

Report



# Plastics to oil products

Final report



Zero Waste Scotland works with businesses, individuals, communities and local authorities to help them reduce waste, recycle more and use resources sustainably.

Find out more at [www.zerowastescotland.org.uk](http://www.zerowastescotland.org.uk)

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## Executive summary

The Zero Waste Plan published by the Scottish Government in 2010 sets targets of 70% of all waste to be recycled and 5% to be landfilled by 2025. In order to help deliver this plan, The Waste (Scotland) Regulations 2012 require that all dry recyclables are collected separately and that disposal of separately collected dry recyclables to landfill or incineration is banned from 1 January 2014.

Plastic items that enter the waste stream are made in a wide range of formats and from a variety of polymer types. According to the market research of material recovery facilities (MRFs), and other waste-processing facilities, conducted as part of this project, there is currently around 18,000–27,000 tonnes per annum (tpa) of low-quality mixed waste plastic film in Scotland which cannot be recovered by current mechanical recycling techniques. The bulk of this material is plastic film from commercial and domestic packaging sources, and arises from municipal MRFs, with the remainder from composting and anaerobic digestion facilities. It is estimated that this volume will increase to up to 50,000tpa as the Zero Waste Plan is implemented. There is the potential to use chemical and thermal processing methods to recover these low-grade mixed waste plastics as useful materials.

The purpose of this report is to review the current state of development of processes for conversion of mixed waste plastic to oil and to compare the technical, commercial and environmental potential of the leading process options for implementation in Scotland. The report also reviews the regulatory and fiscal issues relating to implementation of these technologies in Scotland and makes recommendations for changes which could encourage uptake of these technologies.

Processes for conversion of plastics and other solid hydrocarbon materials to oil are not new. Gasification and pyrolysis techniques for coal were commercialised in Germany during the Second World War and developed further in South Africa during the Apartheid years. Plastic depolymerisation techniques were developed actively during the 1980s and 1990s, but none was adopted commercially as mechanical recycling methods developed rapidly. Over the past 10 years there has been an increase in the amount of research into the conversion of plastic into oil, as oil prices have increased and waste collection and sorting methods have improved. There are now several processes operating close to commercial viability in different parts of the world.

The processes that have the most technical and commercial potential fall into three categories:

- fast gas phase pyrolysis to make synthetic crude oil mixtures;
- liquid-phase catalytic depolymerisation to make mixed distillates; and
- gasification, followed by chemical or biological synthesis, to make high-quality fuels.

The pyrolysis and catalytic depolymerisation processes are limited in scale by the need for external heating of the material to be treated. This means that it is difficult to build these plants with a capacity of more than about 1,000kg/h (approximately 8,000tpa) per individual process unit; for sites processing larger tonnages, several units running in parallel are needed.

These pyrolysis and catalytic depolymerisation processes have a relatively low capital cost and a relatively high yield (60–70% of the feedstock is converted to a liquid). However, the quality of these oil products is low and further processing is required to give a fuel product. Despite this, the high yield improves the environmental and economic viability of these processes.

In comparison, gasification processes with downstream synthesis of high-quality fuels are much more capital intensive, requiring larger economies of scale. These processes have lower product yields (30–60% of the feedstock is recovered as a liquid fuel) but recover energy as electricity from the high-pressure, high-temperature processes.

Although all of the processes considered in this report generate a positive operating income, only pyrolysis, catalytic depolymerisation and gasification with biological conversion to ethanol are financially viable, generating positive 10-year net present values (NPVs). These processes still generate a positive NPV if the gate fee falls to £60 per tonne, which is expected as the market for energy from waste in Scotland grows. Pyrolysis and catalytic depolymerisation generate a positive NPV at a gate fee of zero. These economic assessments were based on capital cost numbers provided by technology suppliers and as such may not reflect the actual capital required for a project. Capital was the biggest sensitivity and hence further refinement in this area is required before the full economics are understood.

The capital required for sufficient capacity to process 27,000tpa is of the order of £20–30M. Lower capacities would require less investment, but the minimum economically viable capacity is estimated to be between 12,000 and 16,000tpa. For pyrolysis and catalytic depolymerisation, this means that installation of a single processing unit is unlikely to be viable.

The report concludes that for Scotland the best technical, environmental and commercial option is likely to be one of the pyrolysis, liquid-phase catalytic depolymerisation or gasification with biological conversion to ethanol processes. Versions of these processes can be found on a scale of 250–500kg/h in the USA, Canada, Germany, Poland, Hungary and China.

There are still substantial technical risks involved in implementing one of these processes in Scotland. None of the demonstration plants appears to be functioning fully commercially at present and there will be particular challenges in collecting and preparing the Scottish mixed plastic waste materials to suit the chosen process.

The quality of the oil produced by catalytic depolymerisation depends on the quality of the feedstock, so it is not yet certain at which point the process could be introduced into the fuel supply chain. Test work on Scottish feed material would be required to establish whether the material could be blended directly into gasoline or diesel at low addition rates (the highest value option) or whether it would need to be introduced to an oil refinery part-way through the crude oil treatment process, in which case the selling price for the oil would have to be lower in order to compensate the refinery for its additional processing costs.

Additional capital costs at the refinery (e.g. for integration or risk mitigation) will also have an impact on the economic viability of the process.

An analysis of the transport costs associated with proposed processing site networks shows that one centralised site based in Grangemouth is the best option. This is dependent on there being a suitable site close to the INEOS refinery that can feed the oil products to the refinery by pipeline, thereby avoiding extra transport costs for the oil products.

The development of plastics-to-oil processes could be further encouraged by adjusting the regulatory and fiscal incentives in order to provide similar incentives for oil and power generated from waste, by advanced thermal conversion processes of the type reviewed in this report, to those (Renewable Transport Fuels Obligation (RTFO), Feed-in Tariff (FiT), Renewable Heat Incentive (RHI)) that are provided for power and liquid fuels produced from biogenic materials.

In particular, consideration should be given to:

- extending the incentives already available for biogenic waste materials to those waste materials that are likely to be banned from landfill in Scotland, by applying RTFO to waste-derived oil products and FiT and RHI to power and heat generated from the manufacturing processes involved in producing oil products from plastics;
- working with the Scottish Environment Protection Agency (SEPA) to provide clear guidance on the criteria by which plastic-to-oil processes could be determined as being energy or chemical manufacturing processes rather than waste management processes (incineration or co-incineration); and
- working with SEPA to provide clear guidance on the 'end of waste' for waste-derived oil products, possibly by development of an appropriate quality standard.

In addition, this report recommends reducing the technical and commercial risk for potential project promoters through the following measures:

- Practical trials should be conducted to demonstrate the quality and composition of the oils that could be produced by one or more of the leading pyrolysis or catalytic depolymerisation processes from low-grade waste plastic sourced in Scotland.
- Feasibility studies (desk based) should be carried out to determine the practically successful waste-plastic-to-oil technologies to understand the technical capability, the energy integration and the project integration of each with a specific end-use partner. Output should be a good estimation of the capital expenditure needed and provide a good understanding of the technical risk and how it can be mitigated.
- Research needs to be conducted to confirm the actual quantities of low-grade plastic film arising from materials recycling facilities, composting facilities and anaerobic digestion plants.
- Studies are needed to fully assess the potential costs of registration of oil products under REACH (Registration, Evaluation, Authorisation & restriction of Chemicals).

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## Glossary

<b>Alkanes</b>	A class of saturated hydrocarbons with the chemical formula $C_nH_{(2n+2)}$ that are a major component of diesel fuels. This class includes methane, ethane, propane, butane, octane, cetane, etc. Also known as paraffins.
<b>Alkenes</b>	A class of unsaturated hydrocarbons with the chemical formula $C_nH_{2n}$ that are a component of road fuels. This class includes ethylene, propylene, etc. Also known as olefines.
<b>Anaerobic digestion</b>	A series of processes in which micro-organisms break down biodegradable material in the absence of oxygen. The process releases biogas consisting of methane, carbon dioxide and contaminants gases.
<b>Animal by-products</b>	Entire bodies or parts of animals, products of animal origin or other products obtained from animals that are <b>not intended for human consumption</b> , as defined by Article 3 of Regulation EC 1069/2009.
<b>Aromatics</b>	A class of hydrocarbons that have alternating double and single bonds between carbon atoms, forming a ring. This class includes benzene, toluene, xylene, etc. Also known as arenes or aryl hydrocarbons.
<b>Carbon footprint</b>	A measure of the total amount of carbon dioxide ( $CO_2$ ) and methane ( $CH_4$ ) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest.
<b>Catalytic depolymerisation</b>	The breaking of long-chain polymers to oligomers and monomers on the application of heat and a catalyst(s).
<b>Composting</b>	A process of controlled biological decomposition of a mixture of organic matter to produce a useful plant nutrient product.
<b>Depolymerisation</b>	The process of breaking a polymer chain to a monomer or mixture of monomers.
<b>Devolatilisation</b>	The separation of volatile materials from solids or liquids.
<b>Distillation</b>	A method of separating mixtures based on differences in volatilities of components in a boiling liquid mixture.

<b>Energy from Waste (EfW)</b>	A process by which waste is thermally treated to produce energy in the form of electricity and/or heat. It includes incineration and co-incineration, pyrolysis and gasification technologies.
<b>Eutrophication</b>	The enrichment of bodies of fresh water by inorganic plant nutrients (e.g. nitrate, phosphate).
<b>Fischer-Tropsch (F-T)</b>	A series of reactions that converts a mixture of carbon monoxide and hydrogen gases to liquid hydrocarbons.
<b>Gasification</b>	A process in which a solid fuel is reacted with a gasifying agent such as air, oxygen or steam to produce a gaseous fuel containing hydrogen and carbon monoxide.
<b>Hydrocarbons</b>	An organic compound consisting entirely of hydrogen and carbon.
<b>Life cycle assessment</b>	A technique to assess environmental impacts associated with all the stages of a products life from cradle to grave.
<b>Net present value (NPV)</b>	A measure of discounted cash inflow to present cash outflow which helps to determine whether a prospective investment will be profitable.
<b>Polymerisation</b>	Polymerisation is the process of reacting monomer molecules together to form polymer chains or three-dimensional networks.
<b>Pyrolysis</b>	A process involving the decomposition of organic materials on the application of heat at an elevated temperature in the absence of oxygen.
<b>Syngas (synthesis gas)</b>	These are product gases from reactions comprising carbon monoxide and hydrogen in varying proportions.
<b>Thermal degradation</b>	The molecular deterioration of a polymer as a result of overheating. Here, the long-chain polymer begins to separate into several shorter chain polymers. The shorter chain polymers then react with each other to bring about a change in the polymer properties.

## Abbreviations

<b>% wt</b>	Percentage, on a weight basis
<b>Capex</b>	Capital expenditure
<b>CHP</b>	Combined heat and power
<b>IPC</b>	Integrated Pollution Control
<b>M</b>	Month
<b>MRF</b>	Materials recovery facility
<b>MTG</b>	Methanol to gasoline
<b>Opex</b>	Operating expenditure
<b>PVC</b>	Polyvinyl chloride
<b>Q</b>	Quarter
<b>RTFO</b>	Renewable Transport Fuel Obligation
<b>w/Bio</b>	With biological conversion of syngas to ethanol
<b>w/F-T</b>	With Fischer-Tropsch conversion of syngas to diesel
<b>w/MTG</b>	With conversion of syngas to methanol and then to gasoline (Methanol-to-Gasoline)
<b>Y</b>	Year

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# 1 Introduction

## 1.1 Background

In 2010, the Scottish Government launched Scotland's first Zero Waste Plan;<sup>1</sup> this laid out several challenging new measures, including a target recycling rate of 70% on all waste and a maximum of 5% waste sent to landfill by 2025. In order to help deliver this plan, the Waste (Scotland) Regulations 2012 require that all dry recyclables are collected separately and that disposal of separately collected dry recyclables to landfill or incineration is banned from 1 January 2014. In addition, the existing cap of 25% of household waste to energy from waste facilities will be replaced with a package of measures to encourage waste prevention, reuse and recycling. In order to deliver these targets, reprocessing options for previously landfilled waste must now be considered.

One of the most prevalent types of waste is plastic; it is estimated<sup>2</sup> that, in 2009, 400,000–600,000 tonnes of plastic waste was disposed of in Scotland, more than 70% of which was landfilled or incinerated. Recovering the majority of this material would be a significant boost in meeting recycling targets.

Recovering plastic for direct reuse can be problematic because of the wide range of different plastic types, applications and formats. This can result in a mixed, contaminated fraction that is unsuitable for existing mechanical recycling methods, which rely on a relatively uncontaminated feed. Separating a wide range of plastic types and formats can be difficult and costly to achieve. An alternative method is to change the plastic mixture into a reusable product via a chemical process. As most plastic is originally created from crude oil, the simplest and most 'closed-loop' solution is to create oil products that can be reused either to make more plastic or as a fuel.

Zero Waste Scotland commissioned Axion Consulting to evaluate the various routes available to treat waste plastics and create oil products, and to assess the Scottish plastic waste arisings that would be available for such processes.

## 1.2 Project objectives

The key objectives of the project were as follows:

- literature review of the process options;
- assessment of the types and sources of available waste plastics, the supply chain for delivery of these plastics and end markets for oil products;
- technological, financial and environmental assessment of selected processes;
- evaluation of the regulations surrounding the construction of a process; and
- investigation into barriers to development and current levels of interest.

### 1.3 Project methodology

A range of methodologies were employed to fulfil the objectives outlined above.

- **Literature review of the process options:** the first part of the review was carried out through Internet research focused on key websites including those of universities, technology providers, industry associations and research bodies, as well as more general web searches. Once key processes were identified, the relevant companies and organisations were contacted directly to discover as much information as possible about each option.
- **Assessment of the types and sources of available waste plastics, the supply chain for delivery of these plastics and end markets for oil products:** a further literature review was carried out to assess the volumes and types of waste plastic arising in Scotland. These volumes were traced back to specific sources within Scotland through discussions with stakeholders in the waste recycling supply chain (e.g. material recovery facilities (MRFs), waste transfer stations, etc.). A Microsoft Excel-based model was used to assess the costs associated with transporting the waste to a variety of processing locations across Scotland. Further discussions were held with end-market stakeholders (e.g. refineries) to evaluate the potential for the oil products produced by the process.
- **Technological, financial and environmental assessment of selected processes:** a set of Microsoft Excel-based models were used to calculate the performance of each process from technical, financial and environmental standpoints; this included reaction modelling for the main chemical processes, mass balance modelling, investment and payback calculations, and an environmental assessment using data from the Carbon Trust's Footprint Expert™ tool.
- **Evaluation of the regulations surrounding the construction of a process:** discussions were held with the Scottish Environment Protection Agency (SEPA) to discuss how thermal and chemical processes for the conversion of waste plastics into oil products would be regulated. This was supplemented by the team's existing knowledge of permitting, which is based on many previous permit applications.
- **Investigation into barriers to development and current levels of interest:** existing Scottish waste processors and other stakeholders were contacted directly to discover their level of interest in the processes proposed in the report, and any potential issues or reservations they would have. This information was considered in conjunction with any problems raised in the previous tasks, such as technical or financial infeasibility, or problematic environmental effects.

## 2 Literature review

### 2.1 Introduction

The recovery and recycling of plastic waste disposed of in landfill has been the subject of much effort over the decades, as it is seen as a valuable resource and is high in the public's perception of what 'waste' is. Progress has been made in the mechanical recycling of post-commercial, industrial and pre-sorted post-consumer waste, but the recovery of value from low-grade mixed plastic waste has always presented technical and economic difficulties.

The conversion of plastic into oil products requires the long polymer chains that are characteristic of plastics to be broken into shorter chains typical of compounds present in crude petroleum. This depolymerisation can be achieved by heating the materials to moderate or high temperatures, and zeolite catalysts (such as those frequently used in oil refineries) are helpful in increasing the rate of depolymerisation.

The basic processes of depolymerisation are pyrolysis, gasification and thermal cracking. All of these processes have been in use in the coal, gas and petroleum refining industries for decades, and as such can be considered to be mature technologies. The use of plastic as a feedstock for these processes has been studied for 20 years, but its uptake has been limited by the relatively low price of oil and the lack of a credible collection infrastructure for this low-density, disperse-source feedstock. During the 1990s a series of demonstration plants were announced, only to disappear after a few years' operation. It is interesting to note that the majority of technology suppliers reported by Juniper in 2001<sup>3</sup> are no longer active in this field, having run out of money or sold the technology to organisations with access to the funds to continue process and project development.

More recently, the increased price of oil and incentives in the USA for energy and fuels from biomass and waste have resulted in renewed activity in these areas. However, in the USA and Europe, there is a preference for investment and government funding (in terms of research, development and final projects) for processes using biomass as a feedstock rather than non-biogenic waste materials. The main reasons for this are:

- The feedstock itself is more homogeneous, and therefore tends to create fewer process problems.
- There is an established collection mechanism, from either agricultural processing or forestry operations.
- The feedstocks are considered to be truly renewable, so can attract incentives aimed at reducing the impact of climate change, etc.

The recognition that waste plastic is a valuable resource has also energised research and development activity in China and India. In Europe, the greater incentives for energy and fuel production from renewable ('biogenic') feedstock materials have meant that research programmes in Europe are concentrating on the conversion of biomass, although the technologies and principles could be adapted for processing waste plastic.

## 2.2 Literature cited

A literature review of process options and technologies for converting waste plastics to oil products was conducted. This was executed by Internet research directed at key websites, including those of universities, technology providers, industry associations and research bodies, as well as more general web searches.

Studies by Aguado et al,<sup>4</sup> Schiers and Kaminsky,<sup>5</sup> and the United Nations Environment Programme (UNEP)<sup>6</sup> indicated that four basic technologies were being offered as commercial plastic-to-oil-product processes in 2000:

- fast pyrolysis to produce a synthetic crude oil;
- liquid-phase catalytic depolymerisation to produce a synthetic diesel grade fuel;
- gasification and Fischer–Tropsch synthesis to produce a synthetic diesel grade fuel; and
- gasification and fermentation to produce fuel-grade ethanol.

More recently, Butler *et al*<sup>7</sup> provided a useful review of the current state-of-the-art processes for the conversion of plastics to liquid fuels and identified 24 commercial processes for the conversion of plastic into oil products. Many of these were reported as having an ‘unknown’ status, indicative of technical or financial problems causing development to stop, but there is a number of processes that still appear to be active.

The American Chemistry Council<sup>8</sup> provides a useful review of plastic conversion to fuel processes in the USA, identifying 12 North American technology providers and 11 from the rest of the world.

The US National Renewable Energy Laboratory is focused on the use of biomass as a potential feedstock, as it represents a renewable feedstock, which waste plastic does not. However, the report does provide useful information on biomass to liquid processes, including gasification with Fischer–Tropsch synthesis to diesel,<sup>9</sup> gasoline<sup>10</sup> and ethanol.<sup>11</sup>

## 2.3 Technology supplier survey

From the above literature sources, and web-based searches, a total of 31 technology suppliers were identified; the below information was gathered by reference to the suppliers’ websites, available literature and telephone interviews with suppliers. Some technology manufacturers required a non-disclosure agreement (NDA) before revealing information that would allow comparison of the technical and economic performance of the technology. However, no NDAs were entered into for the execution of this report.

The key information gathered included:

- the name of the technology supplier;
- the location of the technology supplier;
- whether the technology was specific to a particular feedstock type, and whether plastic was an acceptable feedstock;

- which sources of feedstock had been tested or demonstrated;
- whether the feedstock requires specific preparation before being used by the technology;
- how tolerant the technology is to contamination;
- where a catalyst is used, the consumption and lifespan demonstrated;
- the principal products from the technology;
- the residues and wastes produced by the technology;
- the typical yield from the technology, and how this varies with feedstock;
- the typical operating conditions of the process technology;
- the largest system currently operating; and
- the constraints on scale-up to larger systems.

The results of the review can be found in Appendix A.

## 2.4 Scoring exercise

The information gathered from the literature and technology supplier surveys has been scored on the following basis:

- **Scale of operation:** whether the technology is at laboratory, demonstration or commercial scale. Given the quantity of the low-grade waste plastic arising in Scotland (discussed in section 3), 'commercial scale' is considered as being anything over 10,000 tonnes per annum (tpa).
- **Extent of the technology demonstrated:** whether the operational unit demonstrates the entire integrated process from plastic to oil product, or one or more key stages.
- **Feedstock:** whether the technology has been successfully fed with low-grade waste plastic, higher-grade waste plastic or other materials.
- **Yield:** the proportion of the feedstock converted to oil products, net of any used for process heating.
- **Quality:** whether the oil products are crude products requiring refining, blend components or 'drop-in' fuels.
- **Capital cost of technology:** the capital cost of the technology, in pounds per tonne per annum feed.
- **Operating cost of technology:** the operating cost of the technology, in pounds per tonne of feed.
- **Demonstration operating hours:** the number of running hours reported for the operational unit.

**Table 1** shows the scoring system used for this exercise. **Table 2** presents the results of the scoring exercise.

**Table 1** Scoring system for identified technologies

Score	Scale (tpa of feed)	Extent of demonstration	Feedstock demonstration	Yield (% weight)	Product quality	Capital cost (per tpa)	Operating cost (per tonne of feed)	Operating period
9	Commercial (> 10,000)	Identical to commercial-scale plant	Full range of waste plastic	> 90	Drop-in fuel	< £500	< £50	> 5 years
7	Demonstration (1,000–10,000)	Similar to commercial-scale plant	Limited range of plastic	> 70	Blend component	£500–1,000	£50–100	2–5 years
5	Pilot (100–1,000)	Parts of commercial-scale plant	Relevant wastes (municipal solid waste)	> 50	Mixed distillate	£1,000–2,000	£100–200	1–2 years
3	Laboratory (< 100)	Paper	Non-plastic wastes	> 30	Crude	> £2,000 or confidential	> £200 or confidential	< 1 year
1	Paper	None	Paper	< 30	N/A	N/A	N/A	N/A

**Table 2** Results of the scoring exercise

Technology	Supplier	Scale	Demonstration	Feedstock	Yield	Quality	Capex	Opex	Running hours	Overall score
<b>Pyrolysis processes</b>										
Pyrolysis	Agilyx	7	9	7	7	3	7	1	7	<b>48</b>
Catalytic pyrolysis	Anhui Orsun Env Tech	7	9	7	5	9	3	7	9	<b>56</b>
Pyrolysis	Blest	7	9	7	7	3	5	9	9	<b>56</b>
Microwave pyrolysis	Climax Global Energy	7	9	5	7	3	7	7	1	<b>46</b>
Pyrolysis	Cynar	7	9	7	5	9	5	5	7	<b>54</b>
Fast pyrolysis	Dynamotive	9	5	1	7	3	1	7	5	<b>38</b>
Pyrolysis	Envion	9	9	7	7	3	5	7	7	<b>54</b>
Catalytic pyrolysis	Green Mantra	5	5	5	1	1	1	1	7	<b>26</b>
Catalytic pyrolysis	KiOR	9	7	1	1	3	7	1	5	<b>34</b>
Pyrolysis/gasification	Klean Industries	7	9	7	7	9	3	3	9	<b>54</b>
Catalytic pyrolysis	Natural State Research	3	5	7	1	1	1	1	1	<b>20</b>
Pyrolysis	Niutech Energy	9	9	7	1	1	1	1	1	<b>30</b>
Catalytic pyrolysis	PARC	9	9	7	5	3	1	1	9	<b>44</b>
Catalytic pyrolysis	Plastic2Oil	7	9	7	7	5	1	1	5	<b>42</b>
Pyrolysis	Plastoil	7	9	7	1	1	1	1	5	<b>32</b>
Pyrolysis	Polyflow	5	7	7	7	5	1	1	3	<b>36</b>
Pyrolysis	Promeco	9	9	5	7	5	1	1	5	<b>42</b>
<b>Catalytic depolymerisation processes</b>										
Catalytic depolymerisation	Alphakat	7	9	5	7	5	1	3	5	<b>42</b>
Catalytic depolymerisation	Kemia	7	9	7	7	3	1	1	1	<b>36</b>
Catalytic depolymerisation	Recycle Energy Co	7	9	7	7	5	1	1	3	<b>40</b>
Catalytic depolymerisation	T-Technology	7	9	7	5	3	1	1	7	<b>40</b>

Technology	Supplier	Scale	Demonstration	Feedstock	Yield	Quality	Capex	Opex	Running hours	Overall score
Catalytic depolymerisation	Ventana Cleantech	7	5	7	7	3	1	1	3	34
Catalytic depolymerisation	Vuzeta	9	9	5	3	5	1	1	3	36
<b>Gasification and synthesis processes</b>										
Gasification w/F-T	Bioliq	7	7	1	1	9	9	3	5	42
Gasification w/F-T	Choren	9	9	1	1	9	1	1	5	36
Gasification w/Bio	Coskata	5	5	3	3	9	1	1	5	32
Gasification and ethanol production (non-Bio)	Enerkem	9	9	1	3	9	7	1	9	48
Gasification w/Bio	INEOS Bio	9	9	1	5	9	5	1	7	46
Gasification w/F-T	Rentech	7	5	1	3	9	9	9	5	48
Gasification w/F-T	ThermoChem Recovery Intl	9	9	1	3	9	7	1	7	46
Gasification w/F-T	Velosys	7	5	1	3	9	3	3	3	34

These scores are not intended to give a 'preferred' technology option for the conversion of plastic to oil products, but are indicative of ranking within each of the three classes of technology. The use of the scores to differentiate between the three technology 'groups' in the table above should be treated with caution; for example, some of the gasification processes are demonstrated at scale, but for biomass rather than the target feedstock. Also, care should be taken with the capital expenditure (capex) assessment: as NDAs were not signed with the technology suppliers, it was not possible to obtain full details of the technologies. Capex numbers were obtained for each process but it is not clear what is specifically included or excluded in these numbers. Accurate capex estimation will only be possible when a target project is planned and all necessary equipment is identified.

In general, the pyrolysis processes tend to give good yields but produce a crude oil that needs further refining before being suitable for use. Catalytic depolymerisation processes give similar yields to pyrolysis and produce a mixture of distillates that requires less downstream processing to yield a saleable product. Gasification followed by chemical synthesis produces oil products that are direct replacements for fuels, but have much lower yields.

In terms of scale, the pyrolysis and catalytic depolymerisation technologies are limited by heat transfer considerations such that a single processing vessel has a capacity of no more than 8,000–10,000tpa, although a number of vessels can be connected in parallel to achieve higher throughputs. Gasification processes do not have heat transfer limitations, and can achieve capacities in excess of 35,000tpa in a single process train.

The gasification technology suppliers are more focused on the use of their technology for 'biomass-to-liquids' processes, as biomass is currently the most attractive feedstock to them because it offers the necessary scale of feedstock supply and opportunity for subsidies from the creation of 'biogenic' fuels and oil products. As a result, they have limited data on the suitability of plastic waste as a feedstock and have no demonstration plants routinely using waste plastics.

The pyrolysis and catalytic depolymerisation technology suppliers seem to be more open to the use of non-biogenic feedstocks, especially those arising from industrial processes, and increasingly from waste feedstock sources. However, none of these processes appears to be running at a commercial scale with low-grade 'non-recyclable' waste plastics, which are the target feedstock in this report. In general, these companies publish more information on the Internet and are more responsive at interview, although some declined to provide information without an NDA being in place.

## 2.5 Summary

Processes for the conversion of plastics into oil products have been in development for over 20 years, but the low cost of oil has prevented these from becoming economically feasible. Recent increases in oil prices have caused a resurgence in interest in these technologies, within three basic classes of technology: pyrolysis, catalytic depolymerisation and gasification followed by chemical or biological synthesis.

A total of 31 process technology suppliers were examined by a combination of web survey, telephone interview and e-mail correspondence. Each technology supplier was scored on the information gathered. Pyrolysis and catalytic depolymerisation technologies scored well on product yield, but less well on product quality. Conversely, gasification with synthesis technologies scored less well on yield, but give a higher quality product.

Within each class, there are plants operating at, or close to, commercial scale. None of these technologies has reached the stage where there are multiple commercial-scale operating plants. None of the plants is reported as routinely running at commercial scale with low-grade 'non-recyclable' waste plastics, which are the target feedstock in this report.

## 3 Waste plastics and end-product supply chain

### 3.1 Background

One aim of this project was to assess the potential feedstock material available for a plastic-to-oil process.

There is already a well-established recycling network and infrastructure in both Scotland and the UK as a whole for rigid plastics packaging. High-quality, high-value products can be obtained that are suitable for manufacturing in their original or similar applications, for example high-density polyethylene (HDPE) milk bottles.

The goal of a plastic-to-oil process within the scope of this project would not be to divert higher quality plastic waste from this well-established and high-value recycling route, so alternative, as yet unrecovered sources of waste plastics must be considered as potential feedstock material. The prime example of waste plastic that may be suitable for a plastic-to-oil process is plastic film from the municipal waste stream. As yet, there is no well-developed processing route for waste film from the municipal waste stream, although there is an infrastructure for film waste from the agricultural and commercial and industrial (C&I) sectors. Therefore, the remainder of this report will consider the main infeed material to any plastics-to-oil process to be plastic film from the municipal waste stream.

### 3.2 Plastic supply

It is estimated<sup>12</sup> that between 135,000 and 305,000 tonnes of film waste was generated in Scotland in 2009, less than half of which was recycled.

The wide range in this estimation is a result of C&I waste arisings, as there is a lack of data available on this waste stream. However, it is believed<sup>13</sup> that recycling of the C&I waste stream is very efficient; a large proportion of the waste film produced from C&I sources is suitable for re-extrusion, either directly or with minimal processing, whilst much of the remainder is exported from the UK for reprocessing. A similar story can be seen with agricultural film, almost all of which is reprocessed in the UK. To a lesser extent construction and demolition waste is also recycled, but on more of an ad hoc basis because of the wide variability of the waste material in terms of quality and polymer type.

Therefore, the most promising source for a plastic-to-oil process is household/municipal film waste, approximately 75,000 tonnes of which was produced in 2009.<sup>12</sup> A breakdown of this film waste arisings is shown in **Table 3**. There is currently very little post-consumer/household plastic film recycling activity in Scotland and the UK as a whole.

**Table 3** Scottish household film waste arisings, 2009<sup>12</sup>

<b>Household film waste arisings</b>	<b>Quantity (tonnes)</b>
Carrier bags	20,959
Bin bags	14,655
Plastic packaging	31,788
Other plastic film	7,073
<b>Total plastic film</b>	<b>74,475</b>

The properties and physical characteristics of films make it challenging to separate them from other 'two-dimensional' materials such as paper, and there is a large number of different film types that are difficult to separate from each other. A particularly problematic issue is the existence of multi-layer films, which consist of several different plastic types. Current film separation techniques (handpicking or automated optical sorting) are able only to inspect the outer layer of the film and therefore cannot distinguish between single- and multi-layer films.

