1,4590 (at 2006-06-07)
2. Polymer selling price as a percentage of virgin	47%	60%
3. Power consumption	£ 0,06/ kWh	£ 0,07/ kWh
4. Gate fee (avoided incineration with MSW incl. energy recovery)	£ 35/ ton (€ 51,10/ ton)	£ 45/ ton (€ 65,70/ ton)
5. Drying agent	Not used	Neglected as waste materials will be used
6. Update revenues at incineration with energy recovery (higher oil-prices)	Level: $ 50/ barrel	Level: $ 70/ barrel
Creasolv		
7. Polymer recovery	99%	77%
8. Energy consumption	350 kWh/ ton	288 kWh/ ton
9. Steam consumption:	1050 kg/ ton	4953 kg/ ton
10. Solvent consumption:	14,4 kg/ hr Creasolv 6,0 kg/ hr G-PS-F	14,1 kg/ hr Creasolv 7,4 kg/ hr G-PS-F
Centrifuge - Evaporate		
7. Polymer recovery:	99%	81%
8. Energy consumption:	117 kWh/ ton	112 kWh/ ton
9. Steam consumption:	2217 kg/ ton	1779 kg/ ton
10. Solvent consumption:	11 kg/ hr Toluene	5,67 kg/hr Toluene

Results

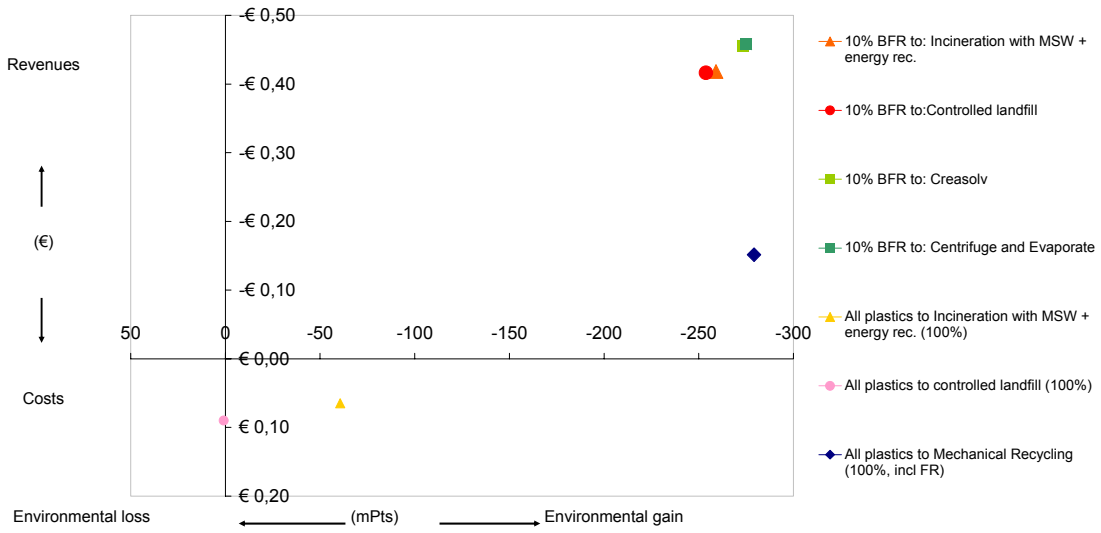
Two basic treatment scenarios are evaluated again with respect to their eco-efficiency:

1. Scenario 1 is the treatment of 1 kg of styrene based BFR plastics (ABS; ABS/PC and HIPS). The outcomes show which processing option for the separated BFR plastics fraction is preferable.
2. Scenario 2 is the treatment of 1kg average mix of WEEE polymers with 10% of BFR plastics (to various options) and 90% non BFR plastics (to mechanical recycling). This comparison shows the added value of the sorting of BFR from non-BFR plastics. As reference points, the incineration with energy recovery and controlled landfill of the total fraction is included.

In the graph below, scenario 1 is demonstrated. .



Scenario 2 is depicted in the following graph:



Conclusions

Scenario 1 shows what the most preferable route is for 1 kg of the 10% BFR plastics. The Creasolv and Centrevap processes are the most economically preferred options and scoring much better than disposal of this separated fraction. Note that the mechanical recycling scenario is only added as a reference point as the BFR content is not removed here, but is still included in the polymer. The higher burden of the solvents and energy needed with compared to mechanical recycling explain the horizontal environmental difference.

Scenario 2 shows especially the added economic value of the separation of 1 kg of 10% BFR and 90% non BFR plastics with respect to direct mechanical recycling. Due to the separation, higher revenues are possible. Main reason is a higher selling price for BFR free secondary plastics.