For these reasons, where film recovery is undertaken it is with the object of cleaning up other streams, in particular paper, for reprocessing. The strategies used for these clean-up operations result in low-quality plastic film streams, often with contamination levels greater than 30%, producing what is known as 'Class C' film. (Film grades range from 98:2 (98 is the percentage film and 2 is the percentage contamination) to 70:30; film of lower quality than this is known as 'Class C'.) An example of a typical bale of Class C film is shown in **Figure 1**.

The 'traditional' waste management method for these streams has been export to China for manual sorting and cleaning; however, China banned the import of household plastic film in 2006. Since that date, anecdotal reports from the waste management industry indicate that the plastic film is now sent directly to landfill or converted into refuse-derived fuel (RDF)/solid-recovered fuel (SRF) to be burned for energy recovery in the Netherlands and other European countries. Meanwhile, in operations in which no recovery is carried out, the film ends up in the residual stream and is also landfilled or converted to RDF/SRF.

**Figure 1** Bale of handpicked Class C film



The target feedstock considered for this report is low-grade film that is too highly contaminated or otherwise unsuitable for reprocessing and recycling. There are two major sources of this type of material, namely MRFs sorting and processing municipal waste and composting facilities, although other potential sources include process residues from anaerobic digestion facilities.

### *3.2.1 Household materials recovery facilities*

The most desirable, currently available source of low-grade film (primarily polyolefin, low-density polyethylene (LDPE), linear LDPE, HDPE, polypropene) is likely to be household MRFs. By the time this type of film has been through the domestic collection and segregation system, it tends to be fairly contaminated and is generally defined as 70/30 or Class C film. This material is not suitable for mechanical reprocessing or extrusion.

It should be noted that MRFs specialising in C&I collections tend to generate higher quality baled film (e.g. from blends of refuse sacks, shrink/pallet wrap). This material generally falls within 98/2, 90/10 or 80/20 categories/grades and is suitable for use within the existing UK reprocessing/extrusion sector.

**Table 4** lists a number of the larger MRFs in Scotland handling this type of municipal comingled material, along with the recyclables input and the estimated arisings of low-grade film. This gives arisings of 12,000tpa of low-grade film based on the listed MRF capacity of 645,000tpa (approximately 1.8%). This agrees with previous work<sup>14</sup> that demonstrated that Scottish mixed dry recyclables typically contain between 1% and 2% plastic film. SEPA's estimate of the quantity of household waste recycled in 2009<sup>15</sup> was 1,061,469 tonnes. Based on this, it is estimated that the MRFs in Scotland could produce a total of 19,000 tonnes of Class C film per year which would potentially be available as feedstock. Included in these figures is any material that may come from waste transfer stations and household waste recycling centres, as the majority of their waste is baled up and delivered to the nearest MRF for sorting and processing.

The requirement for separate collection of dry recyclables comes into effect in Scotland from January 2014, including a ban on the landfilling or incineration of separately collected dry recyclables. According to SEPA,<sup>15</sup> this will require the recycling of an additional 900,000tpa of household waste, with a corresponding increase in recycling capacity. If this capacity is met by an increase in the number of MRFs, total arisings of Class C film from household waste recycling could reach 35,000tpa. The extra quantity recovered will depend on to what extent the definition of dry recyclables, in the guidance that accompanies the regulations, includes plastic films, and whether local authorities are required or choose to collect this type of material as dry recyclables.

**Table 4** Larger Scottish MRFs

Operator	Site	Input recyclate capacity (tpa)	Type of MRF	Estimated quantity of low- grade film (tpa)
Glasgow City Council	Glasgow	80,000	Dry household	2,000
Oran Environmental	Grangemouth	50,000	Dry household	1,000
SAISA – Stirling Fibre	Kilsyth	50,000	Dry household, C&I	300
SAICA – Securecycle	Kirkcaldy	30,000	Dry household, C&I	300
Shanks	Glasgow	100,000	Dry household, C&I	1,500
Shanks	Broxburn	20,000	C&I	200
Shanks	Dumfries	80,000	Mechanical biological treatment	2,000
SITA	Aberdeen	50,000	Dry household, C&I	1,000
SITA	Perth	50,000	Dry household, dirty	1,000
Viridor	Bargeddie	100,000	Dry household, C&I, dirty	2,000
William Tracey	Linwood	25,000	Dry household, C&I	500
William Tracey	Broxburn	10,000	C&I	200
<b>Total</b>		<b>645,000</b>		<b>12,000</b>

### 3.2.2 Composting facilities

Composting facilities are also potential sources of low-grade film suitable for reprocessing. Green waste processed in composting facilities contains plastic film and non-film plastics (e.g. plant pots and seed trays) that are heavily contaminated with organic material. These are undesirable components of the composted material and are currently separated and sent for disposal in landfill at a cost of £80 per tonne. This material is of too low quality to be reprocessed for higher quality/value end markets, and thus would be a candidate feedstock for a plastic-to-oil-products process. These facilities may also produce a certain amount of rigid plastic packaging which would also be suitable for processing in a plastic-to-oil technology.

The segregation of plastic from the other compost contaminants (wood, metal) is not a routine operation for the majority of facilities, but discussions with some operators who are starting to perform this operation indicate that, for a 30,000tpa composting facility, up to 200tpa of waste film could be recovered if there was a suitable end market.

**Table 5** lists the composting facilities studied as part of this report. If each site recovers 0.67% of input as waste film, 2,600tpa of low-grade plastic could be available for plastic-to-oil processes. In total it is estimated that about 2,000–3,000 tpa of plastic film could be recovered from these plants.

Scotland's Zero Waste Plan<sup>16</sup> estimates total municipal arisings of green waste to be 431,000tpa, all of which will need to be composted in order to comply with the ban on biodegradable waste being disposed of to landfill. Given the total composting input capacity of 393,000tpa calculated in **Table 5**,

implementation of the Zero Waste Plan will have only a marginal impact on plastic arising from composting facilities. In the longer term, the maximum low-grade plastic film arisings from composting plants will remain at approximately 3,000tpa.

**Table 5** Composting facilities in Scotland

<b>Operator</b>	<b>Postcode</b>	<b>Input capacity (tpa)</b>	<b>Type of composting facility</b>	<b>Estimated quantity of low-grade film (tpa)</b>
Billy Bowie	KA2 0BA	10,000	In-vessel composting	70
Glasgow Fruit Market	G21 2DU	1,700	In-vessel composting	10
GP Planscape	G74 2LD	25,000	In-vessel composting	170
Gray Composting Services	AB45 2XS	5,000	In-vessel composting	30
Keenan Recycling Ltd	AB53 6YH	32,000	In-vessel composting	210
Levenseat Organics	AB53 6YH	20,000	In-vessel composting	130
Scottish Water Horizons	ML11 8EP	30,000	In-vessel composting and windrow	200
TEG	G68 9AZ	38,000	In-vessel composting	250
AH Tucker	EH55 8LJ	10,000	In-vessel composting	70
William Munro	IV16 9XJ	250	In-vessel composting	2
Andrew Cook	KY1 4DN	10,000	Windrow	70
Angus Council	DD8 2RL	11,200	Windrow	80
Balmaghie Farm	DG7 2AA	1,700	Windrow	10
Barr Environmental	KA18 2RB	18,200	Windrow	120
Billie Bowie	KA2 0BA	1,300	Windrow	10
Binn Farm	PH2 9PX	20,500	Windrow	140
Dundee Council	DD2 3JW	8,340	Windrow	60
Falkirk Council	EH51 0PU	6,500	Windrow	40
Fife Council	KY15 7LU	10,500	Windrow	70
Fife Council	KY12 0RX	21,000	Windrow	140
FRM	EH39 5PP	32,500	Windrow	220
FRM	G64 3QN	1,600	Windrow	10
FRM	EH39 5AH	8,000	Windrow	50
Highland Council	KW1 4TP	2,132	Windrow	10
J Haig Hamilton & Son	EH39 5LL	1,350	Windrow	10
NPL Estates	G2 1PB	4,000	Windrow	30
Orkney Islands Council	Orkneys	750	Windrow	10
Seafield Park	IV12 5RZ	15,306	Windrow	100
Stirling Council	FK7 7JW	12,400	Windrow	80
West Lothian Recycling	EH55 8DD	13,600	Windrow	90
William Tracey	KA15 1HZ	20,000	Windrow	130
<b>Total</b>		<b>393,000</b>		<b>2,630</b>

### 3.2.3 Anaerobic digestion plants

There is a number of anaerobic digestion plants in operation or under development in Scotland. These handle food waste and have issues dealing with any associated plastic packaging, which appears as a heavily contaminated waste stream before or after being processed by the digester. The plastic is contaminated with up to 40% water, undigested organics, paper, card and compostable bin liners. These facilities utilise automated de-packaging equipment before or after the waste is processed in the digester, which removes plastic packaging but does leave it heavily contaminated. The contaminated plastic is currently sent for disposal in landfill at a cost of £80 per tonne. This material is of too low quality to be reprocessed into higher quality/value end markets, and therefore would be a candidate feedstock for a plastic-to-oil-products process. However, the moisture and contamination content of this potential feedstock means that it requires some pre-processing before it can be used by any of the technologies considered in this report.

At present, the anaerobic digestion plants do not actively segregate plastic contaminants from the wastes produced by the plant, but there are several development projects in progress that may be able to generate a segregated plastics waste stream that could be suitable for plastics-to-oil processing.

No details of the actual quantities of low-grade plastic film arising from anaerobic digestion operations are available at present, but assuming a quantity of 2% (confidential data held by Axion) of the food waste feed gives the estimates in **Table 6**. The actual quantity will depend on the nature of the food waste, as domestic food waste collections tend to have less packaging than those from food retail and food manufacturing sources. Overall, anaerobic digestion plants could generate between 4,000 and 5,000tpa of low-grade plastic film suitable for conversion into oil products.

Scotland's Zero Waste Plan<sup>16</sup> estimates total municipal arisings of food waste to be 581,000tpa, all of which will need to be processed by anaerobic digestion in order to comply with the ban on biodegradable waste being disposed of to landfill. Given the total anaerobic digestion input capacity of 212,000tpa found in **Table 6**, implementation of the Zero Waste Plan will significantly increase the quantity of plastic arising from anaerobic digestion plants. In the longer term, the maximum low-grade plastic film arisings from anaerobic digestion plants could increase to 10,000–12,000tpa.

**Table 6** Anaerobic digestion facilities

Operator	Postcode	Input capacity (tpa)	Estimated quantity of low-grade film (tpa)
CNES	H52 9JB	8,000	160
Heat and Power	KW17 2DR	3,000	60
J&A Rennie	AB53 8BP	20,000	400
Scottish Water Horizons	G68 9NB	30,000	600
Shanks	G67 3EN	60,000	1,200
SSE	KA24 4JJ	75,000	1,500
TEG	PH2 9PX	16,000	320
<b>Total</b>		<b>212,000</b>	<b>4,240</b>

### 3.2.4 Others

There is a significant number of other post-industrial/post-consumer film waste streams that are problematic and would benefit greatly from a secure, local outlet for contaminated non-rigid plastic materials. These include:

- **Food processors:** blood-contaminated plastics, fish farm feed bags/liners.
- **Construction and demolition sites:** concrete sheeting (film), rubble bags.
- **Sewerage works:** plastic 'debris'.
- **Biodiesel processors:** contaminated packaging.
- **Agricultural:** netting/bale/twine (not silage film/crop cover).

While the quantities and quality of these other sources has not been fully researched, it is believed that a further 2,000–5,000 tonnes of film waste per annum could be available through these routes.

### 3.2.5 Summary of potential feedstock sources

In total, it is estimated that approximately 18,000–27,000tpa of low-grade plastic film waste is currently available for reprocessing from MRFs, composting facilities and anaerobic digestion facilities. This could be supplemented by up to 5,000tpa from other sources. This is in reasonable agreement with the 24,000tpa estimated recently in a report for Zero Waste Scotland.<sup>17</sup>

The current position is summarised in **Table 7**.

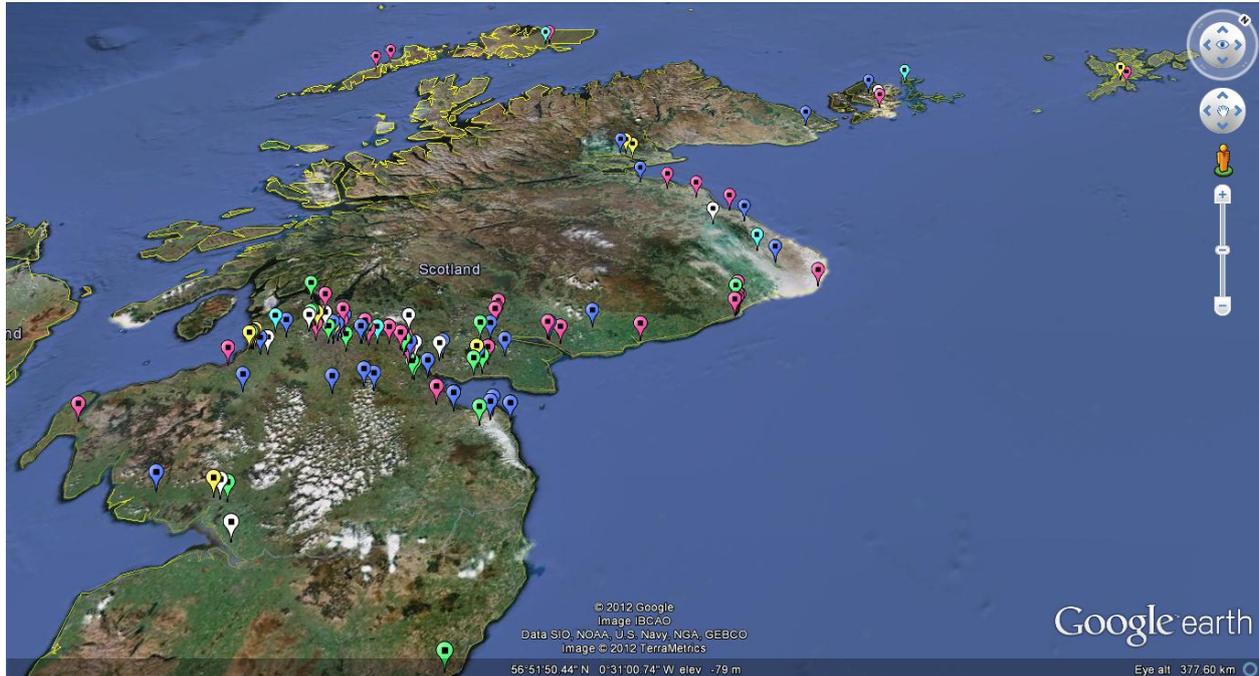
**Table 7** Summary of plastic availability from existing Scottish waste treatment facilities

Source	Quantity (tpa)
Household MRFs	12,000–19,000
Composting facilities	2,000–3,000
Anaerobic digestion facilities	4,000–5,000
Others (not proven)	2,000–5,000
<b>Total (with Others)</b>	<b>18,000–27,000 (20,000–32,000)</b>

### 3.2.6 Mapping of potential feedstock sources

The sections above are not intended to be a full listing of potential feedstock sources, but they provide a sensible basis on which to build an assessment of potential feedstock and test the viability of processes for conversion of otherwise unrecyclable plastics into oil products.

The geographical spread of these sites is displayed in the Google Earth map shown in **Figure 2**. It can be seen that the majority of MRFs, anaerobic digestion plants and composting facilities are located around the Glasgow and Edinburgh areas. This is to be expected, as the vast majority of the Scottish population is situated here.

**Figure 2** Scottish waste treatment sites that could potentially provide plastic film waste

The sites are split into six categories:

- MRFs are shown in green;
- anaerobic digestion plants are shown in light blue;
- composting facilities are shown in dark blue;
- waste transfer stations are shown in pink;
- household waste recycling centres are shown in white; and
- others are shown in yellow.

### 3.2.7 Comparison of distributed and centralised sites for product delivery

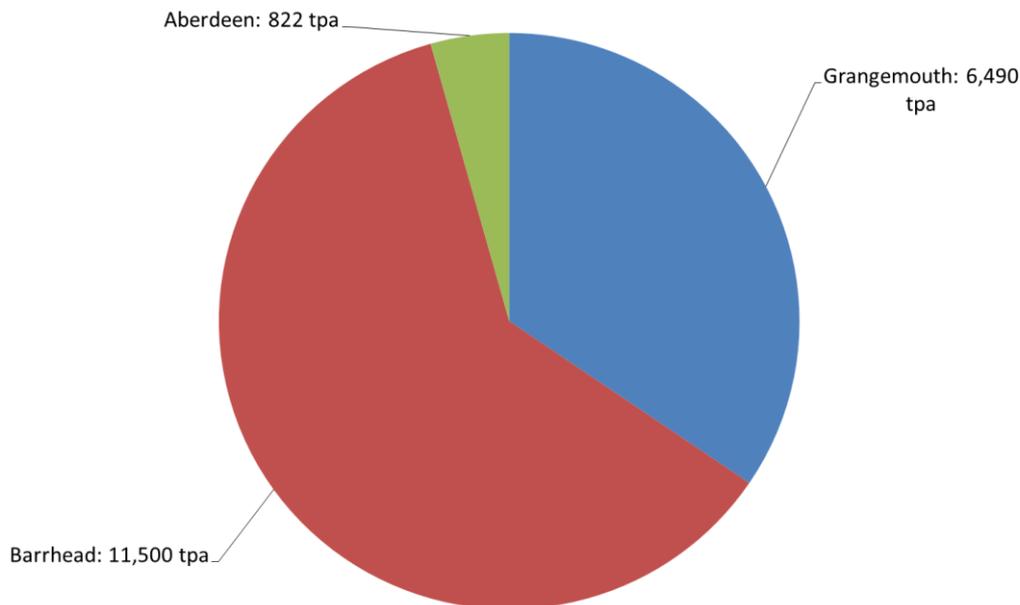
Using the information presented in the previous section, an analysis was carried out on how the location and number of plastic processing sites would affect the costs of transporting the plastic film waste from the locations where it is produced, and the cost of delivering the product to a refinery (assumed, for the purposes of the analysis, to be INEOS's refinery in Grangemouth). The scenarios considered were:

- **Option 1:** A centralised site close to INEOS Grangemouth.
- **Option 2:** A centralised site in Barrhead, near Glasgow.
- **Option 3:** A centralised site near Aberdeen.
- **Option 4:** A distributed network consisting of the three sites above.

Driving distances were calculated for the routes between each film production location and each processing site. For the three centralised options, it was assumed that all material would be delivered directly from the locations where it was produced to the centralised site, while for the distributed

network option it was assumed that film would be sent to the closest site. The estimated amount of material sent to each site annually for Option 4 is shown in **Figure 3**. It can be seen that more than half the material is sent to Barrhead, with most of the remainder being sent to Grangemouth; the site in Aberdeen, meanwhile, receives less than 5% of the total material. This is to be expected from looking at **Figure 2**, which shows that only a few sites are in operation in the north of Scotland; the vast majority of sites are located in the area around Glasgow and Edinburgh.

**Figure 3** Amount of plastic film sent to each of the three sites annually for Option 4 (distributed network)



It was assumed that all film would be baled prior to delivery, with an average bale weight of 400kg, and that each lorry could hold 48 bales. Using this value it is possible to calculate the number of journeys required to deliver the waste film from each location to a particular site. The cost per journey is calculated by assuming a fixed cost per journey of £225, and an additional cost per mile of £1.30; for example, a 100-mile journey would cost £355 (£225 + £130).

The cost of transporting oil products from the production site to the Grangemouth refinery was calculated in a similar way; however, the weight of material per journey was calculated differently as the product is a liquid and is transported in a tanker. The volume of a tanker was assumed to be 38m<sup>3</sup>, and, using estimated densities for each of the products, it was possible to calculate the weight of product per journey. The total amount of product generated was calculated from the mass balance modelling described in **section 4.8**.

An exception to this is the material produced at the Grangemouth site; as the site is close to the refinery, it is assumed that the products would be taken to the refinery via a pipeline. Therefore there is no transport cost associated with this transfer.

The values discussed above are summarised in **Table 8** and **Table 9**.

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**Table 8** Variables used to calculate price per journey and number of journeys for waste film transport

Fixed price per journey	£225
Additional cost per mile	£1.30
Number of baled pallets per lorry	48
Weight of film per pallet	400kg
Weight of material per lorry	19.2 tonnes

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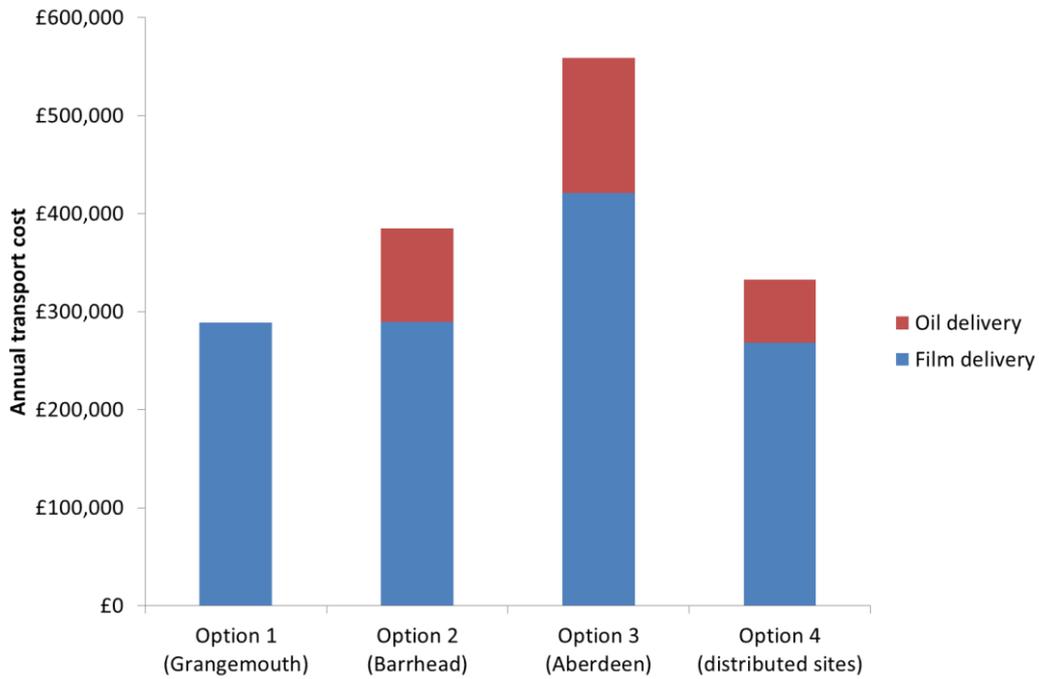
**Table 9** Variables used to calculate the number of journeys for waste film transport

Volume of product per tanker	38m <sup>3</sup>
Diesel density	850kg/m <sup>3</sup>
Gasoline density	720kg/m <sup>3</sup>
Ethanol density	790kg/m <sup>3</sup>

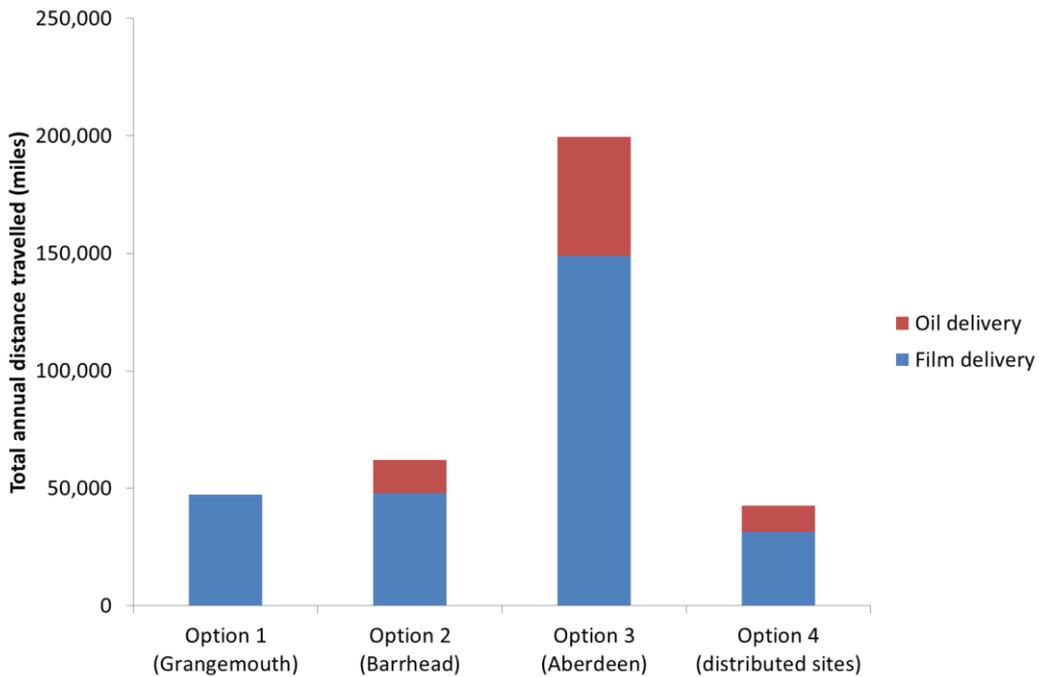
The total annual cost for each route (film production location to processing site and processing site to refinery) was calculated by multiplying the number of journeys per year by the cost per journey; the costs for all the routes were then summed to give the total cost for the option.

These calculations are summarised in **Figure 4** and **Figure 5**, which show the annual cost and distance travelled, respectively, to transport material to and from the processing sites for each option. Note that these values have been calculated using the pyrolysis process, but all other processes show the same qualitative results.

**Figure 4** Cost of transporting material to and from processing sites for each option



**Figure 5** Total distance travelled annually to deliver material to and from processing sites for each option



It can be seen immediately that Option 3 is by far the worst option in terms of both cost and total distance travelled. This is to be expected, as the majority of the material would be transported from the Glasgow/Edinburgh area up to Aberdeen for processing and then back down to Grangemouth for refining, resulting in a significant amount of 'double handling' of the material that arises close to the final destination (the refinery).

The transport costs for film delivery for Options 1, 2 and 4 are very similar; however, there are large differences in the cost of oil delivery, with Option 2 having the largest overall cost, followed by Option 4.

Option 4 gives the shortest total distance travelled, even including oil delivery; this is because each location where film waste is produced can choose to deliver to the closest processing site. However, as shown in **Figure 3**, this results in the Aberdeen site receiving only 820tpa; this annual tonnage is not likely to be economically viable for any of the options considered in this report.

Based on both cost and total distance travelled, therefore, one centralised site based in Grangemouth is the best option. This is dependent on there being a suitable site close to the INEOS refinery that can feed the oil products to the refinery by pipeline, thereby avoiding extra transport costs. However, it may be beneficial to introduce a network of local collection sites where waste plastic can be aggregated before delivery to the processing site in bulk. This will be particularly useful in capturing material from operators who either do not produce enough material to justify a dedicated transport service or do not have the space to store waste material until there is enough of it to transport.

### *3.2.8 Current waste management practices*

Currently there are no reprocessing routes for low-grade mixed film in Scotland. The material that is segregated and baled by MRFs and other producers has three destinations:

- export to Asia (currently restricted because of export regulations, typically at a cost of £0–30 per tonne collected);
- export to the Netherlands as RDF/SRF, with a typical gate fee of £60 per tonne plus transport; and
- landfill, with a typical gate fee of £80 per tonne plus transport.

The 'traditional' outlet (over the last 10–20 years) has been export to Asia and, effectively, has been a 'zero disposal cost' outlet. With this no longer available in the same manner, the 'standard' route is now export as RDF/SRF to energy from waste (EfW) facilities in mainland Europe, which certainly has the capacity to handle all the material of this type generated in Scotland. For example, the Netherlands has an EfW capacity of 6.8 million tonnes of waste per annum. However, there is a significant cost penalty and a typical medium-sized MRF in Scotland will be incurring costs in excess of £100K per annum for disposal of low-grade mixed film through EfW. The additional complications associated with trans-frontier movement of waste, create uncertainties over shipments and can make local landfill a preferred option.

### 3.2.9 Future trends

As discussed in the preceding sections, Scotland's Zero Waste Plan will increase the quantities of household and other waste being processed by MRFs, composting facilities and anaerobic digestion facilities. This will cause a corresponding increase in the quantities of low-quality plastic film available for conversion to oil products. The future availability is summarised in **Table 10**.

**Table 10** Estimated future availability of plastic film from Scottish waste treatment facilities

Source	Quantity (tpa)
Household MRFs	35,000
Composting facilities	3,000
Anaerobic digestion facilities	12,000
Others (not proven)	5,000
<b>Total (with Others)</b>	<b>50,000 (55,000)</b>

The predictions of future arisings assume that the proportion of packaging film associated with household recyclables sent to MRFs and food waste sent to anaerobic digestion facilities remains at its current level. It should be noted that WRAP and others are investigating opportunities for reducing the quantity of packaging associated with food and consumer products. This may mean that the future availability of low-grade plastic film from these sources is overestimated in the table above. However, the table above does not include the additional potential for low-grade plastic film arisings from C&I MRFs or anaerobic digestion facilities processing food waste from food manufacturers or back of store.

As existing landfill capacity for non-hazardous waste is of the order of 16 years, Scotland's Zero Waste Plan has a target of less than 5% of municipal waste to be sent to landfill by 2025. There will be increasing pressure on waste management companies not to use local landfill, by implementation of landfill bans and the increase in landfill tax to £80 per tonne in 2014.

There is a large number of EfW developments proposed for Scotland, with total capacity that exceeds the current 25% cap on local-authority-collected waste treated in EfW plants. The introduction of proposed EfW plants in Scotland will offer an alternative disposal route for low-grade mixed film (and for RDF/SRF) when and if they come on stream. Therefore, a Scotland-based plastics-to-oil-products plant will need to demonstrate a lower operational gate fee than local EfW facilities for it to be viable. It is not clear whether the thermal processes for converting otherwise unrecyclable plastic to oil products will be considered as constituting EfW by the Scottish Government – this question is discussed further in section 7.5.

Clearly any plant/process/technology based in Scotland that can offer a competitive gate fee will attract material. Economics will be the driver and this highlights the need for any proposed project to gain efficiencies by being integrated within an existing chemicals/materials processing facility

(preferably in a 'government-assisted area') where, in addition to services being shared, output streams can achieve highest potential value.

### *3.2.10 Summary – plastic supply*

It is estimated that the quantity of low-grade waste plastic film currently available in Scotland is between 18,000 and 27,000tpa. The majority of this arises from MRFs processing municipal household recyclates, with additional material from composting and anaerobic digestion facilities. Currently, this material is landfilled, exported to Europe as SRF/RDF or exported to Asia for recycling (although the latter is becoming increasingly more difficult).

The implementation of Scotland's Zero Waste Plan will increase the material processed by MRFs, composting facilities and anaerobic digestion facilities such that the quantity of material available for conversion to oil products reaches 50,000tpa. There may be increasing competition for this material as the number of 'conventional' EfW plants in Scotland increases.

An analysis of the transport costs associated with proposed processing site networks shows that one centralised site based in Grangemouth is the best option. This is dependent on there being a suitable site close to the INEOS refinery that can feed the oil products to the refinery by pipeline, thereby avoiding extra transport costs for the oil products.

## 3.3 End markets for oil products

### *3.3.1 Current market for transport fuels*

The 2009 Department of Energy & Climate Change assessment of sub-national road transport fuel consumption estimates Scottish consumption of gasoline at 1.18 million tonnes per year, with diesel fuel consumption at 1.83 million tonnes per year. The majority of this is sold via Scotland's network of over 900 fuel forecourts, with a number of owners, including the major oil companies and supermarkets.

Despite this diversity, the majority of transport fuel in Scotland is sourced from INEOS's Grangemouth oil refinery, which has an annual output of around 8 million tonnes of finished oil products, of which approximately 1 million tonnes is gasoline and 1.8 million tonnes is diesel fuel. Some finished products are imported by ship to marine terminals on the River Clyde, and at other locations, and distributed by independent fuel traders, but these serve less than 25% of Scotland's road transport fuel requirements. Other than the addition of biofuels (ethanol and biodiesel) at these terminals, no fuel blending operations exist other than at Grangemouth. Northburn Industrial Services operates Scotland's only facility for the manufacture of processed fuel oil from waste oil with a capacity of 25,000tpa, although this facility does not make transport fuels. Argent Energy at Motherwell produce up to 45,000tpa of biodiesel from tallow and used cooking oil – this is approximately 50% of the total biodiesel required in Scotland to meet the Renewable Transport Fuel Obligation (RTFO).

The potential scale of a plastic-to-oil-products industry in Scotland is unlikely to have a significant impact on the existing oil refining, oil recovery or biodiesel industry in Scotland.

Changes in vehicle type, vehicle use and engine efficiency mean that diesel is generally in short supply and gasoline long, especially in north-west Europe where refineries are predominantly configured for gasoline production. In this context, a process for converting currently unrecyclable plastic waste to a diesel-type product would be more attractive than a similar process to obtain gasoline or ethanol.

A number of options exist to introduce oil products produced from plastic into the transport fuel supply chain:

- Introduce a plastic-derived crude oil into the Grangemouth refinery.
- Introduce distilled oil products into the fuel blending pool at the Grangemouth refinery.
- Introduce drop-in fuels meeting the specifications of EN590 (diesel) or EN228 (gasoline) into the fuel distribution chain.

### *3.3.2 Introducing plastic-derived crude oil to Grangemouth refinery*

The plastic-derived crude oil products from pyrolysis or catalytic depolymerisation could be added to the feedstock currently used at the Grangemouth refinery. Although the quantity of oil introduced is very much smaller than the 9 million tonnes of geological crude oil processed by the refinery each year, refineries are highly tuned integrated systems, optimised to process a particular feedstock (in this case chiefly crude oil from the North Sea). Small changes in composition or the introduction of unusual contaminants can upset the operation of the plant.

The introduction of plastic-derived crude to the crude distillation unit has been considered and rejected by INEOS on the grounds that unsaturated hydrocarbons would upset product quality and oxygenates would increase gum formation and fouling of the crude preheater train.

A better option would be to introduce the plastic-derived crude to a catalytic cracking unit as this may have less of an impact on the downstream processes. The principal concerns raised by INEOS with this option were the possible presence of metals that would poison the catalyst and the impact of the presence of oxygenates in the unit. These concerns would need to be allayed before proceeding further.

It may be possible, with INEOS, to identify a way to close-couple a plastic-derived crude into the refinery, but this would come at a cost: in the form of increased project capex, which would need to be included in the overall project economics.

### *3.3.3 Introducing distilled oil products to Grangemouth refinery*

At an oil refinery, the production of finished fuel products (diesel, petrol, aviation fuel, etc.) is optimised by blending a number of distilled products from various parts of the refinery such that the final product meets the relevant fuel specification. These distilled products are known as blendstocks. Depending on the technology supplier, processes for the conversion of plastic into oil products either incorporate distillation in the process or produce a plastic-derived crude oil that would need to be distilled in a separate facility. In either case, the distilled plastic-derived oil could meet the finished fuel specification, but is more likely to be useful to the refinery as a blendstock.

The usefulness of any plastic-derived fuel blendstock will depend on its composition and properties, but it is notable that the fuel balance in Scotland means that a distilled diesel blendstock would be better received by INEOS than a gasoline blendstock. In particular, the requirement to meet a maximum density of 850kg/m<sup>3</sup> in the blended diesel and incorporate up to 10% of 'biodiesel' (fatty acid methyl ester) means that a diesel blendstock with a low density, high cetane number and high degree of saturation would have a positive value to any refinery. INEOS suggests that a plastic-derived diesel blendstock would benefit from mild hydrogenation to maximise its value.

Supplying distilled oil products would have a much lower capex requirement than close-coupling a waste-plastic-to-oil unit and should be a lot more acceptable to the refinery.

### *3.3.4 Introducing drop-in fuels to the fuel distribution system*

The manufacture of drop-in fuels to a recognised specification is necessary to satisfy the regulatory requirements of end of waste, and maintain engine manufacturer guarantees. The manufacture of fuels meeting the specifications of EN590 (diesel) or EN228 (gasoline) would require more sophisticated processing of plastic-derived oil products than would be achieved by simple distillation.

INEOS sees little or no added value in further processing to meet the EN590 (diesel) or EN228 (gasoline) specifications, as these are what they aim to achieve in their blending system at the refinery.

However, there may be a marketing advantage in keeping the plastic-derived fuels separate from the main fuel pool. This advantage could then be used by independent fuel traders or operators of vehicle fleets such as bus companies, waste management companies, etc. Once again, this favours the manufacture of diesel fuels, as fleet operators tend to run vehicles using such fuels.

Preliminary contact with Greenergy, Scotland's largest independent fuel trader indicates that they would be interested in distributing oil products derived from waste plastic, or in using them at their marine terminals in Scotland, provided that they could be blended with 'conventional' fuels without compromising the final fuel specification.

This would be the lowest capex integration option and the most attractive if the waste-plastic-to-oil process can supply the required fuel specification.

### *3.3.5 Heating fuels*

The 2002 Scottish Energy Study indicates that domestic and industrial heating accounts for around 15% of the total consumption of oil products in Scotland. Transport fuels consume 66% of oil products and this is known to be equivalent to 3 million tonnes. Therefore, the Scottish heating fuel consumption is approximately 650,000 tonnes per year.

The scale of production of oil products from currently unrecyclable waste plastic is similar to that of operations for fuel oil recovery from engine and other waste oils. If outlets into the transport fuel market proved to be closed, owing to commercial or technical requirements, the existing routes for the use of processed fuel oil for heating should still be available, as the specifications for heating fuel are less stringent than for road fuels.

### *3.3.6 Future trends*

The switch from gasoline engines to diesel engines, and the increased fuel economy of road vehicle engines, has reached the point whereby gasoline sales are on a slow downwards trend. Diesel sales are relatively stable, and the relative shortage of supply compared with gasoline is expected to remain. This suggests that the conversion of waste plastics to diesel products is likely to be a more sustainable business than plastics to gasoline products or ethanol.

INEOS's Grangemouth refinery is likely to continue to be dominant in the supply of oil products for Scotland, at least until such time as crude oil from the North Sea is no longer available. This suggests that the use of Grangemouth to introduce oil products from waste plastic to Scotland's fuel supply chain will give the greatest security of sales into the future.

### *3.3.7 Summary – markets for oil products*

The market for oil products is dominated by oil's use as a road fuel, with Scottish consumption of gasoline at 1.18 million tpa and diesel at 1.83 million tpa. In common with the rest of Europe, diesel is in short supply and this makes diesel the best target for a plastic-to-oil process. Given the current availability of feedstock of only 18,000–27,000tpa, it is likely that the operator of a plastics-to-oil process would need to partner with an existing fuel supplier to enter the market.

Scotland's only oil refinery in Grangemouth dominates domestic supplies, and preliminary discussions confirm that it would be a willing partner in introducing plastic-derived crude oils, mixed distillates or diesel blend components to the fuel supply chain.

In addition, there would be scope for the introduction of blend components or drop-in fuels to the fuel supply chain via independent fuel traders, as long as the resulting fuel blends still met the relevant fuel quality standards.

## 4 Review of process options for conversion of plastics into oil products

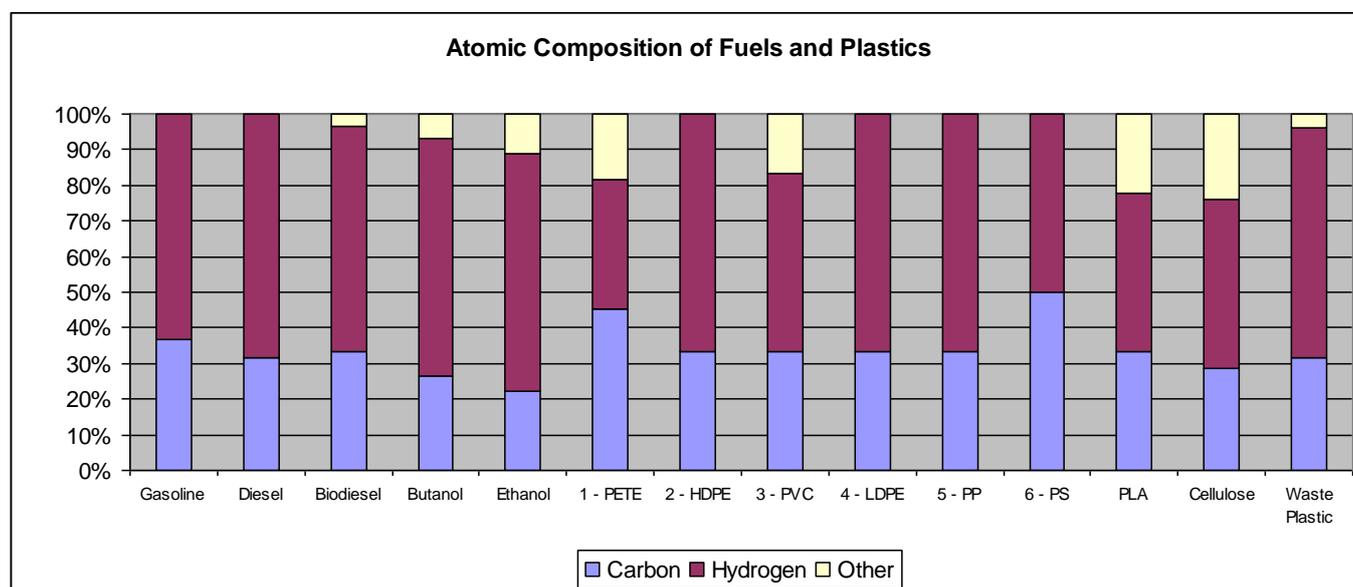
### 4.1 Characteristics of plastics and oil products

Before looking at the process options for the conversion of plastic into oil products, it is worth considering the characteristics of these two materials, to identify where similarities exist, and the basic methods of conversion. The principal similarities are that they are made mostly of carbon and hydrogen, and that they are made of molecules that are formed in 'chains' of carbon atoms.

Crude oil is a complex mixture of hydrocarbons, which are separated and purified by distillation and other processes at an oil refinery. The majority of the crude oil is used for the production of fuels for transportation, heating and power generation. These oil products are not single components, but are a blend of components used to meet the relevant fuel specifications in the most economic manner, given the composition of the crude oil and the configuration of the oil refinery. These components have a wide range of chain lengths: gasoline has compounds with a chain length of between three and 10 carbon atoms, and diesel has compounds with a chain length of between five and 18 carbon atoms, but both contain only hydrogen and carbon.

Plastic is a generic term for a wide range of polymers produced using highly refined fractions of crude oil, or chemicals derived from crude oil, known as monomers. Polymers are formed by the reaction of these monomers, which results in chain lengths of tens or hundreds of thousands of carbon atoms. Some polymers also contain oxygen (e.g. polyethylene terephthalate (PET)), whereas others contain chlorine (polyvinyl chloride (PVC)). It is worth noting that only a small proportion (< 5%) of the crude oil processed in the world is used to produce the monomers (e.g. ethene, propene) used in the manufacture of polymers (e.g. polyethene, polypropylene).

The similarity between oil products and plastics is illustrated in **Figure 6**. The figure demonstrates where the atomic composition in most plastics is similar to those in gasoline and diesel derived from crude oil.

**Figure 6** Atomic composition of fuels and plastics

To convert plastic into oil products, two steps need to be achieved:

- The very long polymer chains need to be broken down to produce compounds with shorter chains.
- Any non-hydrocarbon atoms present (e.g. oxygen, chlorine) need to be removed.

There are essentially two ways to convert plastic into oil products. The first, thermal depolymerisation or pyrolysis, involves the breaking of the polymer chains by heating to moderate temperatures (ca. 400–600°C). Rather than breaking the polymer down to its original monomers, this process tends to make a range of shorter chain compounds, similar in many ways to the mixtures of hydrocarbons found in crude oil and oil products. A catalyst is sometimes used to reduce the operating temperature, but it may also control the quality of the oil product produced.

The second process, gasification, involves much higher temperatures (900–1,100°C) and breaks the polymer chains completely, converting them into carbon monoxide, carbon dioxide, water and hydrogen. In order to convert these simple molecules into short chains suitable for use as oil products, a further chemical reaction or synthesis is required, effectively 'sticking' the carbon atoms back together. This is a more energy intense process than pyrolysis, tending to result in a lower overall yield, but does have the advantage of making 'cleaner' synthetic oil products.

There is a number of technologies offered as commercial propositions for the conversion of plastic to oil products, but, despite differences in the detail of the equipment and the operating conditions, these all fall within the above two categories. Within these two categories, there is a number of sub-categories, as shown in **Table 11**. Each of the sub-categories is discussed in more detail in subsequent sections of this report.

**Table 11** Plastic to oil conversion technologies

<b>Thermal depolymerisation processes</b>	<b>Gasification processes</b>
Pyrolysis	Gasification and conversion to diesel
Catalytic depolymerisation	Gasification and conversion to gasoline
	Gasification and conversion to ethanol

## 4.2 Pyrolysis

Pyrolysis is the thermal degradation of organic materials at temperatures between 400 and 1,000°C in the absence of oxygen. This results in the devolatilisation and decomposition of the feedstock, but the absence of oxygen means that no combustion occurs.

Pyrolysis produces gas, liquid and solid char, the relative proportions of which depend upon the method of pyrolysis and the operating conditions of the pyrolysis reactor, chiefly the rate of heating, the operating temperature and residence time within the pyrolysis reactor. Long residence times and low heating rates are typical of processes such as charcoal manufacture, effectively converting the majority of the carbon present in the feedstock into elemental carbon. As residence time reduces and heating rate increases, the proportion of liquid produced increases as there is sufficient heat in the system to boil off any compounds formed by the breaking of polymer chains. Very short residence times and high temperatures give conditions very similar to those encountered in the gasification process, and consequently produce more gas. For the purposes of conversion of plastic into oil products, maximisation of liquids production is desirable, as this will give a material which can be easily transported and refined. This is achieved by so-called 'fast' pyrolysis, with residence times of less than 2 seconds, rapid heating and temperatures of around 500°C.

The technology manufacturers active in the field of plastics conversion to oil products were identified and are shown in **Table 12**.

**Table 12** Plastics pyrolysis technology suppliers

Company name	Company location	Website
Agilyx	Oregon, USA	<a href="http://www.agilyx.com">www.agilyx.com</a>
Anhui Orsun Environmental Technologies	China	<a href="http://www.oursunchina.com">www.oursunchina.com</a>
Blest	Japan	<a href="http://e-n-ergy.com">http://e-n-ergy.com</a>
Climax Global Energy	South Carolina, USA	<a href="http://www.climaxglobalenergy.com">www.climaxglobalenergy.com</a>
Cynar plc	Ireland	<a href="http://www.cynarplc.com">www.cynarplc.com</a>
Dynamotive	British Columbia, Canada	<a href="http://www.dynamotive.com">www.dynamotive.com</a>
Envion	District of Columbia, USA	<a href="http://www.envion.com">www.envion.com</a>
GreenMantra Recycling Technology	Ontario, Canada	<a href="http://www.greenmantra.ca">www.greenmantra.ca</a>
Klean Industries Inc.	British Columbia, Canada	<a href="http://www.kleanindustries.com">www.kleanindustries.com</a>
Niutech Energy Limited	China	<a href="http://www.niutechenergy.com">www.niutechenergy.com</a>
Plastic Advanced Recycling Corp	Illinois, USA	<a href="http://www.plastic2x.com">www.plastic2x.com</a>
Plastic2Oil	New York, USA	<a href="http://www.plastic2oil.com">www.plastic2oil.com</a>
Plastoil	Switzerland	<a href="http://www.plastoil.ch">www.plastoil.ch</a>
PolyFlow	Ohio, USA	<a href="http://www.polyflowcorp.com">www.polyflowcorp.com</a>
Promeco	Italy	<a href="http://www.promeco.it">www.promeco.it</a>

There is also a number of technology suppliers offering pyrolysis for the conversion of biomass into liquids and gases for energy generation or use as fuel (e.g. Bioliq [www.bioliq.de](http://www.bioliq.de)), which may move into the conversion of plastics in the future.

The companies listed above in **Table 12** are actively promoting their technology for the conversion of plastics into oil products. The technology offerings from these manufacturers vary in terms of the upstream feed processing equipment, the precise design of the pyrolysis unit, the operating conditions of the primary pyrolysis unit and the downstream product processing equipment, but there is a number of common features to all of them:

- Pre-treatment: to process the feedstock so that it can be fed into the pyrolysis unit.
- Pyrolysis: heating the feedstock to between 400 and 500°C, to convert it from solid to vapour and gas.
- Condensation: to recover the vapours from the pyrolysis unit as an unrefined oil product.
- Acid removal: chiefly to remove hydrogen chloride produced by conversion of PVC.
- Purification: to convert the unrefined oil into a material ready for sale.

The 'fast' pyrolysis process operated by all of the companies in **Table 12** produces three outputs: gas, liquid and char.

The gas produced contains carbon monoxide, hydrogen and methane, and has a moderate to high calorific value (ca. 15–17MJ/m<sup>3</sup>). It is often used to provide some of the energy required to heat the feedstock to the operating temperature, either directly or by using an internal combustion engine to drive a generator for electrical heat input.

The liquids produced vary depending on the purification strategy employed by the technology supplier. Generally, the liquid produced by the pyrolysis unit will have a wide boiling point range and include some entrained char. This unrefined oil is only suitable for use as a heating fuel (and some is used for supplying energy to the process), but could be shipped ‘as-is’ for refining in a conventional oil refinery. When refining is an integral part of the process, this is normally achieved by distillation, to produce a diesel product suitable for use as a vehicle fuel, as well as a heavier residue which can be used for process heat.

The char produced contains any materials that do not decompose during pyrolysis, such as metals and glass, and also the carbon that is produced by the pyrolysis reactions. This material is inert and suitable for disposal by landfill, as the metals present are at low concentration and do not tend to leach out from the carbon matrix. In addition, its carbon content also gives it the potential to be used as a solid fuel.

The gross product yields will depend on the type of technology employed, the energy input required and the quality of the feedstock, but information from the technology suppliers suggests the outputs given in **Table 13** below. However, it should be noted that, for the majority of these processes, all of the gas and up to 10% of the liquids produced are used to provide heat for the process.

---

**Table 13** Reported outputs from pyrolysis of plastic to oil products

<b>Output</b>	<b>Gross conversion</b>	<b>Net conversion</b>
Char	2 to 13% wt	2 to 13% wt
Liquid	77 to 90% wt	67 to 80% wt
Gas	8 to 10% wt	0% wt

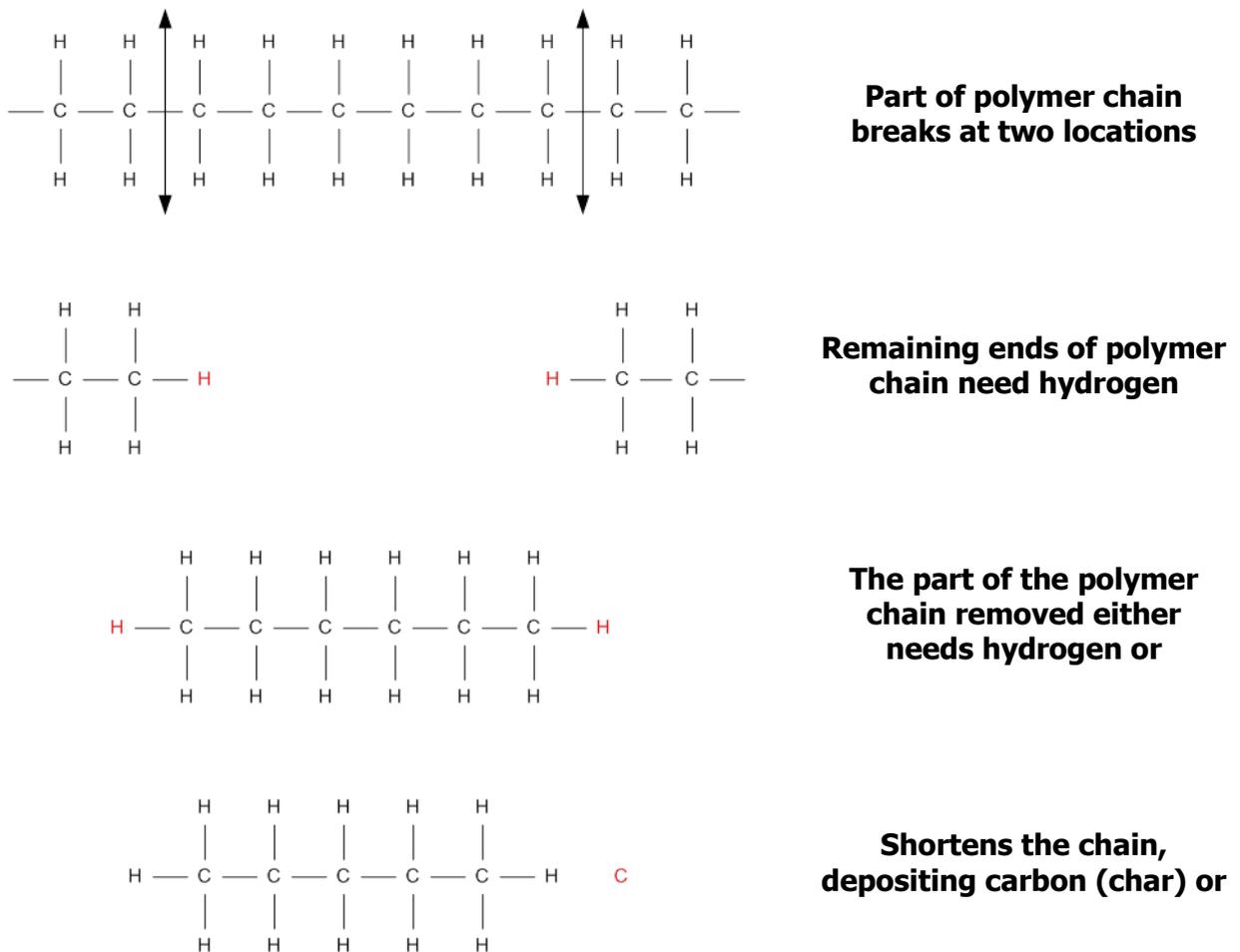
The figures in this table are shown as a percentage of the weight of the plastic fed into the process. ‘Net conversion’ includes accounting for the consumption of gas and liquid for the energy required to reach the process operating temperature. A typical mass and energy balance for a pyrolysis process is given in section 4.8.

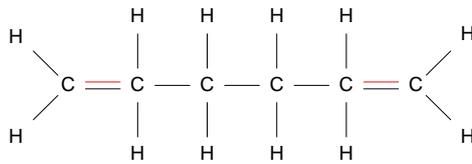
The major shortcoming of the pyrolysis process is the limitation to scale of operation. In the majority of cases, heat is supplied to the pyrolysis chamber indirectly, either by burning the gas and a portion of the liquid product in an external chamber or by application of electrical heating to the walls or floor of the pyrolysis chamber. Increasing the throughput of the plant increases the volume of the chamber in proportional to the required residence time, but the relative surface area of the chamber does not increase in the same proportion. This changing ratio of chamber volume to surface area means that the

maximum throughput of one unit is around 1,000kg/h, giving units that have an annual capacity of 7,500 to 10,000 tpa. This is likely to be a reasonable capacity for a plant based in Scotland, given the low-grade plastic waste arising that have been identified in section 3.2.

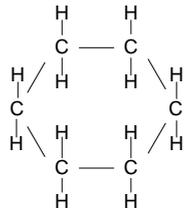
However, there is a fundamental issue with the conversion of plastic into oil products in that there will always be a shortage of hydrogen in the process because of the reduction in chain length. This will lead to the formation of char, cyclic and polycyclic hydrocarbons or reactive groups which are less desirable in oil products, as illustrated below in **Figure 7**.

**Figure 7** Formation of char, cyclic and polycyclic hydrocarbons or reactive groups





**forms undesirable reactive bonds or**



**forms undesirable cyclic hydrocarbons**

In addition, from work involving the pyrolysis of woody biomass, it is known that the presence of oxygen in the feed to a pyrolysis process – either inherent within a polymer such as PET or introduced as contamination (e.g. cellulose from paper labels, etc.) – results in the production of reactive compounds that can result in unstable, poor-quality oil products. For pyrolysis processes to work effectively, the plastic feedstock needs to be clean, with technology suppliers requiring the plastic feedstock to have less than 5% cellulose and PET contamination. Section 8 discusses contamination issues in more detail.

Other advantages and challenges for this technology are summarised in **Table 14** below.

**Table 14** Advantages and challenges for pyrolysis of plastics to oil products

### Advantages

- Relatively high yield as useful product
- Core technology well understood
- Commercial-scale projects operational (3,300tpa demonstrated)
- Moderate operating temperatures mean that conventional materials of construction can be used and this lowers costs

### Challenges

- Scale of operation, although perhaps better suited to distributed operations
- Net hydrogen deficiency
- Susceptibility to contamination
- Most processes produce a 'light sweet crude' oil product, requiring further processing
- Energy requirements consume a portion of products
- Char disposal or utilisation not established

### 4.3 Catalytic depolymerisation

Catalytic depolymerisation is similar to pyrolysis in that it promotes the break-up of the polymer chains in the absence of oxygen to produce smaller molecules. It achieves this at lower temperatures (270–400°C) than pyrolysis by using a catalyst, typically an alumina silicate zeolite. The decomposition of the feedstock results in the deposition of carbon on the catalyst's surface as a result of the net hydrogen deficiency of the process described above, thus reducing the effectiveness of the catalyst. Some processes introduce hydrogen to overcome this problem, therefore lengthening the life of the catalyst and lowering spent catalyst disposal costs. Some processes use a carrier oil to assist with the mixing and dispersion of the molten plastic and catalyst. There are fewer technology manufacturers in this field as can be seen in **Table 15**.

**Table 15** Catalytic depolymerisation technology suppliers

Company name	Company location	Website
Alphakat	Germany	<a href="http://www.alphakat.de">www.alphakat.de</a>
Recycle Energy Corp	Japan	<a href="http://www.cfp-eco.com">www.cfp-eco.com</a>
T Technology	Poland	<a href="http://www.tokarz.pl">www.tokarz.pl</a>
Ventana Cleantech	India	<a href="http://www.ventanacleantech.com">www.ventanacleantech.com</a>
Vuzeta	Italy	<a href="http://www.sigmaconsult.co.uk">www.sigmaconsult.co.uk</a>

The technology offered by these manufacturers varies in terms of the upstream feed processing equipment. One supplier listed the following functional units of its technology:

- Feed preparation: melting the feedstock and suspending it in oil to produce a sludge for ease of processing.
- Catalytic depolymerisation: converting the feedstock into a distilled oil rich in diesel components.
- Ash removal: to extract and cool the solid residue (carbon and catalyst) for disposal.
- Power and heat generation using the gases and approximately 10% of the product oil.

Catalytic depolymerisation produces gas, liquid and solid residues, and information from the technology suppliers suggests the outputs of these given in **Table 16**. However, it should be noted that the majority of these suppliers use all of the gas and up to 10% of the liquids produced to provide heat for the process. Owing to this, yields are quoted in the range of 700–800kg per dry tonne of plastic fed into the reaction vessel.

**Table 16** Reported outputs of catalytic depolymerisation processes

Output	Gross output	Net output
Residues	5 to 10% wt	5 to 10% wt
Liquid	80 to 90% wt	70 to 80% wt
Gas	5 to 10% wt	0% wt

Figures in this table are shown as a percentage of the plastic fed into the process. The net output accounts for the consumption of gas and liquid for the energy required to reach the process operating temperature.

The major shortcoming of the catalytic depolymerisation process is the ongoing consumption of the catalyst by the process. The catalyst becomes coated in carbon, produced as a result of the depolymerisation reaction, and loses its activity. In addition, contaminants in the feedstock may also poison the catalyst. Although the majority of catalysts offered by the technology suppliers are relatively low-cost zeolites, operating costs of the order of £0.20 per kilogram of oil produced have been quoted, the majority of this being the purchase and disposal of the catalyst.

Other shortcomings regarding the scale of the operation and hydrogen deficiency are the same as those of pyrolysis and are described in section 4.2. The impact of feedstock contamination on the process is not clear, but the presence of contaminants may shorten the catalyst's life.

Other advantages and challenges for this technology are summarised in **Table 17**.

**Table 17** Advantages and challenges for catalytic depolymerisation

### Advantages

Relatively high yield as useful product  
 Low operating temperatures mean that conventional materials of construction can be used and this lower costs  
 Commercial-scale projects operational (6,000tpa output)

### Challenges

Catalyst consumption and disposal  
 Scale of operation, although perhaps better suited to distributed operations  
 Net hydrogen deficiency  
 Potential for catalyst poisoning not established  
 Most processes produce a 'diesel/gasoline mixture' requiring purification by distillation  
 Energy requirements consume a portion of products

#### 4.4 Gasification to syngas

Gasification is a partial oxidation process whereby the feedstock and an oxidising agent (air, oxygen, steam or a combination of these) are fed into a chamber operating at between 900 and 1,400°C. This results in the total decomposition of the feedstock into a mixture of gases known as 'syngas', including carbon monoxide, carbon dioxide, hydrogen, water and methane. The decomposition reaction also produces a carbon char, which is oxidised in situ thereby providing the heat required to achieve the high operating temperature. This incomplete oxidation also leads to the formation of tars, which need to be removed from the syngas as they foul catalyst surfaces used for subsequent processing into oil products. The relative quantities of carbon monoxide, hydrogen and methane are determined by the composition of the feedstock and the operating temperature of the gasification reactor. The composition can be estimated by thermodynamic modelling to determine the optimum conditions for a particular feedstock and end product. Typical yields of syngas, tars and char are given in **Table 18**.

**Table 18** Typical outputs from a waste gasification process

##### Output Proportion of total output

Syngas	93% wt
Tars	6% wt
Char	1% wt

Although gasification is an established technology for the conversion of coal and petroleum coke into syngas, the use of this technology for the conversion of waste has been limited to applications that use the syngas directly for fuelling a boiler for generation of steam and electricity. A few technology providers have been looking at the catalytic conversion of syngas from waste or biomass into fuels by Fischer–Tropsch (F–T) synthesis to diesel or methanol-to-gasoline (MTG) processes, and these are listed in **Table 19**.

**Table 19** Gasification to syngas technology suppliers

Company name	Company location	Conversion	Website
Bioliq	Germany	F–T	<a href="http://www.bioliq.de">www.bioliq.de</a>
Biotfuel	France	F–T	
Choren	Germany	F–T	<a href="http://www.choren.com">www.choren.com</a>
Enerkem	Quebec, Canada	Ethanol	<a href="http://www.enerkem.com">www.enerkem.com</a>
Gas Technology Institute	Illinois, USA	F–T	<a href="http://www.gastechnology.org">www.gastechnology.org</a>
Rentech	Colorado, USA	F–T	<a href="http://www.rentechinc.com">www.rentechinc.com</a>
Syngas Technology	Minnesota, USA	MTG	<a href="http://www.syngastechnology.com">www.syngastechnology.com</a>
ThermoChem Recovery International, Inc.	Maryland, USA	F–T	<a href="http://www.tri-inc.net">www.tri-inc.net</a>

The major shortcoming of the gasification process is the need to provide an ultra-clean syngas suitable for downstream catalytic synthesis. Although this has been resolved for coal gasification technologies, it is still relatively unproven for less consistent feedstocks such as biomass, municipal solid waste and waste plastics.

Most conventional gasification processes for the biomass and waste sector use air as the oxidant of choice, because it is the simplest and cheapest substance to use. Air contains approximately 78% nitrogen by volume, and, when the syngas is simply used as a fuel gas in a boiler for steam and electricity generation, this does not present a problem. However, when the syngas is to be used for catalytic synthesis of oil products, the presence of nitrogen increases operating and capital costs, and reduces overall yield.

Most synthesis processes operate at high pressure as this favours the conversion of a number of small molecules (carbon monoxide, hydrogen) into larger ones (oil products).

The energy required to compress the gas is proportional to the total volume of gas present at the compressor inlet, so compressing large volumes of a gas which simply pass through the process unchanged represents a significant cost to no advantage. Because the volume of gas is larger, the equipment (including the gas compressor) must be larger, and therefore more expensive to build. The energy required to heat nitrogen from ambient temperature up to the gasifier operating temperature (ca. 900–1,100°C) increases the quantity of the feedstock that has to be consumed.

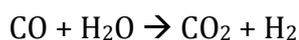
The presence of nitrogen also dilutes the reactive components in the syngas, meaning the synthesis reactor needs to be larger; otherwise more of the gas passes through unreacted, giving a loss in yield. For all of these reasons, any gasifier intended for the production of synthesis gas for subsequent synthesis into oil products is fed with oxygen. The quality of the oxygen is not critical, but it is usually at least 90% oxygen, with the remainder being nitrogen.

Although oxygen is the preferred oxidising medium for gasification and catalytic synthesis, the addition of steam does provide an opportunity to increase the quantity of hydrogen available to downstream processes. Steam will react with carbon char present in the gasifier to produce carbon monoxide and hydrogen as follows:



Carbon + Steam → Carbon monoxide + Hydrogen

Both carbon monoxide and hydrogen are useful in subsequent reactions to form oil products. However, the addition of too much steam risks the loss of carbon monoxide by the 'water-gas shift' reaction, but this still produces useful hydrogen:



Carbon monoxide + Steam → Carbon dioxide + Hydrogen

In this way, the ratio of carbon monoxide to hydrogen can be adjusted by the ratio of steam to oxygen (or steam to air) to that desired for subsequent synthesis of oil products.

As the process is internally heated by partial oxidation of the feedstock and char, it is much more scalable, although with a feed capacity of only a few hundred tonnes per day, existing biomass and waste gasifiers are small when compared with coal gasifiers, which can have feed capacities of over one thousand tonnes per day.

Other advantages and challenges for this technology are summarised in **Table 20**.

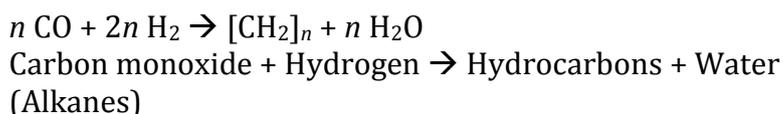
**Table 20** Advantages and challenges for gasification of plastics to syngas

Advantages	Challenges
Scalable, established technology for coal conversion	Syngas clean-up for downstream use
Makes a high-quality synthesis gas	Requirement for oxygen, not air, as the oxidant
Relatively tolerant to contamination	Still developing technology for conversion of plastic and waste into oil products
	Gasifier operation at elevated temperature requires exotic materials of construction, increasing costs
	Gasifier operation at elevated pressures and compression of syngas are both technical issues to be resolved

It should be noted that gasification is currently the preferred process for biomass conversion because, if biomass is fed into a pyrolysis reactor, the presence of oxygen in the feedstock produces crude pyrolysis oil that quickly degrades and solidifies, and requires further chemical processing to yield usable oil products. Gasifying biomass to syngas results in a simpler, more easily defined process and ultimately cleaner, more stable oil products. This is less of an issue with plastics, as, when they are fed into a pyrolysis reactor, the low oxygen content of typical waste plastics generally results in much cleaner, and more stable, pyrolysis oil.

#### 4.5 Fischer–Tropsch conversion of syngas to diesel products

Fischer–Tropsch (F–T) synthesis of syngas to diesel products involves the reaction of carbon monoxide and hydrogen present in the syngas to form water and the ‘CH<sub>2</sub>’ group, which then effectively polymerises to form longer chain hydrocarbons. In the classic F–T synthesis, alkanes are produced by the following reaction scheme:



The reaction forms a mixture of alkanes from  $n = 1$  (methane) to greater than  $n = 19$ . Diesel products are in the range  $n = 5$  to  $n = 18$ , with the lighter gases being recycled or used as a fuel gas, and the heavier liquids (which tend to form solid wax at ambient temperatures) being sold as waxes or undergoing further processing to produce more diesel products.

The precise distribution of products from the F–T synthesis depends on the operating conditions and catalyst used. Low temperatures (200–250°C) and a cobalt catalyst tend to produce mainly alkanes suitable for diesel, whereas high temperatures (350°C) and an iron catalyst produce significant quantities of aromatics and alkenes, but still with a majority of alkanes. This blend can be distilled to separate gasoline and diesel components. To minimise the equipment size and maximise yields, the process operates at between 10 and 30 bars, requiring the syngas to be available at high pressure. Overall, the yield of hydrocarbon liquids from the process will be approximately 40% wt of the input plastic waste.

As mentioned above, the use of a high-pressure catalytic process for the conversion of plastic-derived synthesis gas into oil products requires the use of oxygen (possibly with additional steam) in the gasifier itself. This minimises the size of the equipment and the cost of compression of the synthesis gas, and maximises the product yield.

F–T synthesis is an established oil refinery technology, with a number of large-scale technology licensors, some of which are listed below in **Table 21**. None of these has any significant experience with the use of waste plastic to produce the syngas feed, but some are reported as having interest in biomass-to-liquids processes.

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**Table 21** F–T technology licensors

Company name	Company location	Website
Lurgi	Germany	<a href="http://www.lurgi.com">www.lurgi.com</a>
Oxford Catalysts/Velocys	USA, UK	<a href="http://www.oxfordcatalysts.com">www.oxfordcatalysts.com</a>
PetroSA	South Africa	<a href="http://www.petrosa.co.za">www.petrosa.co.za</a>
Rentech	Colorado, USA	<a href="http://www.rentechinc.com">www.rentechinc.com</a>
Sasol	South Africa	<a href="http://www.sasol.com">www.sasol.com</a>
Shell	Netherlands	

The major shortcoming of the F–T process is the requirement to operate at elevated pressure. This requires either that the gasification process itself is operated at high pressure, significantly increasing the cost of this equipment, or passing the cooled, clean syngas through a compressor. Either option has increased operating and capital costs when compared with a process operating at close to atmospheric pressure. Other advantages and challenges for this technology are summarised in **Table 22**.

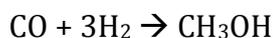
**Table 22** Advantages and challenges for conversion of syngas to diesel by F–T

Advantages	Challenges
Established technology	High operating pressure
Can be very large scale	The need for a clean syngas stream
Produces a high-quality diesel blendstock	Relatively low product yields from feed to gasifier
	Requirement for oxygen-blown gasifier
	Co-produced waxes need further processing to maximise fuel yield

#### 4.6 Syngas conversion to methanol and methanol to gasoline

The conversion of syngas to methanol and methanol's subsequent conversion to gasoline utilises two catalytic transformations, and is an alternative catalytic route from syngas to fuel products, aimed at gasoline.

The first steps include the reactions of carbon monoxide and carbon dioxide with hydrogen to form methanol. These reactions are equilibrium controlled, and conversion of around 90% of the available carbon monoxide and around 10% of the available carbon dioxide can be achieved.



Carbon monoxide + Hydrogen → Methanol



Carbon dioxide + Hydrogen → Methanol + Water

This reaction is performed at approximately 250°C and is favoured by high pressures, typically 50 bar or higher. As with the F–T process, this results in a process with higher capital and operating costs than one that operates at or close to atmospheric pressure.

The methanol is then purified and passes onto the MTG process. Here, methanol is first dehydrated to produce dimethyl ether and then further dehydrated to produce the 'CH<sub>2</sub>' group, which effectively polymerises to form longer chain hydrocarbons.



Methanol → Dimethyl ether + Water



Dimethyl ether → Hydrocarbons + Water

The hydrocarbon mixture produced by this reaction tends to produce more alkenes and aromatics than the F–T process, and thus produces a mixture better suited for use as gasoline. Methanol conversion to gasoline typically exceeds 90%.

Methanol synthesis is an established chemical process technology, with a number of large-scale technology licensors, some of which are listed below in **Table 23**. All of these are focused on syngas produced from partial combustion of coal or natural gas, with none having any significant involvement with syngas generation from plastics or biomass.

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**Table 23** Methanol technology licensors

Company Name	Location	Website
Air Products	Pennsylvania, USA	<a href="http://www.airproducts.com">www.airproducts.com</a>
Haldor Topsoe	Denmark	<a href="http://www.topsoe.com">www.topsoe.com</a>
Lurgi	Germany	<a href="http://www.lurgi.com">www.lurgi.com</a>
Synetix	UK	<a href="http://www.jmcatalysts.com">www.jmcatalysts.com</a>

MTG is a relatively new process with only one significant process licensor: ExxonMobil (see [www.exxonmobil.com](http://www.exxonmobil.com)). Syngas Technology (see [www.syngastechnology.com](http://www.syngastechnology.com)) are licensed to use this process and are actively promoting the conversion of biomass to gasoline by this route.

The major shortcoming of the syngas–to-methanol and MTG processes is the requirement to operate at elevated pressure: around 50 bars for the methanol synthesis. As described above for the F–T synthesis, this requires either that the gasification process itself is operated at high pressure, significantly increasing the cost of this equipment, or passing the cooled, clean syngas through a compressor, with both having an impact on capital and operating costs.

As mentioned above, the use of a high-pressure catalytic process for the conversion of plastic-derived synthesis gas into oil products requires the use of oxygen (possibly with additional steam) in the gasifier itself. This minimises the size of the equipment and the cost of compression of the synthesis gas and maximises the product yield. Other advantages and challenges for this technology are summarised in **Table 24**.

---

**Table 24** Advantages and challenges for conversion of syngas to gasoline by MTG

Advantages	Challenges
Can be very large scale	High operating pressure
Methanol synthesis is a mature technology	The need for a clean syngas stream
Produces a high-quality gasoline blendstock	Relatively low product yields from feed to gasifier
	Requirement for an oxygen blown gasifier
	Single licensor

#### 4.7 Biological conversion of syngas to ethanol

The biological conversion of syngas to ethanol utilises special strains of micro-organisms adapted to the transformation of carbon monoxide and hydrogen into ethanol.



Carbon monoxide + Water  $\rightarrow$  Ethanol + Carbon dioxide



Carbon dioxide + Hydrogen  $\rightarrow$  Ethanol + Water

To achieve these reactions, the syngas is cooled and fed into a conventional fermenter designed for intimate mixing of the gas with the fermenter broth. The majority of ethanol is produced by the conversion of carbon monoxide (90% converted), with a contribution from the conversion of hydrogen (50% conversion), principally because of the poor solubility of hydrogen in the aqueous broth. Ordinarily, ethanol inhibition of the micro-organisms would prevent ethanol concentrations exceeding 1–2%, but the use of membrane technology allows a more concentrated (> 10%) aqueous ethanol solution to be produced, such that application of a conventional distillation and dehydration systems is viable. Technology suppliers claim that up to 40% of the carbon present in the feedstock can be recovered as ethanol.

The biological conversion of syngas to ethanol is a relatively new technology, combining gasification of biomass and waste materials with selective development of micro-organisms. As such, there are fewer technology suppliers for this process, as can be seen in **Table 25**.

**Table 25** Syngas fermentation technology licensors

Company name	Location	Website
INEOS Bio	Illinois, USA	<a href="http://www.ineosbio.com">www.ineosbio.com</a>
Coskata	Illinois, USA	<a href="http://www.coskata.com">www.coskata.com</a>
LanzaTech	New Zealand	<a href="http://www.lanzatech.co.nz">www.lanzatech.co.nz</a>

The major shortcoming of the biological conversion of syngas to ethanol is the low solubility of the syngas components (carbon monoxide and hydrogen) in the fermenter, which results in a low concentration of ethanol in the fermenter product. In one of the processes, this has been circumvented by the use of membrane technology to concentrate the 'beer' to sufficient strength to allow conventional ethanol recovery, but this still remains a weakness.

The size of the fermenter is dependent on the rate of transfer of carbon monoxide, carbon dioxide and hydrogen into the liquid phase. Any inert gases present in the syngas (such as nitrogen) reduce this rate so, although the process operates at atmospheric pressure, an oxygen-blown gasifier is still required.

Other advantages and challenges for this technology are summarised in **Table 26**.

---

**Table 26** Advantages and challenges for conversion of syngas to ethanol by fermentation

#### **Advantages**

Low operating pressure, so no need for gas compression or high-pressure gasifier

Low operating temperature, so can recover heat from syngas for steam and power generation

Produces a high-quality gasoline blendstock

Relatively tolerant to contamination

#### **Challenges**

Few licensors, and therefore limited availability of micro-organisms

Requirement for an oxygen-blown gasifier

Low concentrations in fermenter

Novel process

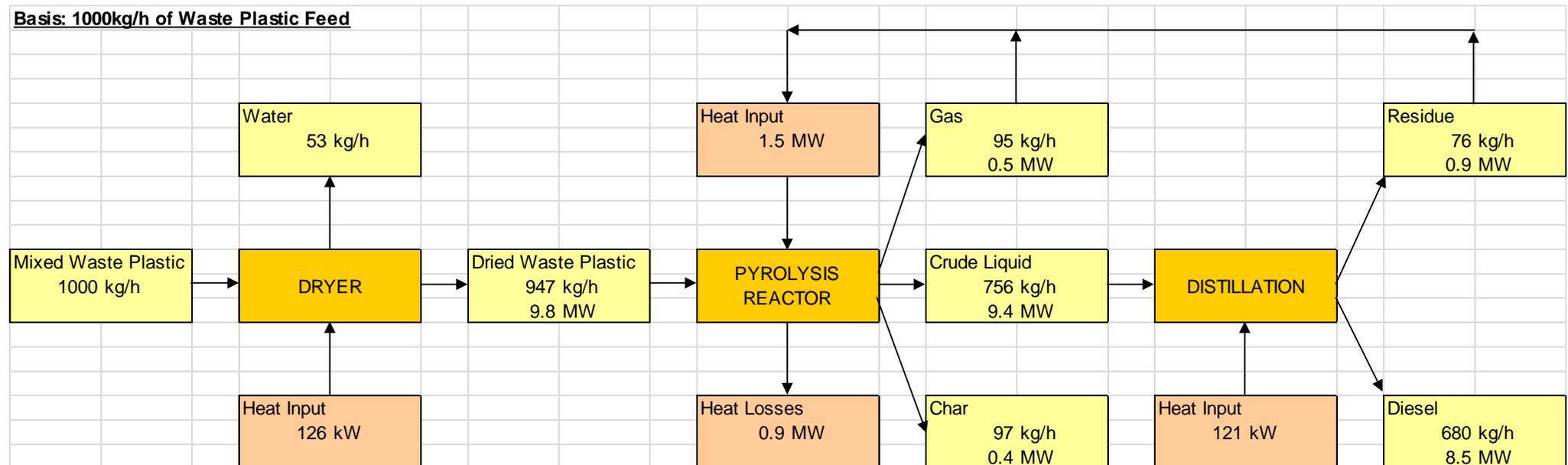
### **4.8 Mass and energy balances**

This section presents mass and energy balances based on publicly available information on the processes described above. The basis is 1,000kg/h of waste plastic fed into the process, including associated water and contamination.

### 4.8.1 Pyrolysis

Figure 8 shows the mass and energy balance for pyrolysis.

Figure 8 Pyrolysis mass and energy balance



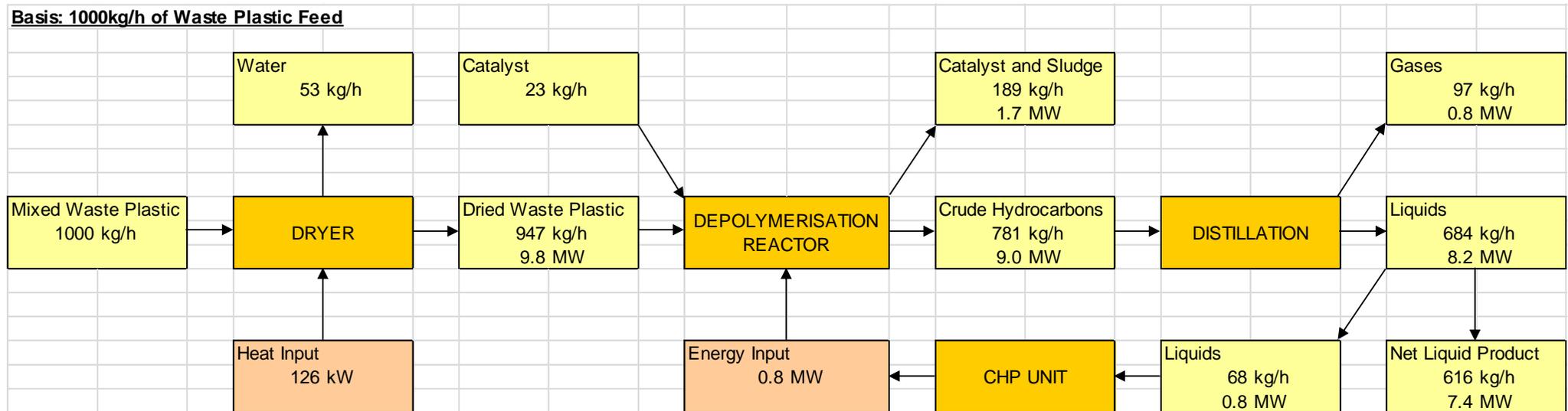
The following major assumptions underpin this mass and energy balance:

- Mixed waste plastic composition as per WRAP report ISS001-001
- Pyrolysis reactor temperature: 400°C
- Pyrolysis reactor products: 10% gas, 80% crude liquids, 10% char
- Heating value of crude liquid: 45MJ/kg
- Dried waste plastic moisture composition of 5% wt (wet basis)
- Pyrolysis reactor endotherm: 2500kJ per kilogram of dried waste plastic
- Heating value of gas: 20MJ/kg
- Distillation recovery as product: 90% wt of crude liquid

#### 4.8.2 Catalytic depolymerisation

Figure 9 shows the mass and energy balance for the catalytic depolymerisation process.

Figure 9 Catalytic depolymerisation mass and energy balance



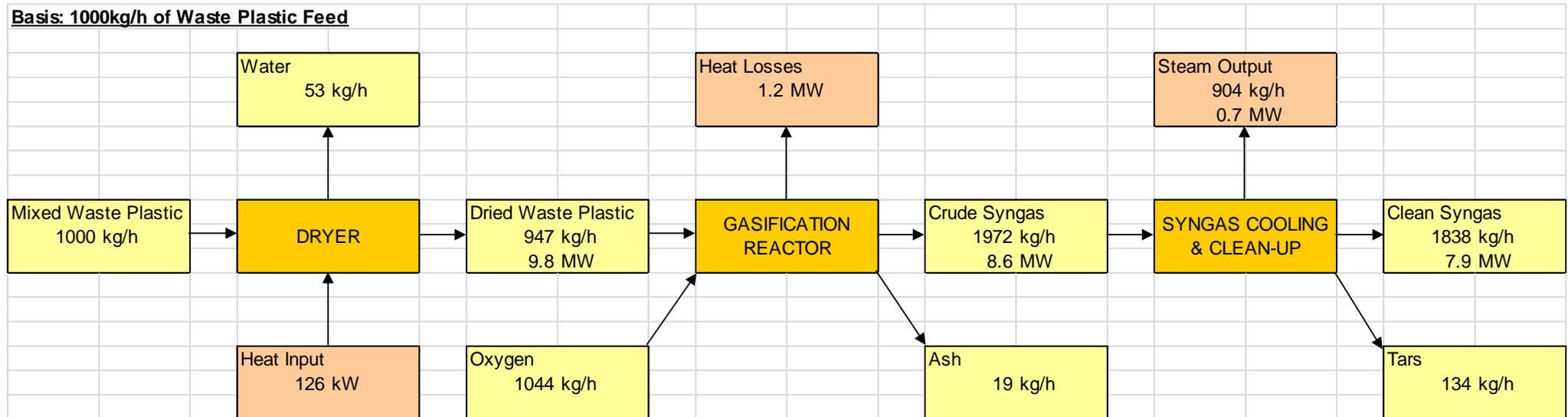
The following major assumptions underpin this mass and energy balance:

- Mixed waste plastic composition as per WRAP report ISS001-001
- Depolymerisation reactor temperature: 270°C
- Depolymerisation reactor products: 12% gas, 85% crude liquids, 3% coke
- Heating value of gas: 50MJ/kg
- Dried waste plastic moisture composition of 5% wt (wet basis)
- Proportion of feedstock unreacted: 15% wt
- Catalyst addition: 3% wt on feedstock
- Heating value of crude liquid: 46MJ/kg

### 4.8.3 Gasification to syngas

Figure 10 shows the mass and energy balance for a gasification to syngas process.

Figure 10 Gasification to syngas mass and energy balance



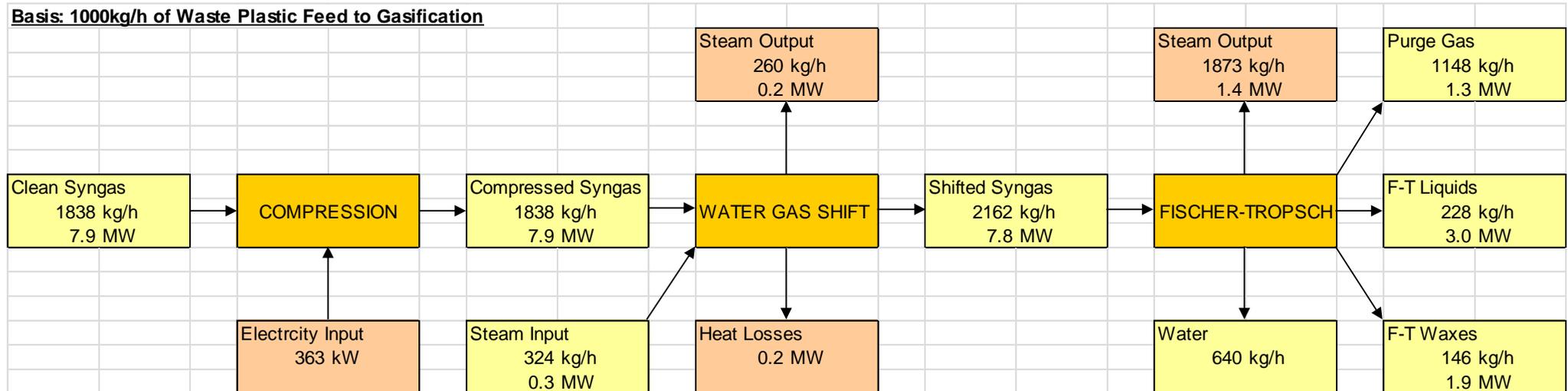
The following major assumptions underpin this mass and energy balance:

- Mixed waste plastic composition as per WRAP report ISS001-001
- Gasification reactor temperature: 1077°C
- Gasification reactor tar yield: 6% wt of feed
- Dried waste plastic moisture composition of 5% wt (wet basis)
- Gasification reactor ash yield: 1% wt of feed
- Heating value of gas: 8MJ/kg

#### 4.8.4 Fischer–Tropsch conversion of syngas to diesel products

Figure 11 shows the mass and energy balance for the F–T conversion process of syngas to diesel product.

Figure 11 F–T mass and energy balance



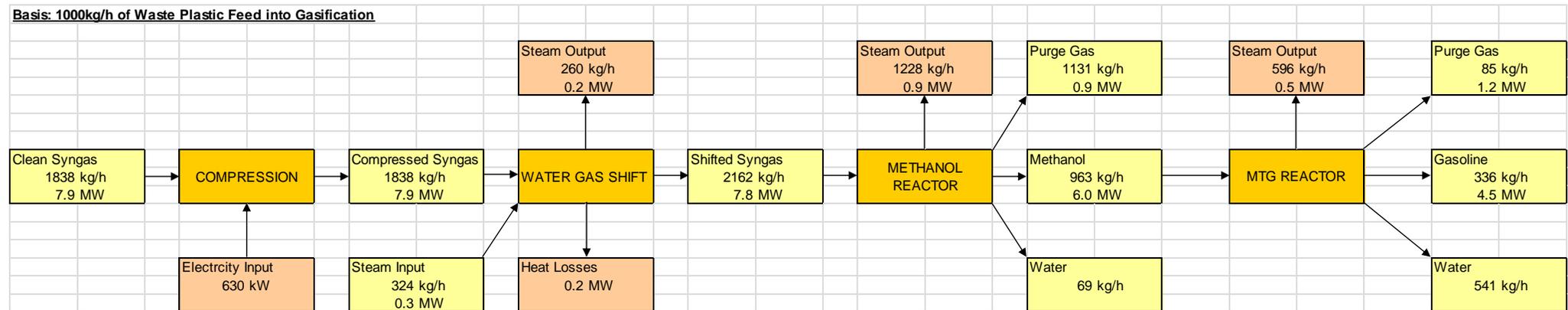
The following major assumptions underpin this mass and energy balance:

- Clean syngas composition as per **Figure 10** above
- Water–gas shift reactor adjusts H<sub>2</sub>:CO to 2:1
- Conversion of carbon monoxide to methane: 10% of feed
- Purge gases have carbon  $n < 4$ ; F–T waxes have carbon  $n > 18$
- Heating value of F–T liquids: 48MJ/kg
- Reactor pressure: 11 bara
- Unreacted carbon monoxide leaving F–T reactor: 5% of feed
- Product distribution according to Anderson–Schulz–Flory, with  $\alpha = 0.9$
- Heating value of purge gas: 2MJ/kg
- Heating value of F–T waxes: 47MJ/kg

#### 4.8.5 Syngas conversion to methanol and methanol to gasoline

Figure 12 shows the mass and energy balance for the syngas conversion to methanol and methanol to gasoline.

Figure 12 Syngas conversion mass and energy balance



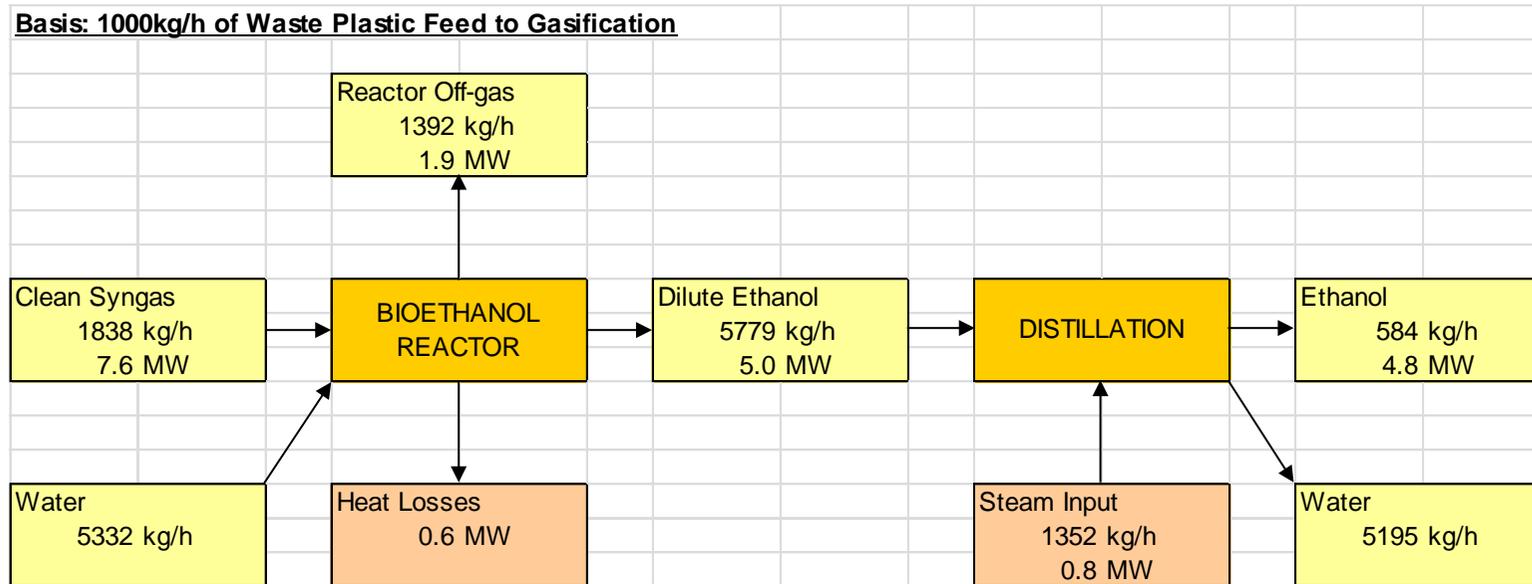
The following major assumptions underpin this mass and energy balance:

- Clean syngas composition as per **Figure 10** above
- Water-gas shift reactor adjusts  $H_2:CO$  to 2:1
- Conversion of MTG components: 80%
- Heating value of methanol reactor purge gas: 1.4MJ/kg
- Heating value of gasoline: 44MJ/kg
- Methanol reactor pressure: 50 bara
- Conversion of carbon monoxide to methanol: 90% of feed
- MTG purge gas has carbon  $n < 4$
- Heating value of MTG purge gas: 50MJ/kg
-

#### 4.8.6 Biological conversion of syngas to ethanol

Figure 13 shows the mass and energy balance for the biological conversion process of syngas to ethanol.

Figure 13 Biological conversion of syngas to ethanol mass and energy balance



The following major assumptions underpin this mass and energy balance:

- Clean syngas composition as per **Figure 10** above
- Conversion of hydrogen to ethanol: 50% of feed
- Distillation energy input from typical maize-to-ethanol rectifier and molecular sieve dehydration system
- Conversion of carbon monoxide to ethanol: 95% of feed
- Dilute ethanol leaves reactor at 10% wt ethanol

## 4.9 Summary

**Table 27** summarises the gross output of oil products from each of the processes considered, in terms of mass and energy content.

**Table 27** Summary of gross output of oil products

	Process				
	Pyrolysis	Catalytic depolymerisation	Gasification and F-T synthesis	Gasification and methanol-to-gasoline synthesis	Gasification and bioconversion to ethanol
<b>Input</b>					
Quantity of waste plastic (kg/h)	1,000	1,000	1,000	1,000	1,000
Power (MW)	9.8	9.8	9.8	9.8	9.8
<b>Output</b>					
Oil product	Plastic-derived Crude	Diesel/gasoline mixture	Synthetic diesel (+ cracked wax)	Synthetic gasoline	Synthetic ethanol
Quantity of product (kg/h)	680	616	228 (374)*	336	584
Power (MW)	8.5	7.4	3.0 (4.9)*	4.5	4.8
<b>Output as percentage of input</b>					
By mass	68%	62%	23% (37%)*	34%	58%
By energy	87%	76%	31% (50%)*	46%	49%

\*Figures in parentheses include the mass and energy values from the waxes also produced by the F-T process. These could be converted to road fuels by the INEOS oil refinery.

The results indicate that the pyrolysis and catalytic depolymerisation processes are more attractive than gasification and syngas conversion both in terms of the mass yield of product per tonne of feed plastic and the proportion of the embodied energy present in the feed that appears in the oil products. This is not unexpected as:

- A proportion of the feedstock is consumed during the gasification process, which is converted to carbon dioxide which does not take part in subsequent synthesis reactions.
- The synthesis reactions do not run to completion, leaving a purge gas rich in carbon monoxide and hydrogen, leading to further loss of embodied energy.

However, the pyrolysis processes tend to produce a crude oil that would be difficult to characterise and is likely to need to be purified at the processing site or moved on (e.g. to a refinery) as a waste for purification. The refining process is likely to create a further yield loss of 10% with additional processing costs of the order of £50 per tonne.

The catalytic depolymerisation processes tend to produce a distilled mixture of gasoline and diesel components that requires less processing to yield a blend component or drop-in fuel. This processing would not create a further yield loss, but would incur additional costs of the order of £25 per tonne.

By contrast, the processes using gasification followed by synthesis produce a well-defined product that could be classified as 'end of waste'. These oil products would be accepted by INEOS or fuel traders without any further processing and they would be introduced to the fuel blending systems without any issues.

## 5 Evaluation of business models

Section 4.8 presented mass and energy balances for a range of process options for converting plastic to oil. This section of the report uses a financial model to evaluate the various options. Sensitivities to changes within the model are also investigated.

### 5.1 Base parameters for model

This section outlines the parameters that were used to construct the base case model.

#### 5.1.1 Process basis

In order to properly compare each option, it is necessary to define a basis on which the models for each option would be constructed. The parameters for the basis chosen were as follows:

- Feed rate: 3,200kg/h.
- Running hours: 8,400 hours per year (therefore a total throughput of 27,000tpa).
- Number of shifts: five.
- Processing costs:
  - Pyrolysis crude oil to finished product: £50 per tonne.
  - Mixed diesel/gasoline distillates (from catalytic depolymerisation) to finished product: £25 per tonne.
- Processing yield losses:
  - Pyrolysis crude oil to finished product: 10%.
  - Mixed diesel/gasoline distillates to finished product: 0%.

Note that the base case assumes that the fuel produced is of the typical quality reported to be produced by the processes, with costs and yield losses applied as required to bring it up to the quality required for use as a product. However, it may be the case that the output is of sufficient quality such that it can be immediately blended with fuel from the refinery. In this case, no refining fee or yield loss would be incurred; this is considered in section 5.3.2.

#### 5.1.2 Revenue

Revenue for each option is generated through two sources: income from product (i.e. oil products) sales and income from sales of on-site power generation. **Table 28** shows a summary of the revenue items for each option.

**Table 28** Summary of price per unit from revenue items

Item	Selling unit	Price per unit
Diesel	Tonne	£564
Gasoline	Tonne	£571
Ethanol	Tonne	£483
Power	Megawatt-hour	£90*

\*Price includes one Renewable Obligation Certificate (ROC) per MWh at £45 per ROC.

### 5.1.3 Capital expenditure and financing options

Capex often accounts for by far the largest fraction of the total spend on a project. Therefore, it is important to have a good estimate of the capex for each part of the plant. The installed capital costs of the available technologies reported by the literature are shown in **Table 29**.

**Table 29** Capital cost summary

Technology	Throughput (tpa)	Capital cost (installed)	Capital cost/ throughput (£/tpa)
Pyrolysis*	10,000	£14M	1,400
Catalytic depolymerisation†	10,000	£14M	1,400
Gasification w/F-T**	500,000	£300M	600
Gasification w/MTG††	500,000	£200M	400
Gasification w/Bio***	500,000	£175M	350

\*Data adapted from stakeholder discussions: \$2M for a dryer with a throughput rate of 1.25 tonnes per hour, \$2M for a pyrolysis unit with a throughput rate of 0.40 tonnes per hour, \$2.5M for a distillation column with a throughput rate of 1.00 tonne per hour.

†Catalytic depolymerisation cost unknown but assumed to be the same as pyrolysis.

\*\*Data from: Swanson, R.M., Satrio, J.A., Brown, R.C., *et al.* 2010. Techno-economic Analysis of Biofuels Production Based on Gasification. NREL Report NREL/TP-6A20-46587, <http://www.nrel.gov/docs/fy11osti/46587.pdf> (last accessed 1 October 2012).

††Data from: NREL. 2011. Gasoline from Wood via Integrated Gasification, Synthesis, and Methanol-to-Gasoline Technologies, <http://www.nrel.gov/docs/fy11osti/47594.pdf> (last accessed 1 October 2012).

\*\*\*Adapted from data referred to in footnote ††.

Pyrolysis processes are relatively simple when compared with gasification and can be built cost-effectively at relatively low throughputs in the range 10,000–15,000tpa. There are physical constraints on pyrolysis processes (related to heat transfer rates and the geometry of pyrolysis reactors), which make it difficult to scale up individual pyrolysis reactors beyond about 1 tonne per hour.

Processes based on gasification are significantly more complex than pyrolysis processes. In addition to the plant required to heat the feedstock to the gasification reaction temperature, they require plant to generate oxygen, and further plant for the catalytic reactions of the gases to produce oil products, some of which use expensive catalysts and operate at high pressure. Processes of this type have been developed and scaled up for processing coal and similar materials over many years and can be built with large capacities. However, the complexity of these processes means that they are also only economically viable at large scale, typically 300,000–500,000 tpa. At this scale the capital cost per tonne per year of input material can be lower than that for the pyrolysis processes. However, the lower yield of hydrocarbon liquids from gasification-based processes means that the capital cost per tonne of output product is more comparable.

The result of these trade-offs is that pyrolysis processes can be built only at a relatively small scale at each site with low absolute capital cost per site but higher capital cost per tonne per hour throughput, whereas gasification processes can only be built at very large scale with high absolute capital costs per site in the range £150–300M, but with lower capital cost per tonne per hour of throughput.

It is unlikely that it would be feasible to collect enough low-grade waste plastic in one place in Scotland to supply a gasification-based process with 300,000–500,000tpa of feed. It is more likely that a pyrolysis process would match the expected volumes of low-grade plastic feed material.

For the purpose of comparing the different process options, it is necessary to estimate the likely capital cost for a fixed throughput, even though plants based on pyrolysis and gasification would in reality be built at very different scales.

It is generally accepted in the process engineering world that it is reasonable to use a ‘0.6 power’ scaling factor to adjust initial capital cost estimates up or downwards from a base case throughput. For example, if a capital cost estimate is available for a plant with a throughput of 100,000 tonnes, then, for initial comparison only, it is accepted that it would be reasonable to multiply the base case capital cost by  $(200,000/100,000)^{0.6}$  to arrive at an estimate of probable capital cost for a plant with 200,000 tpa throughput. This approach has been used in **Table 30** below to adjust the capital cost estimates shown in **Table 29** for the expected throughput of 27,000tpa for a commercial scale plant in Scotland.

Note that the resulting capital cost per tonne per year ratios are different to the figures shown in **Table 29**.

**Table 30** Estimated capex costs for each option

Item	Installed capex
Pyrolysis	£17.1M
Depolymerisation	£17.1M
Gasification w/F-T	£38.1M
Gasification w/MTG	£28.9M
Gasification w/Bio	£25.2M
CHP recovery unit*	£100,000–£6.0M

\*Combined heat and power (CHP) recovery unit cost £1,000 per 1kW generated.

There is a reasonably high confidence level in the scaling factors when scaling up from 10,000tpa to 27,000tpa, but the numbers used when scaling down from 500,000tpa need to be treated cautiously.

The total capex is in the range £17M to £40M, depending on the option chosen; it is not normally feasible to provide this amount of investment purely from business equity, so some level of external investment is required. This is normally provided through leases; however, not all items in **Table 30** are leasable as they require the lessor to ‘own’ the item for the lease period. This is not possible for installation and project management, so these are non-leasable items. Therefore, these items must be financed through a mixture of equity and loans, which offer less favourable interest rates. It is the balance between these loans and the equity that will be crucial to a positive financial assessment, and this depends heavily on the level of equity that an interested party is able and willing to invest.

For the initial base cases, the financial return calculations are based on 70% of leasable capex being funded by a lease and 50% of non-leasable capex being funded through loans, with the remainder of the capex funded by equity investment by shareholders. It should also be noted that there is the possibility of grant funding, which incurs no interest and need not be repaid; however, this has not been considered in the present work. A summary of the breakdown of the amount of equity, lease and loan required for each project is shown in **Table 31**.

**Table 31** Breakdown of equity, lease and loan values for each project

Option	Equity investment	Lease value*	Loan value*
Pyrolysis	£8.9M	£6.0M	£4.8M
Depolymerisation	£9.4M	£6.0M	£4.8M
Gasification w/F-T	£23.M	£13.7M	£10.3M
Gasification w/MTG	£14.8M	£9.9M	£7.6M
Gasification w/Bio	£14.1M	£9.7M	£7.4M

\*Note this is the initial lease/loan value; the total amount paid back is greater.

#### 5.1.4 Operating expenditure

Operating expenditure (opex) represents the money needed to keep the plant running: this can be divided into production costs (e.g. power, water and transport) and annual fixed costs (e.g. business rates, staff salaries and maintenance). Production costs, like production revenue, scale relative to the amount of material the plant processes (e.g. processing 20,000 tonnes will use about twice as much power as processing 10,000 tonnes), whereas annual fixed costs are constant – staff must be paid whether or not the plant is functioning. Therefore, it is very important to begin full-scale production as soon as is feasible to cover the annual fixed costs. , **Table 33** and **Table 34** show the production and fixed costs relevant to each option.

**Table 32** Heat, electricity, water and oxygen demands for each option

Option	Heat (kW)	Electricity (kW)	Water (kg/h)	Oxygen (m <sup>3</sup> /h)
Pyrolysis	5,500	50	N/A	N/A
Depolymerisation	3,400	50	N/A	N/A
Gasification w/F-T	470	1,210	N/A	2,550
Gasification w/MTG	470	2,070	N/A	2,550
Gasification w/Bio	2,790	1,840	17,060	2,550

**Table 33** Material purchase and disposal costs

Item	Cost
Feed gate fee (revenue for plastic-to-oil plant)	£80/tonne
Water purchase cost	£1.20/tonne
Water disposal cost	£1.20/tonne
Oxygen purchase cost	£30/tonne
Landfill cost	£80/tonne

**Table 34** Fixed annual costs

**Staff costs**

Plant operators (three staff/shift)	£400,000
Yard team (two staff)	£53,500
Maintenance team (one staff)	£35,500
Management team (two staff)	£110,000

**Other fixed costs**

Site size	80,000 ft <sup>2</sup>
Business rates	£2.00/ft <sup>2</sup>
Site rental rate	£2.50/ft <sup>2</sup>
Yearly maintenance contract	£130,000 + 3% of capex
Loader and fork lift rental	£10,500
Audit costs	£5,000
Insurance	£150,000
Travel	£20,000
Communications, marketing and public relations	£12,000

The fixed and operating cost estimates are based on Axion's experience from its own recycling operations. The maintenance cost estimate assumes that there will be some maintenance costs that will be independent of capital cost (for site infrastructure) and the rest will be related to the value of the equipment that is installed.

**5.1.5 Working capital**

At various points throughout the project, it may be necessary to inject extra investment (working capital) to deal with rising costs that are not covered by capex investment or operational revenue, for example interest repayments or wages incurred before production has begun. This working capital can be funded from either equity or loans and is injected as needed; however, using this model will give a good indication of the bottleneck points at which more investment is needed, as well as the magnitude of the cash required.

**5.1.6 Capex, opex and working capital phasing**

It is not sensible to draw down all lease and loan money on the first day of the project, as this will begin incurring interest immediately and will probably not be usable (e.g. equipment will not be purchased until the design, site purchase and initial civil work have been completed). Therefore, the economic model allows loans to be drawn down in phases, in order to fit the construction schedule. This would also be useful for equity injections, if taking into account existing cash flows as well. In the base case, the capex for the majority of items was assumed to be split into three payments of 40%, 50% and 10%. This is representative of the typical payment schedule for equipment (i.e. 40% payment on order, the majority of the remainder on delivery, with 10% kept back until after commissioning or performance achievement). For other items, however, the phasing was slightly different; all phasing schedules are outlined in **Table 35**. It should be noted that the civil work is split into three payments: this is to account for preliminary civils and installation work once equipment has arrived.

**Table 35** Estimated capex phasing schedules

Item	Phasing schedule
Plant capex	40% Y1M3, 50% Y1M7, 10% Y2M12
Installation	30% Y1M8, 30% Y1M9, 30% Y1M10, 10% Y1M11
Design and project management	Equal payments of 10% per month

Similarly, opex and production revenue should be scaled relative to the productivity of the plant. Obviously, until the plant is constructed there is no production, so opex and revenue are zero. Once the plant is completed, there is a period of several months during which the plant is 'ramped up', to ensure that no major problems are encountered by overloading the equipment; therefore the revenue and production costs should be scaled accordingly. However, even during this period, the fixed annual costs are charged at full rate.

In the base case, all construction is assumed to be complete by the end of Y1M12. Therefore, the fixed annual costs are applied from Y1M12 onwards, whereas the production revenue and costs are scaled up from 25% in Y1M12 to 100% in Y1Q4.

#### *5.1.7 Operating income and cash flow*

Operating income for a given period is calculated as the total revenue in that period (section 5.1.2) minus the annual opex (section 5.1.4) and annual repayments of capex (section 5.1.3) in that period. By calculating these figures over consecutive periods, a cash flow forecast can be created, which tracks the closing position (essentially the amount of 'cash in the bank') at the end of each period. In the early stages of the project, i.e. during construction and startup, the operating income may vary from quarter to quarter or month to month. Therefore, for the first year the cash flow is calculated monthly, then quarterly until the lease and loan are paid off (year 5). From this point, the operating income is constant, so cash flow is calculated annually. The cash flow forecasts for the base case are shown in Cash flow.

#### *5.1.8 Net present value*

The net present value (NPV) is a measure of the current value of a project, based on its future cash flows over a period of years. The NPV calculation uses a 'discount rate' (a figure representing the rate of return that could be earned on an investment) to give lower value to future cash flows. In the results presented in the following section, NPVs for each project are calculated over 10 years with a discount rate of 10%.

The amount of working capital required for each option is adjusted such that the closing position of the cash flow calculation never becomes negative during the construction and lease repayment phase – after this point any loss-making options are allowed to have negative closing positions.

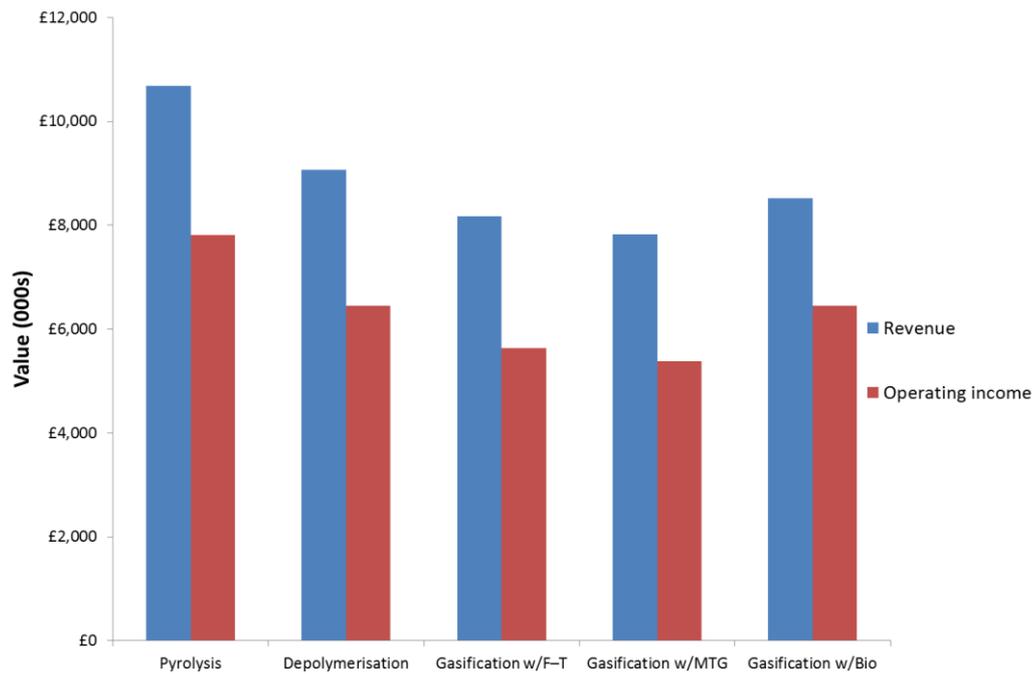
## 5.2 Base case model results

This section presents the results gathered from applying the above base case parameters to the financial model.

### 5.2.1 Revenue and operating income

**Figure 14** shows the annual revenue and operating income for the base case for each option; the pyrolysis option has a much higher revenue and therefore operating income (as the operating costs for each option are very similar). The numbers underlying the figure are shown in **Table 36**.

**Figure 14** Annual revenue and operating income for the base case for each option

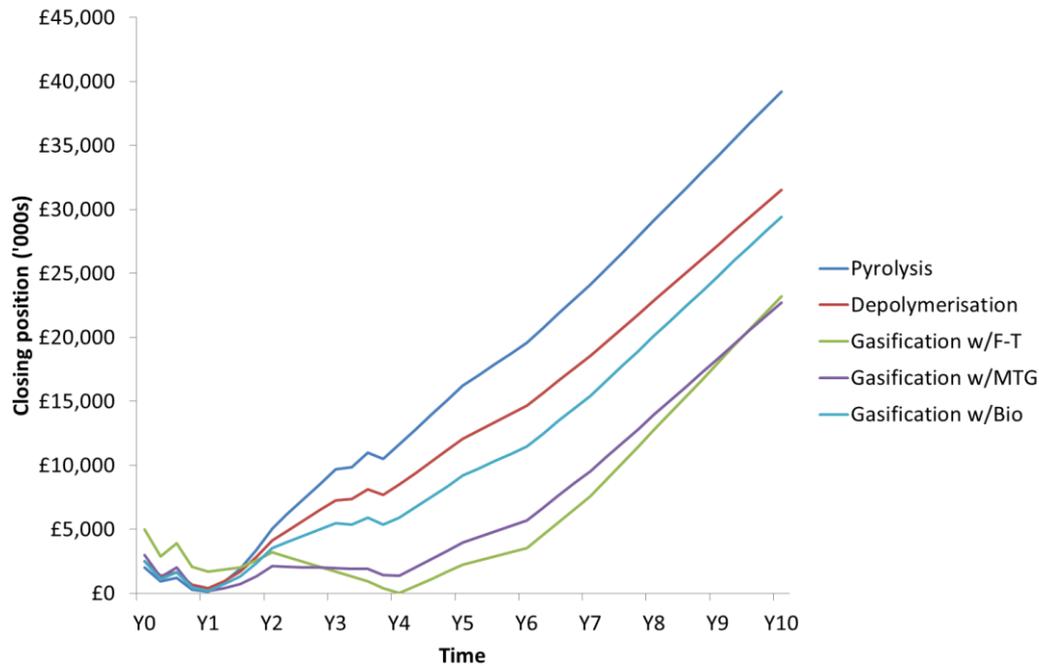


**Table 36** Income summary

	Pyrolysis	Catalytic depolymerisation	Gasification w/F–T	Gasification w/MTG	Gasification w/Bio
<b>Process data</b>					
Total plastic input (tpa)	26,880	26,880	26,880	26,880	26,880
Total saleable plant output (tpa)	16,000	18,000	10,000	9,000	16,000
Overall process yield	60%	67%	37%	33%	60%
On-site electricity generation (MWh/y)	0	1,605	5,303	5,875	469
<b>Yearly revenue</b>					
Gate fee revenue	£2,150,000	£2,150,000	£2,150,000	£2,150,000	£2,150,000
Product revenue	£8,908,000	£10,377,000	£5,666,000	£5,164,000	£7,578,000
Electricity sales revenue	£0	£605,000	£1,610,000	£1,775,000	£185,000
Total net revenue	£11,058,000	£13,132,000	£9,426,000	£9,089,000	£9,913,000
<b>Yearly costs</b>					
Feed material costs	£0	£3,707,000	£898,000	£898,000	£1,070,000
Operating costs	£1,462,000	£1,075,000	£591,000	£650,000	£546,000
Fixed costs	£1,410,000	£1,545,000	£1,937,000	£1,800,000	£1,519,000
Waste disposal costs	£372,000	£360,000	£363,000	£362,000	£332,000
Total costs	£2,439,000	£6,282,000	£3,636,000	£3,484,000	£3,467,000
<b>Operating income</b>	<b>£7,814,000</b>	<b>£6,445,000</b>	<b>£5,637,000</b>	<b>£5,379,000</b>	<b>£6,446,000</b>

### 5.2.2 Cash flow

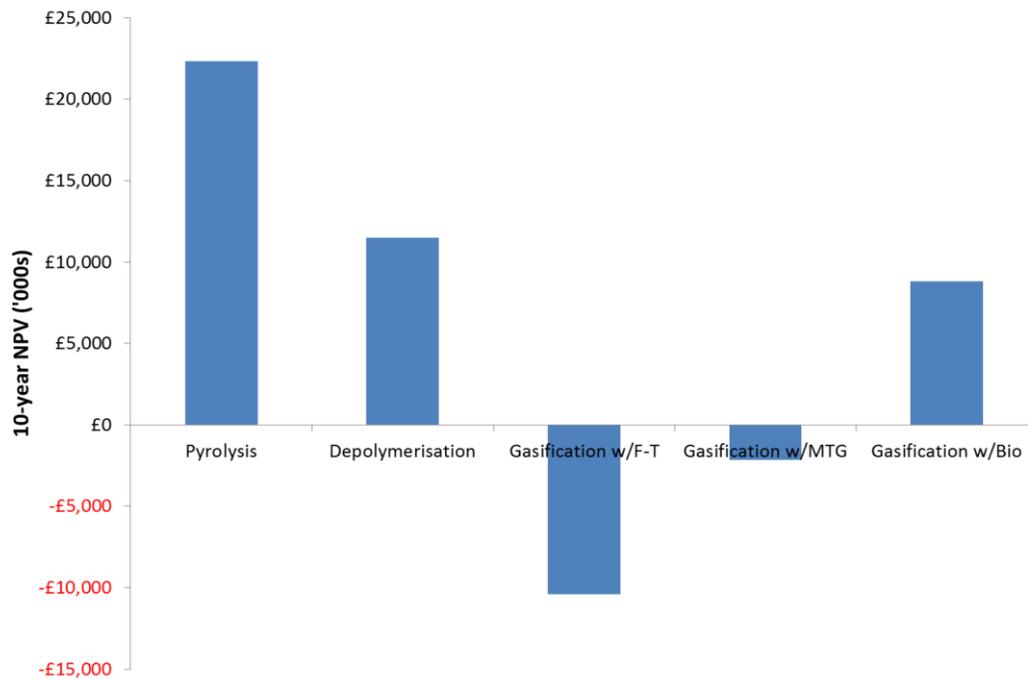
**Figure 15** shows the projected cash flows for the base case models. The working capital was adjusted for each option to ensure that it never has a negative closing position; this can be seen in **Table 37**. It can be seen that, despite having significantly more working capital than all the other options, the gasification with F–T process makes losses period on period until year 4 – at this point the majority of the loans have been paid off and the process begins to make a profit. However, the other options all make profits as soon as operations begin, even while the loans are still being paid off. The option with the highest cash flow, by a significant amount, is pyrolysis, with a 10-year closing position of nearly £40M. Depolymerisation and gasification with biological treatment are on similar levels (£30M), whereas the other two gasification options are lower at around £23M.

**Figure 15** Projected base cash flows for each option

**Table 37** Working capital required for each option (funded from equity)

Option	Working capital
Pyrolysis	£2,000,000
Depolymerisation	£2,500,000
Gasification w/F-T	£5,000,000
Gasification w/MTG	£3,000,000
Gasification w/Bio	£2,500,000

### 5.2.3 Net present value

**Figure 16** shows the 10-year NPV for the base case of each option. As with the previous charts, the NPV shows that the pyrolysis option is significantly better than all the other processes, with a 10-year NPV of £22M. Depolymerisation and gasification with biological treatment have similar NPVs (£11.5M and £9M, respectively), whereas the other two gasification options both have negative NPVs (-£10M for F-T and -£2M for MTG).

**Figure 16** 10-year NPV (base case) for each option

### 5.3 Model sensitivities

As well as assessing the performance of the base case models, it is important to study the sensitivity of each option to changes in the major assumptions, in case small changes in the market tip a financially viable project over to infeasibility. Alternatively, the models can be used to identify minor changes that can be made to a loss-making option to make it attractive. The following sections present the results from varying several key assumptions in each model.

#### 5.3.1 Feed buying price/gate fee

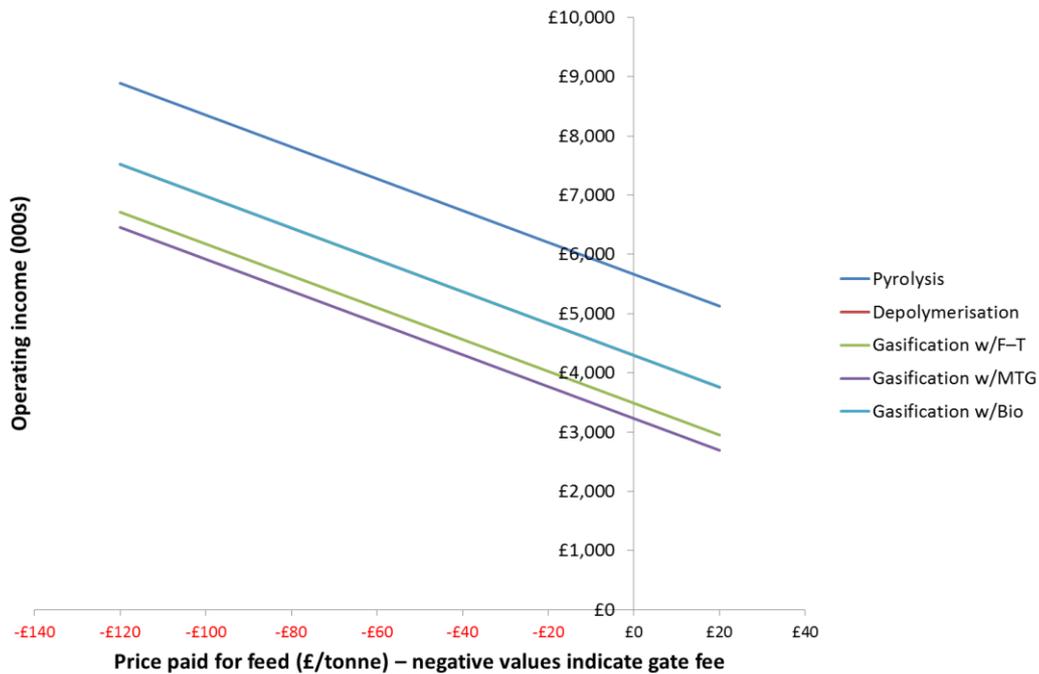
An important sensitivity is the price paid (or gate fee charged) for the feed material, i.e. plastic. In the base case, a gate fee of £80 per tonne is charged, the same rate as landfill disposal costs. However, the plastic stream required for these plants may become more valuable for the manufacture of SRF/RDF or use in EfW plants than residual waste that is typically landfilled. In this event, it may be the case that a lower gate fee needs to be charged to attract the material: in the extreme case it may even need to be purchased. Recent reports<sup>18</sup> suggest that if the plastic was sent to EfW plants, it would attract a gate fee of approximately £60 per tonne.

**Figure 17** and **Figure 18** show the sensitivity of operating income and 10-year NPV to changes in the feed buying price. The values used to generate the graphs are shown in **Table 38** and **Table 39**. It can be seen that each option displays a similar negative linear dependence on feed price, i.e. increasing feed price (or decreasing gate fee) decreases operating income and 10-year NPV. Each option's operating income is large enough such that even a £140 per tonne swing in feed price makes no difference to the qualitative outcome. For the NPV, the pyrolysis and depolymerisation options show similar behaviour when a gate fee is applied, with the large swing in feed prices not affecting the qualitative outcome;

however, once a purchase price rather than gate fee is chosen, the NPV of the depolymerisation option becomes negative. On the other hand, the NPV of the gasification with F-T option remains negative for all of the feed prices tested, and the NPVs of the gasification options with methanol to gasoline and biological treatment change from positive to negative as the gate fee is decreased/purchase price increased.

In addition to this, break-even points were found for each option, based on operating income and 10-year NPV (i.e. the feed prices at which operating income and NPV are zero). This information is shown in **Table 40**; based on operating income, these figures indicate that there is the potential for all options to purchase feed for upwards of £100 per tonne and remain profitable. The figures for 10-year NPV are significantly lower, as they include the capex required for the project. However, the values show that the pyrolysis and catalytic depolymerisation options would be able to purchase the infeed material and still be profitable over 10 years.

**Figure 17** Sensitivity of operating income to changing feed buying price. Note that depolymerisation is hidden behind gasification with biological processing as they have very similar values



**Figure 18** Sensitivity of 10-year NPV to changing feed buying price



**Table 38** Operating income values at given feed prices (all income values in 000s)

Option	-£120	-£80	-£60	£0	£20
Pyrolysis	£8,900	£7,800	£7,300	£5,700	£5,100
Depolymerisation	£7,500	£6,400	£5,900	£4,300	£3,800
Gasification w/F-T	£6,700	£5,600	£5,100	£3,500	£3,000
Gasification w/MTG	£6,500	£5,400	£4,800	£3,200	£2,700
Gasification w/Bio	£7,500	£6,400	£5,900	£4,300	£3,800

**Table 39** 10-year NPVs at given feed prices (all NPVs in 000s)

Option	-£120	-£80	-£60	£0	£20
Pyrolysis	£27,800	£22,300	£19,600	£11,400	£8,700
Depolymerisation	£17,000	£11,500	£8,800	£600	-£2,100
Gasification w/F-T	-£4,900	-£10,400	-£13,100	-£21,300	-£24,000
Gasification w/MTG	£3,300	-£2,200	-£4,900	-£13,100	-£15,800
Gasification w/Bio	£14,300	£8,800	£6,100	-£2,100	-£4,800

**Table 40** Break-even feed prices for each option (based on operating income and 10-year NPV)

Option	Break-even feed price	
	Operating income	10-Year NPV
Pyrolysis	£210	£85
Depolymerisation	£160	£5
Gasification w/F-T	£130	-£155
Gasification w/MTG	£120	-£95
Gasification w/Bio	£160	-£15

Feed prices based on operating income are for one year only. Feed prices based on 10-year NPV assume constant feed price for 10 years.

### 5.3.2 Product selling price

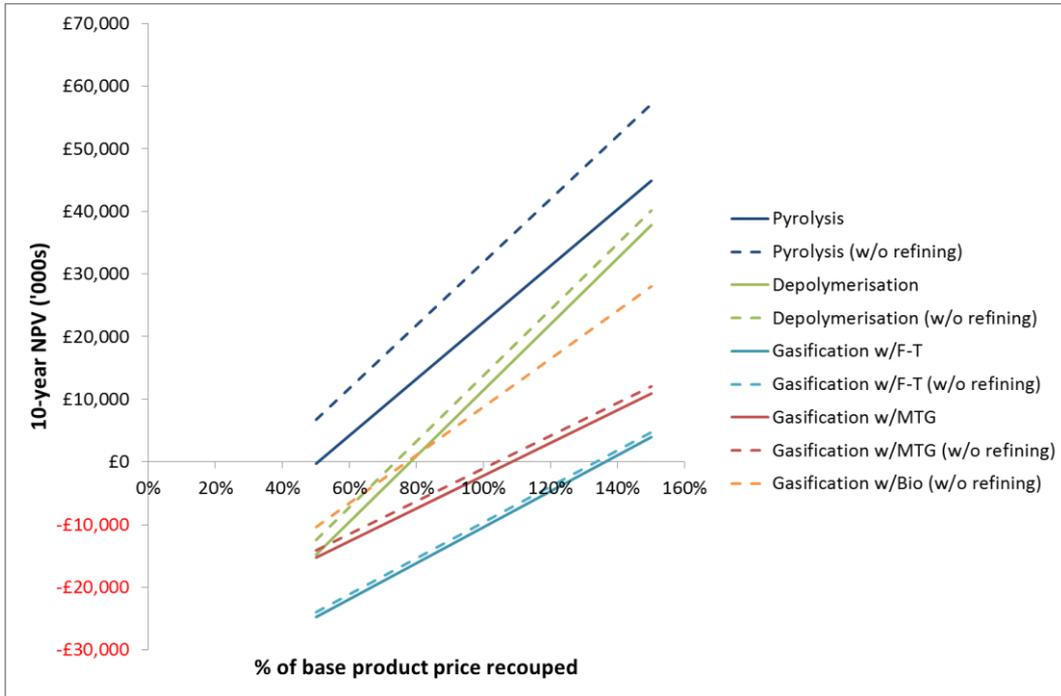
Similar to feed price, the product selling price is a key determinant in the profitability of each option. Not only does the volatility of the fuel market mean that this revenue may change dramatically during the lifetime of the plant, but also the quality of the product itself may influence the selling price; a product that can be immediately blended with fuel will attract a higher price than one which requires further refining.

**Figure 19** and **Figure 20** show the sensitivity of operating income and 10-year NPV to changes in the product selling price, for both a crude product requiring further refining (solid lines) and one which requires no refining (dashed lines). Ethanol will always be produced at a high purity, so refining charges are not applied. Note that, as different options produce different fuels (diesel, gasoline and ethanol), the changes have been expressed as a percentage of the base case price to allow easier comparison.

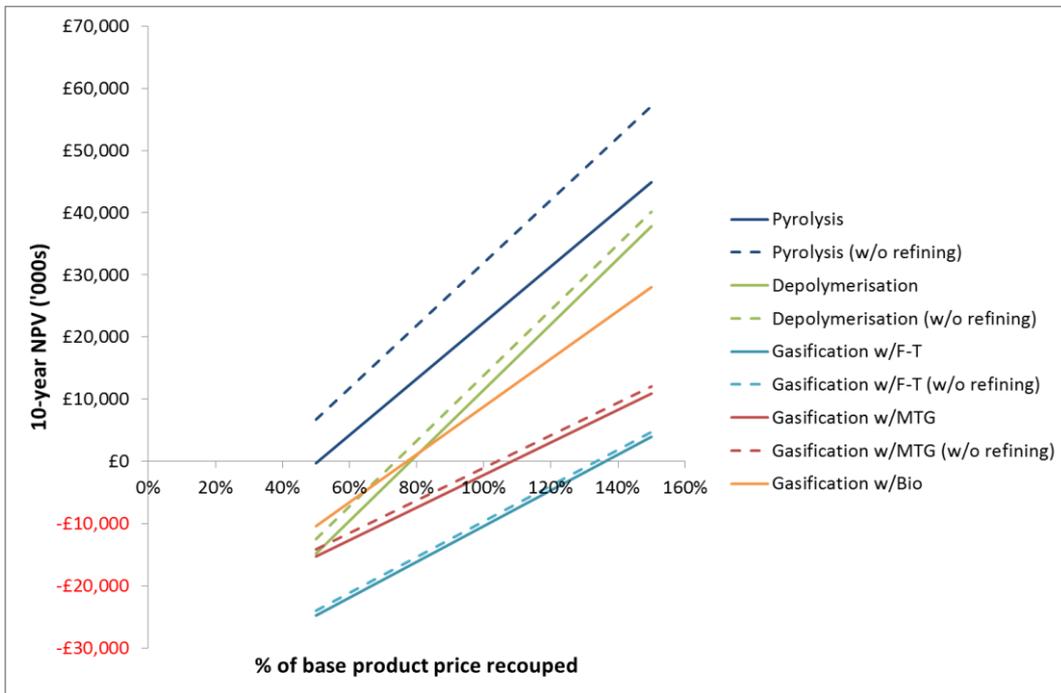
As with the feed price, each option shows the same linear response to changing product price, although in a positive direction (increasing product price increases income and NPV). As would be expected, adding the refining cost causes a reduction of up to £500,000 in yearly revenue. However, in none of the cases is this significant enough to cause a yearly loss. For NPV, increasing the product selling price by 50% is sufficient to make each option profitable over 10 years, while halving the price results in a negative NPV for each option (except for pyrolysis). In each case, increasing the feed price causes the depolymerisation option to accelerate rapidly away from gasification with biological processing, in terms of profitability, because of the large volumes produced by this option.

**Table 41** shows the break-even product prices for each option (again as a percentage of base price), based on operating income and NPV being zero; this shows that all options could cope with a massive reduction in selling price and still have a positive operating income, even with refining costs included. The gasification options with F-T and methanol to gasoline are even in the position whereby the product can be sold for a small negative price; this is because of the large income from the sales of heat and power by-products. In contrast, the 10-year NPV break-even points show that these two options would need to attract a higher selling price than the base case to be profitable over 10 years. The other three options can all withstand significantly lower selling prices before showing a negative NPV.

**Figure 19** Sensitivity of operating income to changing product selling price (dashed lines include increased income owing to no refining costs)



**Figure 20** Sensitivity of 10-year NPV to changing product selling price (dashed lines include increased income owing to no refining costs)



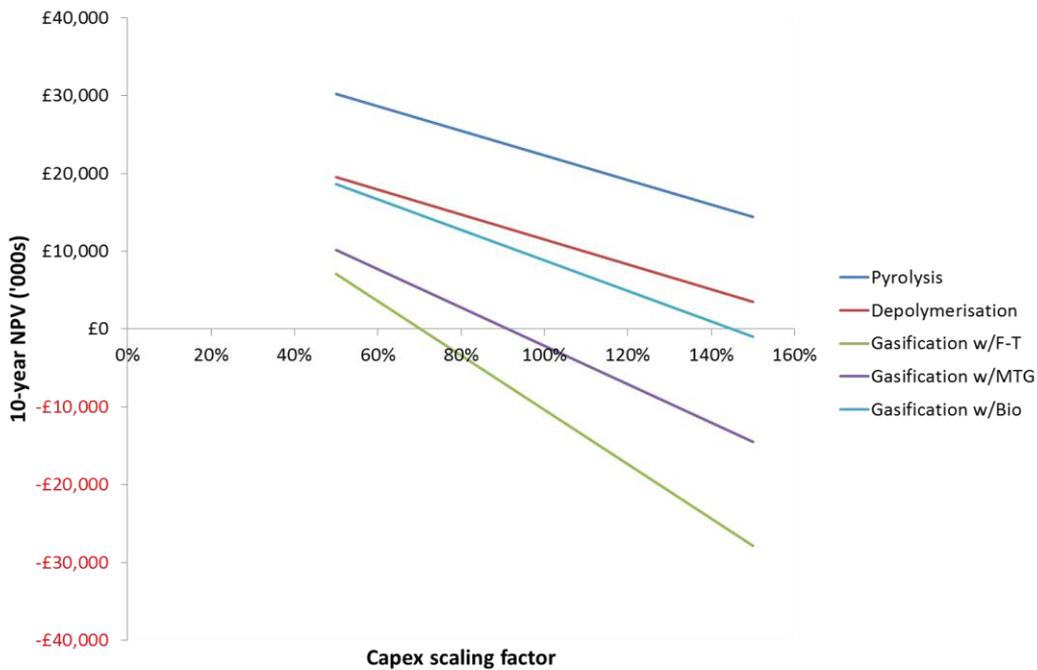
**Table 41** Break-even product prices for each option

Option	Base price per tonne	Break-even price (per cent of base price) (price) Operating income	10-year NPV
Pyrolysis	£564	12% (£70)	51% (£283)
Pyrolysis (no refining)	£564	2% (£15)	37% (£205)
Depolymerisation	£564	38% (£215)	78% (£440)
Depolymerisation (no refining)	£564	33% (£190)	74% (£415)
Gasification w/F-T	£564	0% (£0)	136% (£770)
Gasification w/F-T (no refining)	£564	-2% (-£10)	133% (£750)
Gasification w/MTG	£571	-4% (-£25)	108% (£620)
Gasification w/MTG (no refining)	£571	-9% (-£50)	104% (£595)
Gasification w/Bio	£483	12% (£70)	77% (£370)

### 5.3.3 Capex cost

Changes in the total capital cost can have a large impact on the financial viability of a project. **Figure 21** shows the sensitivity of the 10-year NPV calculations to changes in the capex cost. As with the product selling price, these changes are expressed as percentages of the base cost, as each option has a different capex cost. A negative linear trend is seen again, with increasing capex costs causing a decrease in the NPV. All three gasification options are affected qualitatively by this variation, moving from positive NPV at 50% capex to negative NPV at 150% capex. These negative figures indicate that, over the first 10 years, the proposed facilities would make a financial loss. The pyrolysis option is particularly noticeable in that it still shows a very high NPV (£14M) even when capex has been increased by 50%.

**Figure 21** Sensitivity of 10-year NPV to changing capex cost



**Table 42** 10-year NPVs at given capex scalings (all capex values and NPVs in 000s)

Option	Base capex	50%	75%	100%	125%	150%
Pyrolysis	£8,600	£30,200	£26,300	£22,300	£18,400	£14,400
Depolymerisation	£8,600	£19,500	£15,500	£11,500	£7,500	£3,500
Gasification w/F-T	£19,900	£7,100	−£1,700	−£10,400	−£19,100	−£27,900
Gasification w/MTG	£15,300	£10,200	£4,000	−£2,200	−£8,300	−£14,500
Gasification w/Bio	£12,200	£18,600	£13,700	£8,800	£3,900	−£1,000

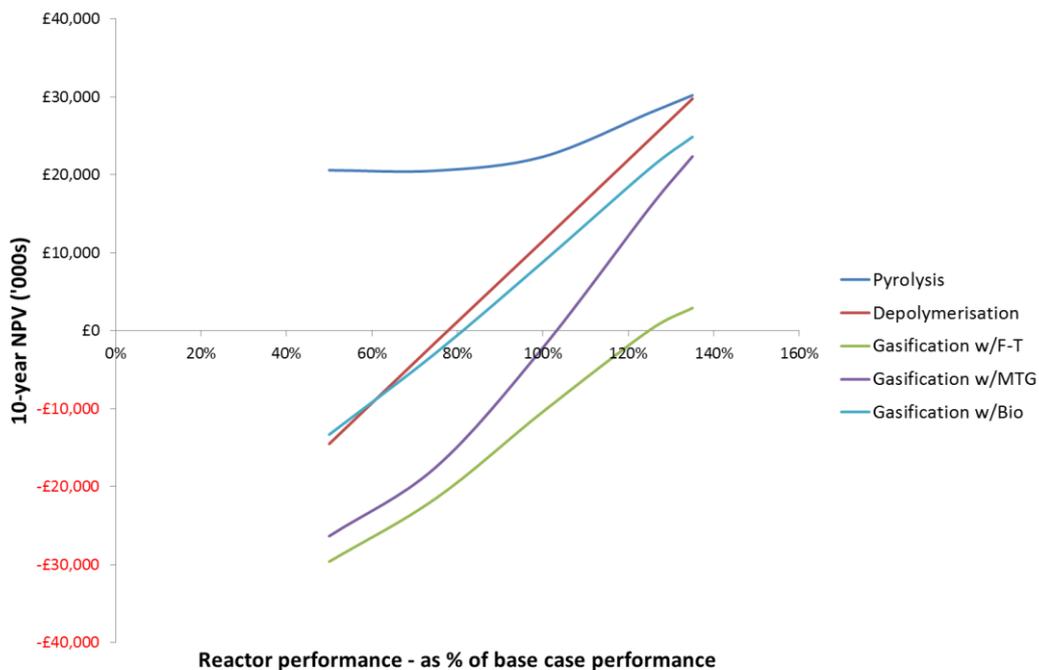
Capex has a major bearing on the project economics. In this assessment of capex, reliance has been placed on published capex data on the various processes and these have been scaled to the estimated availability of feedstock. The above data need to be treated with some caution as there is uncertainty as to what equipment is specifically included or excluded from the various technology suppliers. There is also likely to be a requirement for additional project capex to mitigate other factors, such as risk and integration with the existing refinery complex.

### 5.3.4 Process performance

As the technology/feedstock combinations used in each option are novel, it has not been possible to find independently verified data on process performance; instead the conversion figures are based on a combination of small-scale academic research, manufacturers’ literature and theoretical modelling. Therefore, there is still some uncertainty over the ‘real-world’ performance of each process. It is useful to study the impact of varying the performance of the process (chiefly the reactor yield) on the economic viability of each process.

**Figure 22** shows the sensitivity of operating income to changes in reactor performance. In the absence of the detailed modelling required for fully determining reactor outputs, ‘performance’ is defined as the amount of main product created by the reactor. As the performance is varied, the increase or reduction in main product is a result of changing the other outputs to balance the reactor mass balance. Note that for the gasification options, which have more than one reaction stage, all reactors are varied at once, with the same increase or decrease in performance. Note also that conversion is capped at 100%, so some reactors with high product creation in the base case cannot reach 135% performance. This can be seen in the lines that flatten out slightly. Yet again, there is a positive linear relationship between operating income and reactor performance (better performance gives greater income). The depolymerisation and gasification with bioprocessing and methanol to gasoline options show the most dramatic increases, almost overtaking the pyrolysis option at the highest performance increase.

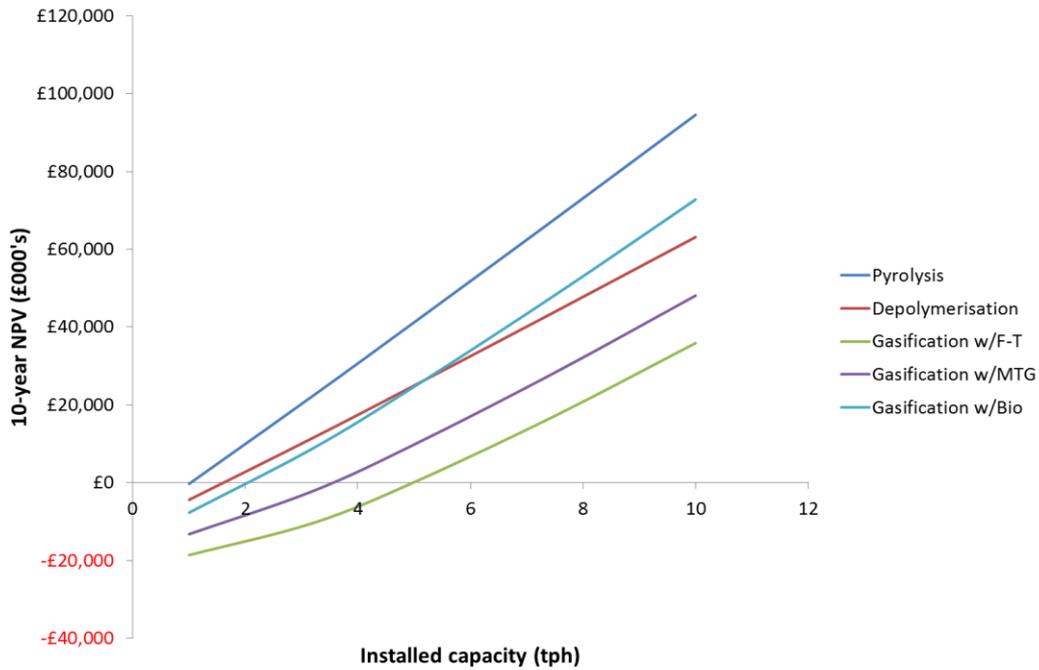
**Figure 22** Sensitivity of operating income to changing reactor performance



### 5.3.5 Installed capacity

The literature survey revealed that gasification processes are often carried out at a large scale, whereas pyrolysis and depolymerisation processes are often small scale. Processes designed for larger throughputs are often not cost-effective at a smaller scale. Therefore, the installed capacity of each process was varied to see the effect this would have on the 10-year NPV. Note that, because pyrolysis and depolymerisation units have a maximum size, several units must be run in parallel at larger throughputs. In contrast, the reactors needed for the gasification processes can be scaled up continuously. The results are shown in **Figure 23** and **Table 43**; it can be seen that increasing the installed capacity has a positive effect on each process’s NPV, particularly on the gasification with biological treatment option, which overtakes the catalytic depolymerisation option at higher throughput rates.

**Figure 23** Sensitivity of 10-year NPV to changing installed capacity



**Table 43** 10-year NPVs at given throughput rates (all NPVs in 000s)

Option	Throughput rate (tonnes per hour)				
	1	3.2	5	7.5	10
Pyrolysis	-£300	£22,300	£41,200	£67,800	£94,500
Depolymerisation	-£4,400	£11,500	£25,000	£43,900	£63,100
Gasification w/F-T	-£18,600	-£10,400	£100	£17,200	£35,900
Gasification w/MTG	-£13,200	-£2,200	£9,800	£28,300	£48,100
Gasification w/Bio	-£7,700	£8,800	£24,700	£48,200	£72,800

### 5.4 Summary

The results from the modelling show that there are three financially feasible options (i.e. ones that have a positive 10-year NPV) for the conversion of plastics to oil products in Scotland: pyrolysis, catalytic depolymerisation and gasification with biological conversion to ethanol.

This is the case even if gate fees for feed material fall to £60 per tonne, this being the estimated value of this material to EfW plants. Pyrolysis and catalytic depolymerisation give a positive NPV even with a gate fee of zero.

The capital investment required for all of these processes is significant, and each process requires a sizeable supply of feedstock to justify this investment. The break-even scale for these processes is somewhere between 1.5 and 2 tonnes per hour (12,000 and 16,000tpa); this means that, under the market and technology conditions considered by this report, single pyrolysis or catalytic

depolymerisation units (typically with a maximum throughput of 10,000tpa) would not be economically viable, and instead multiple units would need to be installed at a single location. The results are based on simplified capex estimations and could be less attractive when additional factors, such as risk mitigation or project integration, are taken into account.

## 6 Environmental performance

The following section covering environmental performance is not intended to represent a full carbon account or life cycle analysis for specific technologies or technology suppliers. The methodology employed gives an indication of environmental performance; therefore any projects being developed or trialled further should consider the environmental impacts in more detail once verified environmental performance indicators are available from technology suppliers. These indicators will in most cases require a documented NDA with the technology supplier; no NDAs were entered into as part of this project, hence the environmental impact indicators documented here are intended as an indication only.

An initial environmental assessment for each of the process options considered in this report was carried out in order to review the environmental performance against the current baseline disposal methods of landfill and incineration. The goal of the assessment was to quantify the environmental benefits or burdens likely to arise from commercialising any of the alternative thermal treatment technologies.

The process options considered were:

- landfill (base case)
- incineration (an alternative base case)
- pyrolysis
- catalytic depolymerisation
- gasification with F-T
- gasification with methanol conversion to gasoline
- gasification with biological conversion of syngas to ethanol.

The assessment highlighted the carbon footprint emissions associated with each technology option and the baseline cases. Full workings are detailed in Appendix B.

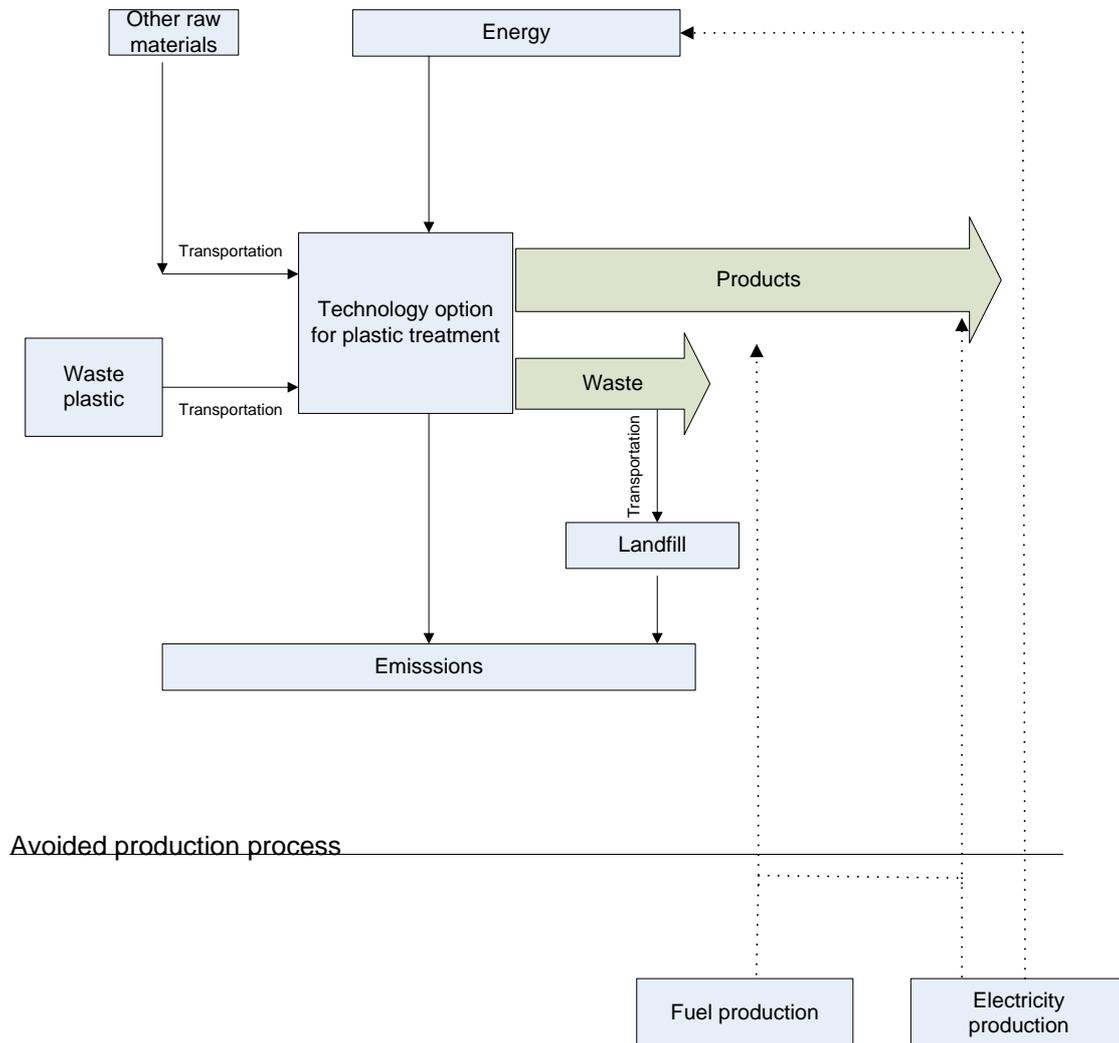
### 6.1 Functional units and system boundary

The functional unit applied as a basis for a like-for-like comparison among the various plastic-to-oils conversion technologies was 1,000kg of wet mixed plastic waste. This feed comprises 77% mixed plastic materials, 10% moisture and 13% contaminants, the contaminants being mostly cellulosic materials such as paper and/or card.

A 'gate-to-grave' or 'gate-to-gate' assessment rather than a full life cycle assessment was considered in this study to allow a consistent comparison of each plastic-to-oils conversion technology.

For each technology, the boundaries of the study were limited to the point at which the waste-plastic-rich material leaves the MRF as a waste and to the point at which it is disposed or reused and the emissions associated with these processes. Where reuse occurs and other product manufacture is displaced, the avoided greenhouse gas (GHG) emissions associated with the displacement are included.

The boundary limits are shown below in **Figure 24**.

**Figure 24** Generic process diagram showing boundary limits

Excluded from this study are GHG emissions associated with the production or maintenance of vehicles used for transport, machineries and buildings used for the process. Emissions associated with human labour, office energy consumptions and small amounts of miscellaneous materials used were all excluded. Detailed calculations can be found in Appendix B.

## 6.2 Allocation

In order to provide a like-for-like comparison between the technologies, the functional unit is based on a fixed material input feeding each technology option. This means that all the emissions associated with transport, disposal and savings from reuse can be allocated to the input stream and do not need to be allocated across a number of product streams. Emissions associated with production and the emissions avoided by displacement are also allocated to the input stream.

### 6.3 Data sources

Data were collected from a number of sources including:

- Carbon Trust Footprint Expert database<sup>19</sup> for the calculation of emissions associated with the transportation of feed materials, products and the on-site processes; and
- USA Environmental Protection Agency<sup>20</sup> (EPA) for the emissions associated with petroleum, diesel and fuel production.

It was assumed for all the thermal treatment options that 70% of the feed materials would be sourced from MRFs along the M8 corridor that links Glasgow and Edinburgh, that is within a 100km radius. The remaining 30% would be sourced nationally, travelling an average distance of 350km to the site. MRF materials transported to landfill, as well as any waste generated on site and transported to landfill, were assumed to travel a distance of 25km.

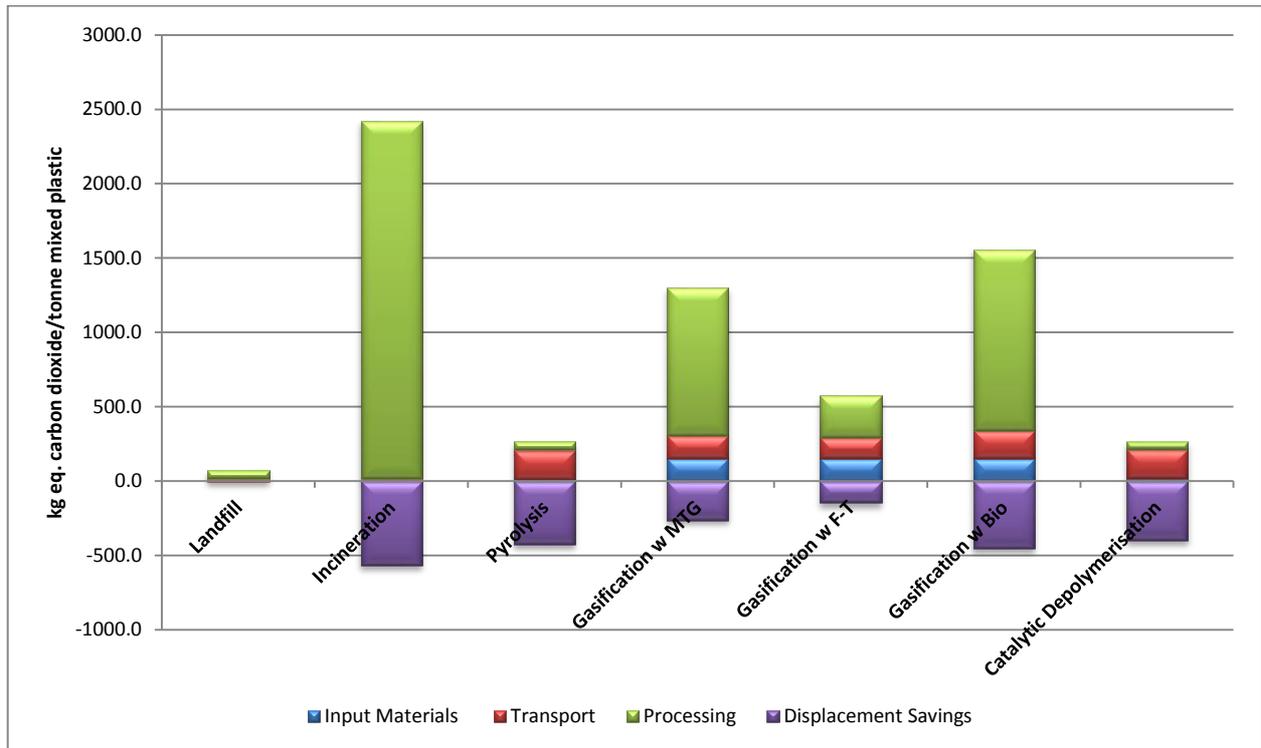
Where applicable, it was also assumed that the required heat and power for the process would be provided by the process itself, by incineration off-gases or product oil and by steam generation through heat recovery. Any excess energy generated would be exported to the national grid.

### 6.4 Results

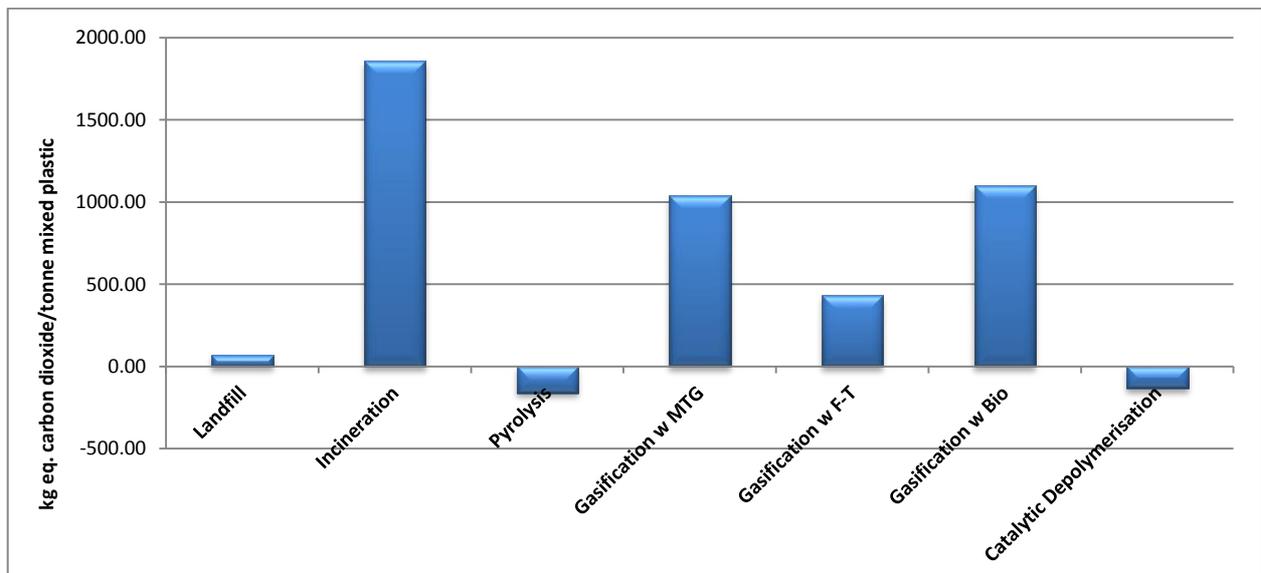
The GHG emissions associated with each technology are shown in **Figure 25** and compared with the two baseline cases, i.e. disposal to landfill and incineration. This chart also includes the emission savings that can be achieved by product displacement.

**Figure 26** shows these data as net emissions, which are calculated by subtracting the savings from product displacement from the emissions associated with each new technology.

**Figure 25** Carbon impact comparison for waste mixed plastic disposal options (including displacement savings)



**Figure 26** Net carbon impact comparison for waste mixed plastic disposal options



Taking pyrolysis as an example, the emissions associated with treatment of 1 tonne of mixed plastic are as follows:

- Emissions associated with manufacture of other raw materials (excluding the waste plastic stream) are 13.0kgCO<sub>2</sub>(e). For the case of pyrolysis these are owing to hydrogen that is consumed within the process.
- Site emissions from incineration of pyrolysis gases, distillation residues and 3% of the diesel product generated are 56kgCO<sub>2</sub>(e).
- Emissions associated with all elements of transport (products and waste) are 197kgCO<sub>2</sub>(e).
- Based on these figures the emissions associated with pyrolysis are 266kgCO<sub>2</sub>(e).
- Displacement savings associated with replacing fossilised diesel production are 426kgCO<sub>2</sub>(e).
- Overall the net emissions for pyrolysis are -160kgCO<sub>2</sub>(e).

A summary of the emissions related to each plastic-to-oil conversion technology and the savings achieved by displacement are shown below in Table 44.

**Table 44** GHG emissions and displacement for each technology

	<b>GHG emissions (kgCO<sub>2</sub>(e) per tonne of mixed plastic)</b>				<b>Net emissions</b>
	<b>Input materials</b>	<b>Transport</b>	<b>Processing</b>	<b>Displacement savings</b>	
Landfill	0.0	15.1	55.7	0.0	<b>70.8</b>
Incineration	0.0	15.1	2408.0	-565.5	<b>1857.6</b>
Pyrolysis	13.0	197.2	55.6	-425.5	<b>-159.7</b>
Gasification w/MTG	153.7	153.7	995.5	-261.7	<b>1041.2</b>
Gasification w/F-T	153.7	139.3	285.2	-147.1	<b>431.1</b>
Gasification w/Bio	153.7	187.7	1217.1	-454.9	<b>1103.6</b>
Catalytic depolymerisation	16.0	197.5	51.0	-397.4	<b>-132.8</b>

From the data, it is evident that the baseline case of landfilling generates minimal GHG emissions. Both pyrolysis and catalytic depolymerisation result in a small net reduction in emissions, as the savings from displacement of the oil-based products generated is greater than the emissions associated with the additional processing.

The water-gas shift reaction is responsible for the high levels of CO<sub>2</sub> emissions for the gasification with F-T and gasification with methanol-to-gasoline process options; however, this is a vital process required for the production of hydrogen needed to produce the diesel and gasoline fuels. Likewise, the gasification with biological conversion option produces additional CO<sub>2</sub> as a by-product of the fermentation process.

For each gasification option a net increase in GHG emissions would be observed over landfill. However, increases associated with gasification are lower than the increases that would be associated with incineration, if an alternative to landfill had to be found.

## 7 Licensing and permitting

### 7.1 Environmental permitting

In Scotland, potentially polluting processes are controlled under the Pollution Prevention and Control (Scotland) Regulations 2000.<sup>21</sup> These are essentially the same as the regulations used in England and Wales prior to the commencement of the Environmental Permitting Regulations.

These regulations divide potentially polluting processes into two categories:

- 'Part A' activities are considered as the most potentially polluting and are subject to scrutiny in terms of releases into the air, into water and onto land. This integrated approach ensures that pollution is not simply transferred from one environmental medium to another. Part A activities are controlled and authorised by SEPA.
- 'Part B' activities are considered as having a lower pollution potential, and are subject to scrutiny in terms of releases into the air only. Part B activities are also controlled and permitted by SEPA.

The regulatory requirements are set by SEPA on a site-by-site and process-by-process basis. Although the regulations and SEPA guidance provide common rules, permits are specific to a site and a process. In accordance with the regulations, processes for the conversion of plastic into oil products may be deemed as falling under one or more of the following activities listed in Schedule 1 of the regulations:

#### **Chapter 1 Energy Industries**

##### **Section 1.1 Combustion(Note)**

###### *PART A*

*(b) Burning any of the following fuels in an appliance with a net rated thermal input of three megawatts or more otherwise than as an activity which is related to a Part B activity:–*

- (i) waste oil;*
- (ii) recovered oil;*
- (iii) any fuel manufactured from any other waste.*

###### *PART B*

*(c) Burning waste oil or recovered oil as a fuel in an appliance with a net rated thermal input of less than 3 megawatts.*

*(d) Burning solid fuel which has been manufactured from waste by a process involving the application of heat in an appliance with a net rated thermal input of less than 3 megawatts.*

*(e) Burning fuel manufactured from waste, other than waste oil or recovered oil or such fuel as is mentioned in paragraph (d) in any appliance with a net rated thermal input of less than 3 megawatts but more than 0.4 megawatts or which is used together with other appliances, which each have a net rated thermal input of less than 3 megawatts, where the aggregate net rated thermal input of all the appliances is at least 0.4 megawatts.*

#### **Chapter 4 The Chemical Industry**

##### **Section 4.1 Organic Chemicals**

###### *PART A*

*(a) Producing or manufacturing by chemical means organic chemicals including–*

- (i) hydrocarbons, linear or cyclic, saturated or unsaturated, aliphatic or aromatic;*

## Chapter 5 Waste Management

### Section 5.1 Incineration and co-incineration of waste

#### PART A

*(c) The incineration of non-hazardous waste in an incineration plant with a capacity of 1 tonne or more per hour.*

*(e) Unless carried out as part of any other Part A activity, the incineration of non-hazardous waste in a co-incineration plant.*

*(g) Unless carried out as part of any other Part A activity, the incineration of non-hazardous waste in an excluded plant with a capacity of one tonne or more per hour.*

*Note: If the thermal energy output of the process (or an aggregate of processes) exceeds 50MW, it will be necessary to consider whether the Large Combustion Plants Directive applies.*

The prime purpose of the installation is determined by SEPA, after having assessed all of the circumstances and likely emissions into the environment that may arise from the process. Whichever process is selected as being the main activity being carried out, the activity will require a permit from SEPA prior to commencement of operations. In terms of the permitting regime and the control of emissions from the installation, there will be little difference between an Integrated Pollution Control (IPC) Authorisation for manufacturing hydrocarbons and one for (co-)incineration. However, planning implications and adverse publicity may arise if the installation is deemed to be an incineration or co-incineration process. Obtaining a permit as a chemical process will not lead to less stringent requirements from the regulator, but will assist the public perception of the installation.

When an IPC Authorisation is received based on Chapter 1 or 4 of the IPC regulations, it is necessary to apply for a waste management licence to allow receipt of waste plastic, unless the installation is located on a site for which a waste management licence already exists. A waste management licence may also be required for management of the 'products' from the process if they are deemed to be waste.

If the process produces a plastic-derived crude oil that requires further refining before it is considered to be a product meeting the 'end-of-waste' criteria, the site receiving the plastic-derived crude oil will need to have a waste management licence in place prior to receipt.

It should be noted that the Scottish Government and SEPA have recently consulted on an Integrated Framework of Environmental Regulation<sup>22</sup> which may make the permitting of sites requiring IPC Authorisations and waste management licences simpler in the future.

## 7.2 Waste Incineration Directive

The Waste Incineration Directive (WID)<sup>23</sup> was transposed into Scottish Legislation through the Waste Incineration (Scotland) Regulations<sup>24</sup> and, in practice, through the Pollution Prevention and Control regime. SEPA was also directed by Scottish Ministers (The Pollution Prevention and Control (Waste Incineration Directive) (Scotland) Directions 2003) to ensure that permits included such conditions as it considered necessary to give effect to the provisions of WID.

The Scottish Government's guidance on the Waste Incineration (Scotland) Regulations<sup>25</sup> describes thermal treatment by relating it to the nature of the change that is undergone in the waste. A chemical, non-reversible change (such as cracking or partial oxidation) would qualify as a thermal treatment process for WID purposes; a physical, reversible change (such as drying, distillation), whereby the separated products could be re-assembled to produce the original waste, would not be considered a thermal treatment under WID. **All of the conversion processes considered by this report, including**

**catalytic depolymerisation at comparatively low temperatures, would be considered thermal treatments under WID and the subsidiary regulations.**

WID encompasses two types of activity: incineration, for which the primary purpose of the activity is the destruction of waste, and co-incineration, for which the formation of material products or energy is the primary purpose. In some cases (e.g. the use of wastes as a fuel in a cement kiln), it is comparatively easy to say that the primary purpose of the activity is the production of material products (cement) and that the waste is being used as a fuel. Where the primary purpose of the activity may be producing energy, it is not sufficient to say that energy is being produced. WID requires that, even for incineration activities, energy is recovered as far as practicable. The test is to determine whether energy generation is the **primary** objective, and guidance<sup>26</sup> is available for making this assessment.

In the case of the production of oil products from waste plastics, whereby the product can be used without being labelled as waste, there is a strong argument that it is a co-incineration activity. This view might have to be modified if the yield of product is small and most of the energy content of the waste is not recovered optimally.

When the conclusion for WID purposes is that the operation is an incineration activity, it will normally be permitted under S5.1 of the regulations.

When the conclusion for WID purposes is that the operation is a co-incineration activity, it may be permitted as a S5.1 activity, except that this activity description is caveated by an exclusion for activities described elsewhere in Part A of Schedule 1 (e.g. S1.1 for Combustion and S4.1 for Organic Chemicals).

When an activity falls into one of these non-incineration categories, it will be permitted under that activity description, **but such plants will have the WID co-incineration requirements applied to them.**

When a portion of the products (gas, liquid or solid) are combusted to provide heat for the process, WID requirements would be applied to the emission of the combustion gases into the air, unless the materials being burned pass an end-of-waste test, and they are burned with no greater pollution risk than burning a relevant conventional fuel.

### 7.3 End of waste

The materials produced by any of the technologies considered by this report will have to pass an 'end-of-waste' test before they are allowed to be combusted in equipment that does not meet the requirements of WID.

End-of-waste status is determined by SEPA, using established definitions within existing waste legislation, and with regard for the Waste Framework Directive and relevant case law. Its determination is based on the following considerations, given in the SEPA publication 'Is it Waste?':<sup>27,28</sup>

*(i) What is the non-waste material that it will be substituting for and is it a suitable substitute?*

*In some cases a treated waste may meet specific product specifications (such as a British Standard). Most standards however, relate to performance only and do not take into account potential environmental and human health impacts. In this case they are not suitable as evidence of full recovery on their own. A treated waste may contain contaminants that the material it is proposed to substitute for does not.*

*(ii) Will the material actually be used in the same way as the non-waste material it is being compared with?*

*(iii) Is further processing required before use? If the answer is 'yes', the substance or object may still be waste.*

*(iv) If used in the same way as the comparable non-waste material, can it be used under the same conditions of environmental protection as the non-waste material without any greater danger of harm to human health or the environment?*

*It will only be possible to make this claim if the treated waste has been properly characterised, taking into account the former characteristics and use of the material and any subsequent processing it has been subjected to.*

*(v) Is there certainty that the waste will be used and will it be used in accordance with (ii)?*

*(vi) Is the person accepting this recovered 'waste' being paid to accept it?*

In order to assist this determination, SEPA uses the following methodology, whereby applicants provide information in a series of three steps, with SEPA consultation between each step:

- Step 1: Initial description of the process and identification of a suitable non-waste comparator.
- Step 2: Comparative analysis including statistical sampling, selection of analysis and comparative assessment.
- Step 3: Demonstration that the material can be used under the same conditions as the non-waste comparator, and results in environmental emissions that are no worse than that comparator.

It is worth noting that, in England and Wales, the Environment Agency has issued guidance<sup>29</sup> on waste-derived fuel products applying English case law: the 'OSS end of waste test'. This has three criteria, all of which must be satisfied: (i) the waste has been converted into a distinct and marketable product; (ii) the waste-derived fuel can be used in the same way as ordinary fuel; and (iii) the waste-derived fuel can be stored and used with 'no worse' environmental effects than the fuel it is intended to replace. In terms of liquid fuels arising from the conversion of plastic to oil products, the Environment Agency would apply the end-of-waste test incorporated within the Quality Protocol for Processed Fuel Oil.<sup>30</sup>

Confirmation is required from SEPA that a similar end-of-waste test would be applied to that in England and Wales. In addition, confirmation is required that, if a crude plastic-derived oil and conventional crude oil are co-processed at an oil refinery (e.g. INEOS at Grangemouth), all of the product fuels from the refinery will pass the end-of-waste test, as plastic-derived products will have been subjected to similar processing and be inseparable from those from conventional crude oil. It should be noted that the application by SEPA of a different end-of-waste test from England and Wales could restrict movements of plastic-derived oil products between Scotland and England and Wales.

## 7.4 REACH

REACH (Registration, Evaluation, Authorisation and restriction of CHemicals)<sup>31</sup> is a system in the EU that provides a high level of protection of human health and the environment from the use of chemicals. This requires the manufacturer of a chemical substance to register and evaluate new

substances prior to their manufacture and appearance on the market. Within REACH, there are exemptions for this process, including waste as defined in Directive 2006/12/EC,<sup>32</sup> and crude oil.

If the substances produced by the technologies do not meet 'end-of-waste' criteria determined by SEPA, then they remain waste and REACH does not apply. However, in this instance, they cannot be used in equipment that does not meet WID, so further processing and recovery would be required.

Article 2(7)(d) of REACH allows an exemption from registration for recovered substances, provided that they have already been registered, and information (such as that in a safety data sheet) is available to the establishment undertaking the recovery. This exemption can be used for substances for which there is a 'virgin equivalent', but it is not clear whether oil products from plastic waste will be considered as recovered substances under REACH.

If there is an obligation to register the oil products as substances under REACH, then the full weight of the process comes into play, requiring registration and characterisation of the substance and testing of health and environmental impacts. In terms of the technologies considered in this report, a number of substances produced from pyrolysis and other thermal processing of plastics have already been pre-registered under REACH, with a target for full registration in 2013. This means that other manufacturers have registered their interest in the oil products derived from waste plastics, and it may be possible to share the burden of providing relevant health, safety and environmental data with these other manufacturers, but this will involve sharing of costs as well.

In order to allow sharing of data of registered or pre-registered substances, or utilise the exemption for recovered substances, it must still be demonstrated that the plastic-derived products are the same as those already pre-registered (or registered). As a minimum this will require some form of mass analysis, such as gas chromatography with mass spectroscopy (GC-MS), which will be more appropriate for distilled and clean oil products rather than those which are contaminated with solids, tars and other contaminants.

## 7.5 Zero Waste Plan – 25% cap on energy-from-waste facilities

Annex A of Scotland's Zero Waste Plan<sup>33</sup> confirms that the 25% cap on municipal waste processed through EfW facilities will remain in force until the Government replaces the cap with restrictions on the types of materials that can be processed in EfW facilities.

The objectives of future restrictions would be to:

- Ensure that waste materials that could be reused or recycled are not incinerated;
- Complement the source segregation and landfill ban measures and ensure that waste management in Scotland does not simply move one step up the hierarchy from landfill to incineration; and
- Replace the 25% EfW cap for local-authority-collected municipal waste with an approach that requires equivalent treatment standards for all waste streams and sectors (household, commercial and industrial waste), irrespective of which party collects the waste.

SEPA guidance<sup>34</sup> states that EfW facilities include pyrolysis and gasification, which are key components of the technologies considered by this report. Furthermore, the Waste (Scotland) Regulations 2012 also ban the incineration of source-segregated materials from January 2014.

The future restriction of inputs into EfW plants, to residual wastes remaining after all reasonable efforts have been made to separate out recyclable materials, is not a threat to plastic-to-oil-product processes that are using low-quality plastic films as a feedstock.

However, the inclusion of plastic-to-oil-products processes within the EfW definition may make them less attractive to investors, especially if there is already sufficient 'conventional' EfW capacity in Scotland to reach this cap.

More clarity is required as to whether processes converting plastics to oil products fall within the definition of EfW and will be subject to the EfW cap and/or the ban on 'incineration' of source-segregated materials. It is recommended that such processes are excluded from the EfW definition, subject to suitable criteria regarding yield, energy efficiency, etc.

## 7.6 Summary

Environmental permitting of the plastic-to-oil processes considered in this report is relatively straightforward, but it needs to be borne in mind that SEPA determine whether the process is classified under the heading 'Energy Production', 'Hydrocarbon Production' or 'Waste Management'. The regulatory framework is the same in any case: the process would need to comply with WID regardless, but the last heading may bring adverse publicity for any prospective investor.

The determination of end of waste is also performed by SEPA, and failure to meet this test would result in the plastic-derived oil products being unfit for sale, and the material would need to be disposed of as a waste. There is an existing quality protocol for processed fuel oil, but this is not directly applicable to plastic-derived oil products, nor does it apply in Scotland. Similarly, England and Wales apply an end-of-waste test that is not applicable in Scotland.

If the material passes the end-of-waste test, it falls under regulation by REACH. Although some plastic-derived oil products have been pre-registered by other parties, the costs of joining the consortium to share health and safety data, or generating the data necessary for full registration, need to be borne in mind by a prospective process operator.

## 8 Contamination issues

### 8.1 Feedstock composition

It is important to understand the polymer composition of the feedstock for a process converting plastic into oil products, as the presence of some polymers, such as PVC and PET, can be detrimental to the performance of the process.

The majority of rigid plastics will be suitable for recycling into polymers for re-extrusion and reuse, leaving a residue of the more difficult to recycle plastic films. Pardos Marketing<sup>35</sup> estimated total world plastic film consumption in 2005 (see **Table 45**), giving a first estimate of the probable polymeric composition of the feedstock. These data have been adjusted to include the polymeric composition of multi-layer films (which may contain more than one type of polymer) used for packaging, also by Pardos Marketing.

**Table 45** Estimated world consumption of plastic films, 2005<sup>35</sup>

Component	Quantity (tonnes; 000s)	Percent of total
Polyethylene total	35,591	68.5%
Polypropylene total	7,036	13.5%
PET	2,418	4.7%
Aluminium foil	2,318	4.5%
PVC and PVDC	1,180	2.3%
Ethylene-vinyl acetate	935	1.8%
Paper	818	1.6%
Polystyrene	600	1.2%
Polyamide	593	1.1%
Other polymers	280	0.5%
Cellophane	125	0.2%
Biodegradable films	70	0.1%
<b>Total</b>	<b>51,965</b>	<b>100.0%</b>

From the data given in the report, it is difficult to determine whether this is truly representative of the 'low-grade' plastic film arising from household MRFs, composting facilities and anaerobic digestion facilities, but it suggests that the more problematic polymers such as PVC and PET will be present at no more than 7% of the total polymeric feed (i.e. excluding water and contamination).

A study by WRAP<sup>36</sup> looked in more detail at the composition of plastic film from a number of sources, including three commercial and industrial sources, two post-consumer MRFs and post-consumer residual 'black bag' waste. Although the purpose of the study was to examine the potential for cleaning and recycling these waste streams, the data may be considered as better representing the target feedstock than world film consumption. **Table 46** summarises the composition found by that report.

**Table 46** Composition of residual mixed plastic film from various sources<sup>36</sup>

	UK commercial/industrial #1	UK commercial/industrial #2	UK post-consumer dry MRF	UK black bag waste	Czech commercial/industrial	Czech post-consumer
PET	0.1%	0.1%	0.2%	0.4%	0.0%	0.1%
HDPE	23.0%	31.0%	16.0%	12.0%	12.0%	13.0%
PVC	0.2%	0.1%	0.3%	0.5%	0.0%	0.2%
LDPE	43.7%	36.7%	50.8%	40.2%	54.3%	51.7%
Polypropylene	16.5%	11.6%	17.4%	22.5%	1.3%	13.5%
PS	0.3%	0.1%	0.6%	1.0%	0.1%	0.3%
Moisture	10.0%	12.0%	8.0%	10.0%	20.0%	15.0%
Contamination	6.1%	8.5%	6.8%	13.4%	12.2%	6.1%
<b>TOTAL</b>	<b>100.0%</b>	<b>100.0%</b>	<b>100.0</b>	<b>100.0%</b>	<b>100.0%</b>	<b>100.0%</b>

From the point of view of contamination, film recovered from UK residual black bag waste represents the worst case from the above selection, as it has the highest proportions of PET and PVC. Even so, these are much lower than those suggested by Pardos. The WRAP/Nextek study also includes contamination by organic material such as food, paper, etc. and moisture.

The presence of contamination in 'non-recyclable' plastic by 'unwanted' polymer types and other materials can have an impact on the processes of conversion to oil products. The impact of each of these on the processes is outlined below.

## 8.2 Chlorine/polyvinyl chloride

Chlorine is present in the plastic feedstock as a result of the presence of PVC as a minor component of the feedstock. During the conversion of the plastic to oil products, this will produce the acidic gas hydrogen chloride, which can attack the equipment resulting in premature failure. This can be tolerated by the use of exotic acid-resistant materials at locations where the acid is likely to condense, or by the use of a neutralising agent such as calcium carbonate. The use of a neutralising agent increases the quantity of solid waste produced by the process.

However, it is not necessary to ensure that no PVC enters the process: technology vendors report that levels of PVC of up to 35% wt in the feedstock can be tolerated, although less than 10% is desirable. The analyses above suggest that PVC is unlikely to be a significant problem for any of the technologies considered by this report, as it constitutes 0.5% or less of the target feedstock.

## 8.3 Polyethylene terephthalate

The presence of PET in the feedstock of a pyrolysis or catalytic decomposition process can result in the presence of terephthalic acid and benzoic acid in the oil products. These are weak acids, but again they have the potential to damage the processing equipment, and also result in engine damage where the

resulting oil products are used. The acids can be removed by washing the oil products with an aqueous alkaline solution.

A second consequence of the presence of PET in the feedstock to a pyrolysis unit is that the presence of oxygen tends to result in the formation of other reactive species in the oil products. While this is not as pronounced as when biomass is pyrolysed, the resulting oil products will need to be washed with water before extended storage. This subject is discussed in greater detail below when considering contamination with paper and other biomass.

It is not necessary to ensure that no PET enters the pyrolysis process: technology vendors report that levels of PET of up to 15% wt in the feedstock can be tolerated, although less than 5% is desirable.

The presence of PET in the feedstock to a process involving gasification is not a problem, as the plastic breaks down to form the gases carbon monoxide, carbon dioxide and hydrogen and water (i.e. just the same as any plastic other than PVC).

The analyses above suggest that PET is unlikely to be a significant problem for any of the technologies considered by this report, as it constitutes 0.4% or less of the target feedstock.

## 8.4 Water

The presence of water in the feedstock increases the thermal load, as the water needs to be heated up to the operating temperature of the process. If the feedstock is very wet, there will be problems reaching the operating temperature, and the product liquids and gases will be heavily contaminated with tar.

Some water (up to around 5%) is desirable, as it can partly remedy the overall hydrogen shortage of the process by taking part in the carbon–steam and water–gas shift reactions.

From the analyses above, the target feedstock will have a moisture content of between 8% and 20%, being towards the lower end of the range for MRF sources and towards the higher end for composting and anaerobic digestion sources. It is likely that any process for conversion of these feedstocks to oil products will require a dryer of some sort, to achieve the desired moisture content of 5%.

All of the thermal processes for conversion of plastic to oil products have an excess of low-grade heat available for drying the feedstock, and the plastic itself does not absorb water, so this is not anticipated to be a serious problem. However, the need for a feedstock dryer does add to the capital cost of the process.

## 8.5 Cellulose and biomass

The presence of cellulose (paper) and other biomass and organic material in the feedstock to a pyrolysis process can present significant problems with the quality and stability of the crude oil produced. Experiments with the fast pyrolysis of biomass produce a complex mixture of reactive chemicals. If these are present during the pyrolysis of plastic, they will react with the liquids produced from the plastic portion of the feedstock, and continue to react during storage, producing solids that need to be removed prior to use of the oil products.

However, it is not necessary to ensure that no cellulose or biomass enters the pyrolysis process. Technology manufacturers suggest acceptable contamination levels of 5–15%, although there seems to be no trend whereby one technology type is more robust than another: gasification and catalytic depolymerisation processes quote similar tolerances to pyrolysis.

Given the analyses above, which suggest that the target feedstock may contain cellulosic/organic contamination of between 6 and 13%, it is likely that any process for conversion of plastic to oil products will require a cleaning step to prepare the feedstock for use. In order to test the robustness of the technology to a particular feedstock, it is essential that any trial samples are taken using a statistically balanced technique, ideally across a number of potential sources.

## 8.6 Catalyst residues

The manufacturing of plastics typically involves the use of catalysts at very low concentrations, and these catalysts remain within the product. Conversion of plastics to oil products will release these catalysts, which may remain in the solid residues or be vaporised into the oil products. The metals antimony (used for PET manufacture), titanium (used for polyethylene and polypropylene manufacture) and zirconium (used in polypropylene manufacture) will all accumulate in the solid residues. The presence of antimony may restrict the disposal routes available for these residues, but is unlikely to have any significant impact on the performance of the process or the quality of the oil products.

## 8.7 Animal by-products

The disposal of animal by-products is strictly controlled to prevent the spread of disease amongst livestock. The by-products are ranked into three categories according to their potential for disease, and authorised treatments and disposal processes for each category are listed below in **Table 47**.

**Table 47** Animal by-product categories

	<b>Authorised treatment process</b>
Category 1	Direct incineration; or Rendering followed by direct incineration
Category 2	Direct incineration; or Rendering or other authorised treatment process followed by incineration, landfill, composting or biogas production
Category 3	Incineration; or Rendering followed by incineration or landfill; or Anaerobic digestion; or Alkaline hydrolysis; or Composting

As the regulations stand, plastic contaminated with animal by-products should not be processed to produce oil products. However, there is a provision in the overarching EU legislation for a process to become authorised.

Given the high operating temperature and residence time of gasification and pyrolysis processes, it could be argued that these processes are very similar to incineration, and it may be relatively simple to gain authorisation. The lower operating temperature of catalytic decomposition would make this argument more difficult, but the conditions are still similar to the rendering process, so it should still be possible to argue the case that it is as effective at pathogen destruction. In both cases, questions would still need to be addressed regarding the destruction of any pathogens present in any solid residues and in any undistilled liquid residues. The use of plastics contaminated by animal by-products may also have an impact on the opinion of the environmental regulator in terms of the permitting regime to be applied.

## 8.8 Impact of contamination

The impact of contamination of the levels described above on the yield and quality of the oil products produced by the various processes has not been reported by the technology suppliers. The assumption of this report is that a feedstock with the levels of contamination described in **Table 46** will produce oil products in the yield and quality described in section 4. However, some processes, notably pyrolysis, are reportedly sensitive to contamination, and this may reduce the quality and quantity of the oil products produced.

If this is the case, and less-contaminated feedstock materials are required, then it will be necessary to remove the contamination prior to the thermal processing stage. As the objective is to use otherwise unrecyclable feedstocks, the purchase of higher quality material would not be allowed.

It is usually possible to remove such contaminants prior to the thermal processing stage. However the removal processes will add cost and may reduce yield. For example, equipment for the 'dry' cleaning of 27,000tpa of contaminated plastic film has an estimated capital cost of £250,000. The impact of this additional capex on the profitability of the process can be determined from the sensitivity analyses given in section 5.

Practical testing of one or more of the short-listed technologies would be required to assess their sensitivity to the contaminants found in the most likely feed streams and to estimate how much pre-processing would be required for the thermal treatment part of the process to be viable.

## 8.9 Summary

The technology options considered in this report are tolerant of the contaminants likely to be present in waste plastic, although there are differences among the degrees of tolerance.

Processes involving gasification as a first step, followed by chemical or biological synthesis of oil products, are more robust, as they operate at higher temperatures and break down all of the plastic and other organic materials present into simple gases.

Pyrolysis processes are more susceptible to the presence of oxygen in the feedstock, resulting either from the presence of PET or from the presence of organic (cellulosic) materials. These are known to promote undesirable reactions in the pyrolysis chamber, and the presence of contaminants for these processes should be limited to a maximum of 5% wt in order to produce a product liquid that does not require extensive upgrading before use.

The impact of contamination on catalytic depolymerisation processes is not clearly reported, although it is foreseeable that poisoning of the catalyst from contaminants could occur. The use of catalytic depolymerisation for the processing of biomass suggests that it is more tolerant of organic (cellulosic) contaminants than pyrolysis.

The relative tolerances described above assume that the levels of contamination are consistent: if the quality of the feedstock is variable, in terms of polymer type distribution, water content or contamination, then this reduces the tolerance of all of the processes considered.

However, the target feedstock for this study is relatively highly contaminated, and as such is atypical of materials demonstrated by the technology suppliers. Physical trials with the target feedstock are essential to determine whether any of the technologies is sufficiently robust when presented with typical feedstock and contamination, including the performance of the pretreatment cleaning and drying steps that are likely to be required.

## 9 Barriers to development and levels of interest

### 9.1 Barriers to development

#### 9.1.1 Critical mass

The minimum economic scale of operation of any of the technologies considered in this report is between 12,000 and 16,000tpa, that is approximately half of the arisings in Scotland of low-grade waste plastic film, which is the target feedstock of currently 'unrecyclable' waste plastic.

The sources of low-grade waste plastic film are dispersed across the populated areas of Scotland, but, with no single site producing more than 2,000tpa, there is a need for consolidation of the arisings to make conversion to oil products economically viable. The absence of a single large producer of low-grade waste plastic film increases the commercial risk of any potential investor.

This could be resolved by the formation of a consortium of producers of the waste to form a joint venture to invest in waste-plastic-to-oil-products conversion technology.

#### 9.1.2 Unknown composition

In the majority of cases, the target feedstock – unrecyclable waste plastic – is currently disposed of to landfill. As it is a waste material with no perceived value, its composition has not been fully evaluated. The typical composition used in this report is based upon WRAP ISS-001 Cleaning and Recycling of Mixed Residual Film, which by its definition is not unrecyclable.

The absence of any compositional data for the target feedstock makes the technology manufacturers very cautious, and they are reluctant to offer estimates of performance. They have performance data based on a 'clean' feedstock (e.g. post-industrial waste), but the impact of unknown contaminants means that extrapolation introduces technical risk for any potential investor.

This could be resolved by statistical sampling and analysis of potential feedstocks from a range of sources, and establishing the average and range of compositions that are present in Scotland. This would need to be done at different times of the year, to account for seasonality in composition and contamination.

#### 9.1.3 Unproven technology

Although all of the technologies considered in this report have been around for some time, none has a demonstrated track record of handling low-grade waste plastic film.

These technologies are all confronted with the fact that waste material is an inhomogeneous feedstock, with variations in composition due to location and seasonality. This makes the technology manufacturers cautious, and they concentrate their development efforts on materials which, although wastes, are more consistent in quality, such as dedicated post-industrial sources, or agricultural biowastes. As a result, technical performance can only be demonstrated within a relatively narrow range of feedstocks.

The lack of any performance data for any of the technology options when presented with the target feedstock introduces technical risk for any potential investor.

This could be resolved by performance of a feasibility study that includes the collection of the target feedstock from a number of sites in Scotland and conducts performance trials at the technology manufacturers' pilot or demonstration unit.

#### *9.1.4 Incentives for biomass conversion*

All of the technologies considered in this report could be used for the production of energy or oil products from biomass. In so doing, they would attract various incentives from the UK and Scottish governments, such as ROC, FiT and RTFO. This has the effect that potential investors in green technologies see those feedstocks as being more attractive and also the technology manufacturers recognise that it is more likely that the development of their process to suit these feedstocks will bring rewards in the form of technology sales. This acts as a disincentive to putting time and effort into performance trials with non-biogenic feedstocks, such as low-grade waste plastic films.

This could be resolved by the introduction of incentives to manufacture oil products from waste plastic, perhaps by modification of the RTFO rules to allow inclusion of waste-derived fuels as well as fuels of biogenic origin. Modification of the ROC/FiT rules would be counterproductive to Scotland's Zero Waste Plan, as it would also incentivise waste-to-energy schemes. Such incentives would need to take into account the possible displacement of recyclable plastics (e.g. rigid plastic, clean film, agricultural plastics) into the oil products processes and would therefore undermine the recycling targets for these materials.

#### *9.1.5 Competition for feedstock*

Currently, the target feedstock of low-grade waste plastic film is typically sent for disposal via landfill. Scotland's Zero Waste Plan sets the target of less than 5% of the total waste arisings sent to landfill by 2025. The feedstock has a high calorific value of around 25–30MJ/kg, making it a useful source of energy by combustion.

The RDF produced, by conversion of the feedstock through simple mechanical processes, would find a ready market either on mainland Europe, where exports of RDF into Germany and the Netherlands continues at pace, or in Scotland's own EfW market, where capacity of over 3 million tpa is going through the planning process. The Lafarge cement works at Dunbar is currently not authorised to use RDF, but could enter this market if its supplies of other waste-derived fuels (tyres and recycled liquid fuels) become constrained.

The development of a significant waste-to-energy industry in Scotland could result in long-term contracts for waste being signed by the plant operators. The presence of such competition for feedstock and the availability of a low-risk outlet for a variety of waste streams, may discourage producers of low-grade plastic waste film from investing in as yet unproven technology.

This is partly resolved by the presence of the cap on waste-to-energy plants at 25% of total waste arisings, but development of the plastic-to-oil-products industry in Scotland needs to be accelerated before these plants come on stream.

### 9.1.6 Regulation

There is a number of uncertainties in the regulatory framework that need to be resolved to give confidence to prospective operators of a process to convert waste plastic into oil products.

#### 9.1.6.1 Environmental permitting

Although the process of obtaining an authorisation to operate from SEPA is straightforward, registration of the process as an incineration or co-incineration process may result in adverse public opinion.

Guidance from SEPA is required as to the limits (e.g. on yield, energy consumption, etc.) that would be applied to determine the primary purpose as something other than 'Waste Management'.

#### 9.1.6.2 End of waste

The determination of end of waste is performed by SEPA, and failure to meet this test would result in the plastic-derived oil products being unfit for sale. There is an existing quality protocol for processed fuel oil, but this is not directly applicable to plastic-derived oil products, nor does it apply in Scotland. Similarly, England and Wales apply an end-of-waste test that is not applicable in Scotland.

The development of a quality protocol (or equivalent criteria) for plastic-derived oil products would provide a common benchmark for testing the various technologies and processes, and thus improve confidence that end-of-waste status can be achieved.

Where the process produces a plastic-derived crude oil, it will clearly remain waste. However, confirmation is required from SEPA that, if a crude plastic-derived oil and conventional crude oil are co-processed at an oil refinery (i.e. INEOS at Grangemouth), this will not affect the status of the product fuels from the refinery, that is the addition of a small quantity of plastic-derived crude will not result in the entire refinery output being classified as waste.

#### 9.1.6.3 REACH

If the plastic-derived oil products do meet the end-of-waste criteria, they will need to become registered under REACH. Although some plastic-derived products have been pre-registered, it is not clear whether the data included in the pre-registration are relevant. The costs involved in either joining the existing consortium that has made a pre-registration or generating the required data are not insignificant and need to be determined.

#### 9.1.6.4 The 25% energy-from-waste cap

Scotland's Zero Waste Plan includes the continuation of the 25% cap on the proportion of household waste sent to EfW. It is not clear whether plastic-to-oil-product processes fall within the definition of EfW. If they do, this may make them less attractive to investors, especially if there is already sufficient 'conventional' EfW capacity in Scotland to reach this cap.

More clarity is required regarding whether processes converting plastics to oil products fall within the definition of EfW and will be subject to the EfW cap and/or the ban on incineration of source-segregated materials. It is recommended that such processes are excluded from the EfW definition, subject to suitable criteria regarding yield, energy efficiency, etc.

## 9.2 Levels of interest

### *9.2.1 Waste producers*

Preliminary discussions have been held with a number of operators of MRFs, anaerobic digestion plants and composting facilities, including Oran, Shanks and Scottish Water Horizons.

These companies all see low-grade waste plastic film as an operational problem, both in terms of the impact on the operability of their processes and as a waste disposal cost. They would see any alternative to their current practice of landfill as beneficial, in terms of both cost leverage and meeting their corporate commitments to reducing waste from their operations.

### *9.2.2 Oil producers*

Preliminary discussions have been held with INEOS's Grangemouth refinery, which is keen to maximise the use of the refinery site and other assets. It considered a number of options whereby crude or partly refined oil products could best be introduced to the refinery (subject to a more comprehensive technical appraisal of the materials produced from plastics). It was also keen to emphasise the land, services and skilled workforce that would be available to an investor choosing to locate a plastic-to-oil-products facility at Grangemouth. The question of whether the refinery would be willing to invest in such a facility was not raised directly, but such an investment is unlikely given that such a facility would be outside their core expertise.

Preliminary discussions have also been held with Greenergy, a leading national provider of road fuel; the company would be willing to consider blending oil products from waste plastic into its Scottish fuel supply, as long as they had met the end-of-waste test required by SEPA, and would not require a complex blending scheme to ensure that the fuel sold meets the relevant fuel standard. Again, this would need to be subject to a more comprehensive technical review by the company before proceeding.

## 10 Conclusions

### 10.1 Waste plastics supply chain

It is estimated that the quantity of low-grade waste plastic film currently available in Scotland is between 18,000 and 27,000tpa. The majority of this arises from MRFs processing municipal household recyclates, with additional material from composting and anaerobic digestion facilities. These sources are concentrated within the main area of population, i.e. the central belt of Scotland encompassing Glasgow and Edinburgh.

Currently, this material is landfilled or exported to mainland Europe as SRF/RDF. Export of mixed MRF films to China is currently banned by the Chinese Government, although there is anecdotal evidence within the industry that substantial quantities are still being exported to the Far East from the UK.

The implementation of Scotland's Zero Waste Plan will increase the material processed by MRFs, composters and anaerobic digestion facilities such that the quantity of material available for conversion to oil products reaches 50,000tpa.

This plan includes a ban on landfilling and incineration of separately collected dry recyclables from January 2014, so the only viable disposal outlet for this low-grade plastic material will be EfW by mass burn incineration until alternative processing routes are developed. These potential alternatives are:

- conversion into RDF for export to countries where there is EfW capacity;
- use as fuel for cement processing or similar kiln-based industrial processes;
- mechanical recycling; and
- conversion to oil products.

There is one significant cement plant in Scotland (Lafarge Cement at Dunbar). This facility is already well supplied with alternative fuels, although it may be interested in the higher gate fees that are likely to be available for low-grade mixed plastics once the landfill ban is enforced in Scotland.

Mechanical recycling options for low-grade mixed films are very limited with current technology, so technologies for conversion to oil or gas are potentially of great interest.

### 10.2 Process options for conversion of plastic into oil products

Processes for the conversion of plastics into oil products have been in development for over 20 years, but the low cost of oil has prevented these from becoming economically feasible. Recent increases in oil prices have caused a resurgence in interest in these technologies, with three basic classes of technology:

- pyrolysis
- catalytic depolymerisation
- gasification followed by chemical or biological synthesis.

Two key parameters for assessing these processes are product yield and product quality.

**Pyrolysis** processes have the highest yield (around 68%) but produce a light synthetic crude that requires substantial processing to yield a saleable product, incurring a yield loss of around 10% and additional processing costs.

**Catalytic depolymerisation** processes have a slightly lower initial yield (around 62%) but produce a mixed distillate that may be useable as a blend component, but is more likely to require limited processing to yield a saleable product, with minimal loss of yield.

**Gasification** processes followed by chemical synthesis have the lowest yields (around 23–58%) but produce high-quality products that can be immediately used as blend components.

In terms of scale, the pyrolysis and catalytic depolymerisation technologies are limited by heat transfer considerations such that a single processing vessel has a capacity of no more than 8,000–10,000tpa, although a number of vessels can be connected in parallel to achieve higher throughputs. Gasification processes do not have heat transfer limitations, and can achieve capacities in excess of 35,000tpa in a single process train.

Within each class, there are examples of plants operating at or close to commercial scale. None of these technologies has reached the stage whereby there are multiple commercial-scale operating plants. None of the plants is reported as routinely running at commercial scale with low-grade ‘unrecyclable’ waste plastics, which are the target feedstock in this report.

### 10.3 Financial assessment of process options and site

Although all of the processes considered in this report generate a positive operating income when using the simplified capex estimations, only pyrolysis, catalytic depolymerisation and gasification with biological conversion to ethanol are financially viable, generating positive 10-year NPVs. These processes still generate a positive 10-year NPV if the gate fee falls to £60 per tonne, which is expected as the market for EfW in Scotland grows. Pyrolysis and catalytic depolymerisation generate a positive 10-year NPV at zero gate fee.

The capital required for sufficient capacity to process 27,000tpa is approximately £20M. Lower capacities would require less investment, but the minimum economically viable capacity is estimated to be between 12,000 and 16,000tpa. For pyrolysis and catalytic depolymerisation, this means that installation of a single processing unit is unlikely to be viable.

The true capital requirement will depend on the specific project chosen, and capital costs could increase as a result of mitigation of the new technology risk (if parts of the technology have not been demonstrated at commercial scale) or of integration and partner requirements (in the case of close coupling to a refinery unit). A detailed feasibility study will be required on the chosen technology(s), with the respective downstream partners, to assess viability with respect to:

- technical capability
- energy integration
- product integration.

For the majority of the waste plastic volume within Scotland there is no real advantage in a spoke-and-hub collection model whereby plastics from a number of sources are bulked up and pre-processed to crude liquid in order to reduce the transport volume before refining at a central plant. This is because transport distances for most of the waste volume are relatively small and the capital cost and minimum economic scale of the depolymerisation technology are high. In the case of the more remote areas of the country it is unlikely that the collection volumes available would justify investment in pyrolysis or

gasification. Mass burn incineration or transport for processing in the Edinburgh–Glasgow zone are more likely to be viable.

#### 10.4 Environmental assessment, licensing and permitting

The environmental performance of the processes in terms of GHG emissions favours pyrolysis or catalytic depolymerisation over gasification because of the higher yield of these processes and therefore the higher substitution of fossil fuels.

Environmental permitting of the plastic-to-oil processes considered in this report is relatively straightforward, but it needs to be borne in mind that SEPA determine whether the process is classified under the heading 'Energy Production', 'Hydrocarbon Production' or 'Waste Management'. The regulatory framework is the same in any case – the process would need to comply with WID regardless – but the last heading may bring adverse publicity for any prospective investor.

The determination of end of waste is also performed by SEPA, and failure to meet this test would result in the plastic-derived oil products being unfit for sale. There is an existing quality protocol for processed fuel oil, but this is not directly applicable to plastic-derived oil products, nor does it apply in Scotland. Similarly, England and Wales apply an end-of-waste test that is not applicable in Scotland.

If the process manufactures a fuel product and passes the end-of-waste test, it will be necessary to register the substance under REACH, or at least join an existing consortium for sharing of health and environmental information. Although some plastic-derived oil products have been pre-registered by other parties, the costs of joining the consortium to share health and safety data, or generating the data necessary for full registration, need to be borne in mind by a prospective process operator.

#### 10.5 Contamination issues

Low-grade waste materials contain contaminants which may interfere with the thermal treatment process. The most important of these are PVC (estimated at around 0.5%) and oxygenated materials such as PET and paper (estimated at up to 13.4%).

The impact of contamination of the levels described above on the yield and quality of the oil products produced by the various processes has not been reported by the technology suppliers. The assumption of this report is that a feedstock with the levels of contamination described above will produce oil products in the yield and quality claimed by the technology suppliers.

However, some processes, notably pyrolysis, are sensitive to contamination, and this may reduce the quality and quantity of the oil products produced. If this is the case, and less-contaminated feedstocks are required, then it will be necessary to remove the contamination prior to the thermal processing stage. (As the objective is to use otherwise unrecyclable feedstocks, the purchase of higher quality material would not be allowed.)

It is usually possible to remove such contaminants prior to the thermal processing stage. However the removal processes will add cost and may reduce yield. For example, equipment for the 'dry' cleaning of 27,000tpa of contaminated plastic film has an estimated capital cost of £250,000. The impact of this additional capex on the profitability of the process can be determined from the sensitivity analyses given in section 5.

Practical testing of one or more of the short-listed technologies would be required to assess their sensitivity to the contaminants found in the most likely feed streams and to estimate how much pre-processing would be required for the thermal treatment part of the process to be viable.

## 10.6 Barriers to development and levels of interest

The market for oil products is dominated by oil's use as a road fuel, with Scottish consumption of gasoline at 1.18 million tpa and diesel at 1.83 million tpa. In common with the rest of Europe, diesel is in short supply and this makes diesel the best target for a plastic-to-oil process. Given the current availability of feedstock of only 18,000–27,000tpa, it is likely that the operator of a plastics-to-oil process would need to partner with an existing fuel supplier to enter the market.

Scotland's only oil refinery at Grangemouth dominates domestic supplies, and preliminary discussions confirm that it would be a willing partner in introducing plastic-derived crude oils, mixed distillates or diesel blend components into the fuel supply chain.

In addition, there would be scope for the introduction of blend components or drop-in fuels into the fuel supply chain via independent fuel traders, as long as the resulting fuel blends still met the relevant fuel quality standards.

Levels of interest in the project from Scottish waste management companies, composters, anaerobic digestion plant operators and the INEOS refinery are high.

The main barriers against uptake of plastic-to-oil processes are:

- the dispersed nature of the feedstock available – no one producer has sufficient arisings to make a plant economically viable;
- the unproven performance of the technology, especially when dealing with low-quality plastic waste with relatively high levels of contamination;
- uncertainty within the regulatory framework with respect to environmental permitting, end of waste and whether processes fall within the EfW cap;
- the unknown potential costs of REACH; and
- the lack of incentives for production of non-biogenic fuel from waste.

## 11 Recommendations

Consideration could be given to adjusting the regulatory and fiscal incentives in order to provide similar incentives for oil and power generated from waste by advanced thermal conversion processes, of the type reviewed in this report, to those (RTFO, FiT, RHI) provided for power and liquid fuels produced from biogenic materials. Whatever the incentives considered, they will still have to remain within applicable EU Legislation, such as the Waste Incineration Directive, etc.

In particular, further consideration could be given to:

- extending the incentives already available for biogenic waste materials to those waste materials which are likely to be banned from landfill, by applying RTFO to waste-derived oil products and FiT and RHI to power and heat generated from those manufacturing processes;
- working with SEPA to provide clear guidance on the criteria by which plastic-to-oil processes will be determined as being energy or chemical manufacturing processes rather than waste management (incineration or co-incineration) processes; and
- working with SEPA to provide clear guidance on the end of waste for waste-derived oil products, possibly by development of an appropriate quality standard.

Zero Waste Scotland should reduce the technical and commercial risk for potential project promoters by conducting practical trials to demonstrate the quality and composition of the oils that could be produced by one or more of the leading processes from low-grade waste plastic sourced in Scotland.

Zero Waste Scotland should conduct feasibility studies (desk based) on the practically most successful waste-plastic-to-oil technologies to understand the technical capability, the energy integration and the project integration of each with a specific end-use partner.

Zero Waste Scotland could reduce the technical and commercial risk for potential project promoters by conducting practical trials to demonstrate the quality and composition of the oils that could be produced by one or more of the leading pyrolysis or catalytic depolymerisation processes from low-grade waste plastic sourced in Scotland.

Zero Waste Scotland could reduce the commercial risk for potential project promoters by conducting surveys to confirm the actual quantities of low-grade plastic film arising from MRFs, composting facilities and anaerobic digestion plants.

Zero Waste Scotland could reduce the commercial risk for potential project promoters by conducting studies to fully assess the potential costs of registration of oil products under REACH.

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## Appendix A: Literature review

### A.1. Pyrolysis

#### ■ Agilyx

- Location: OR, USA.
- Process 'type': conventional pyrolysis process.
- Specific feed type for system: mixed waste plastics. Resins 1 to 7, primarily resins 3 to 7. LDPE, polypropylene, polystyrene, polycarbonate, fibreglass, nylon (except nylon 6). Can handle up to 70% PVC and mix rigids and films and engineering grade resins.
- Feed source: some post-consumer, post-industrial samples.
- Feed preparation: commingled waste grinded and shredded to density 320–336kgm<sup>-3</sup>.
- Toleration of contamination: robust system can handle contaminants such as metal, glass, wood, paper, moisture. Yield is affected adversely with increase in contamination levels.
- Products: light sweet crude oil (80%), natural gas (12%). Product needs further refining. This light sweet crude oil typically refines to 15–20% more ultra-low sulphur diesel than fossil crude.
- Residue: powdery carbon residue (8%).
- Acid treatment: none.
- Process yield: 80%, 1 tonne producing six barrels of oil. Process energy ratio of 1:5 (5BTU (saleable) out for every 1BTU of energy in).
- Operation temperature: 593.3°C.
- Operating pressure: vacuum.
- Residence time: approximately 5 hours per batch, with concurrent vessels running with staggered start times of 1.5 hours.
- Precise design of process unit: can only be disclosed under NDA.
- Current system capacity: 9 tonnes per day (3,500tpa). Can be scaled to 10,000tpa.
- Limits to scale-up: Scale-up can be achieved only by adding several vessels.
- Number of facilities in operation/reference plant (if any): one facility in operation for over 2 years. Four commercial systems of about 40 tonnes per day with one system making oil already.
- Contact details:
  - Contact person: Lew Feucht – Business Development.
  - Address: 9600 SW Nimbus Ave, Suite 260, Beaverton, OR 97008, USA.
  - Web address: [www.agilyx.com](http://www.agilyx.com)
  - Phone: +1 503 906 5231
  - Mail: [lfeucht@agilyx.com](mailto:lfeucht@agilyx.com)

#### ■ Anhui Orsun Environmental Technologies

- Location: Hefei, Anhui, China.
- Process 'type': use of microwave frequencies to extract oils and gas from plastic in the presence of catalyst.
- Specific feed type for system: No. 1 to 7 resins, engineering grade resins and polyactic acid.
- Feed source: information not available.
- Feed preparation: information not available.

- Toleration of contamination: maximum tolerance unknown; however, contamination affects oil yield.
- Products: diesel 85%, crude oil 85%. Product ready for use by consumer.
- Residue: carbon black, used as fuel.
- Acid treatment: information not available.
- Process yield: 50–85% conversion per tonne of plastic processed. A tonne of raw material might produce 60kg of useable product.
- Operation temperature: information not available.
- Operating pressure: atmospheric pressure.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: 8,000tpa; can be scaled to 18,000tpa.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): two facilities in operation for 8 years.
- Contact detail:
  - Contact person: Jane Tall.
  - Address: 11F Finance Building, No 384 Jinzhai Road, Hefei, China.
  - Web address: [www.oursunchina.com](http://www.oursunchina.com)
  - Phone: +86 13965124132
  - Email: [janegll@hotmail.com](mailto:janegll@hotmail.com)

#### ■ Blest

- Location: Japan, USA.
- Process 'type': conventional pyrolysis process.
- Specific feed type for system: polyethylene, polypropylene and polystyrene only.
- Feed source: Municipal and private MRF waste, agricultural waste and waste from independent suppliers.
- Feed preparation: Granulating to 10–20mm in size. Pre-cleaning if needed.
- Toleration of contamination: a small amount of contamination, 5% or less, is in general fine. Organic matter will burn off. However, there is a need to pre-process the plastic, and, if there is significant contamination, a cleaning system will need to be in place.
- Products: a mixed synthetic light sweet crude oil. Unrefined oil used by consumer for boilers, heating oils and generators and as an accelerant fuel for biodiesel or as a diesel substitute in heavy equipment, gardening equipment, older diesel car and trucks, and marine diesel. Unrefined oil can be sold to a commercial refiner or used in the Blest hydrocarbon refiners (BOR-20 and BOR-50) with a yield of 20–30% for each type of fuel.
- Residue: carbon char or non-toxic plastic ash. Amount produced is less than 1% of plastic input.
- Acid treatment: none.
- Process yield: 75–85% conversion.
- Operation temperature: up to 400°C.
- Operating pressure: atmospheric pressure.
- Residence time: information not available.
- Precise design of process unit: cylindrical.
- Current system capacity: current unit runs 10 to 100kg per hour, and up to four can be combined under a single controller.

- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): more than 60 sites in Japan, Africa and Asia since 2007. First North American site to be installed in Canada in July 2012. Reference site visits or telephone calls can be arranged.
- Contact detail:
  - Contact person: Charles Nahal (UK representative).
  - Address: information not available.
  - Web address: <http://e-n-ergy.com>
  - Phone: +44(0)207 112 8516.
  - Email: [charles.n@BioEnergySciences.com](mailto:charles.n@BioEnergySciences.com)

#### ■ 1Climax Global Energy

- Location: SC, USA.
- Process 'type': microwave pyrolysis, no catalyst employed.
- Specific feed type for system: post-consumer waste/resins 1 to 7 only.
- Feed source: municipal and private MRF residue.
- Feed preparation: feedstock shredded.
- Tolerant of contamination: accepts contamination such as paper, rocks, metals and water; however, yield is affected by these.
- Products: product similar to crude oil (75%). Product needs further processing. Commodity wax is produced at a rate of 6 million MMBTUs per barrel
- Residue: char, which is incinerated or landfilled.
- Acid treatment: none.
- Process yield: a tonne of plastic producing five barrels of synthetic crude oil.
- Operation temperature: 400°C.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: 1,000tpa.
- Limits to scale up: none reported.
- Number of facilities in operation/reference plant (if any): one facility in operation for approximately 2 years.
- Contact details:
  - Contact person: John Griffith.
  - Address: 450 Springfield Ave, Suite 201, Summit, NJ 07901, USA.
  - Web address: [www.climaxglobalenergy.com](http://www.climaxglobalenergy.com)
  - Phone: +1 9082772227.
  - Email: [johngriffith@climaxglobalenergy.com](mailto:johngriffith@climaxglobalenergy.com)

#### ■ Cynar plc

- Location: Ireland.
- Process 'type': pyrolysis with specific distillation of product gas.
- Specific feed type for system: resin 2 to 6. PET, expanded polystyrene and polyurethane are not suitable. System can accept less than 10% of the total weight of materials other than specified resin codes.

- Feed source: household segregation and kerbside collection sourced from MRFs and also other agricultural waste plastics.
- Feed preparation: MAS washer/drier to get product moisture content (if any) down to 5–8%. Size reduction carried out also.
- Toleration of contamination: accepts paper and dirt if less than 5%. Food waste to be wet-washed. Metal contaminants avoided.
- Products: diesel EN590 (70–80%) requiring further cleaning, kerosene (10–20%), which can be blended or used in lightly amended engines, and gas (5%).
- Residue: char (5–10%).
- Acid treatment: none.
- Process yield: 1 tonne produces 700l of diesel (EN590).
- Operation temperature: information not available.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: 10 tonnes per day (3,000tpa; can be scaled up to 12,000tpa). 10 plants in the UK designed to process 5,500–6,000tpa.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): one facility in operation for approximately 4 years.
- Contact detail
  - Contact person: Phil Holland – Development Manager, SITA UK.
  - Address: Euston Fitzrovia, 85 Tottenham Court Road, London W1T 4TQ.
  - Web Address: [www.cynarplc.com](http://www.cynarplc.com)
  - Phone: information not available.
  - Email: [phil.holland@sita.co.uk](mailto:phil.holland@sita.co.uk)

#### ▪ Dynamotive

- Location: BC, Canada.
- Process 'type': fast pyrolysis.
- Specific feed type for system: no evidence of plastic feedstock used, just biomass. Biomass used includes hard wood and grass.
- Feed source: information not available.
- Feed preparation: information not available.
- Toleration of contamination: feed is dried to less than 10% moisture and size reduced to 1–2mm particle size.
- Products: BioOil (60–75% by weight) and non-condensable gases (10–20% wt). These proportions are greatly influenced by feedstock type.
- Residue: char (15–20% wt).
- Acid treatment: none.
- Process yield: 100% of feedstock is utilised in the process to produce BioOil and char.
- Operation temperature: 450–500°C.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: pilot 15 tonnes per day. Can be scaled up to 200 tonnes per day.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): two facilities in operation.

- Contact detail:
  - Contact person: information not available.
  - Address: Suite 800–1040 West Georgia Street, Vancouver, BC, V6E 4H1, Canada.
  - Web address: [www.dynamotive.com](http://www.dynamotive.com)
  - Phone: information not available.
  - Email: information not available.

- **2Envion**

- Location: DC, USA.
- Process 'type': far infrared heating process.
- Specific feed type for system: PET, HDPE, LDPE/LLDPE, polypropylene, polyethylene, polystyrene, PVC and several other plastic types such as general-purpose polystyrene, EPS, high-impact polystyrene, and polyamide. PVC is not acceptable but tolerated.
- Feed source: MRF.
- Feed preparation: Pre-sorting, magnetic removal of contaminants, size reduction to 1.5 inches, melting at 300°C and screening.
- Tolerant of contamination: can accommodate paper contamination well but not dirt and organics.
- Products: product similar to crude oil (70%), needing further processing, and natural gas (15%).
- Residue: residue (15%) converted to emulsified heavy oil and vent gas recycled within unit for electricity generation.
- Acid treatment: yes.
- Process yield: 62%. A tonne of plastic waste produces three to five barrels of refined petroleum.
- Operation temperature: information not available.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: 10,000tpa. Scalable through the addition of extra reactors.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): one facility in operation for approximately 2.5 years.
- Contact detail:
  - Contact person: information not available.
  - Address: 1027, 23rd St. NW, Washington, D.C. 20007, USA.
  - Web address: [www.envion.com](http://www.envion.com)
  - Phone: +1 2029655030.
  - Email: [pgoco@envion.com](mailto:pgoco@envion.com)

- **GEEP**

- Location: ON, Canada.
- Process 'type': conventional pyrolysis process.
- Specific feed type for system: resins 1 to 7, engineering plastic grades.
- Feed source: plastics from electronics.
- Feed preparation: none.
- Tolerant of contamination: can handle up to 40% moisture contamination.

- Products: 100% diesel no gasoline.
- Residue: carbon/oil sludge.
- Acid treatment: yes.
- Process yield: 75% for primary feedstock containing acrylonitrile butadiene styrene. 96–98% conversion with polystyrene and polypropylene feed material. 12–15% conversion with PVC. Conversion varies largely with feed type.
- Operation temperature: ambient.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: current capacity 6,000tpa.
- Limits to scale-up: none recorded.
- Number of facilities in operation/reference plant (if any): one facility in operation for approximately 5 years.
- Contact detail:
  - Contact person: Patrick Oberle.
  - Address: 220 John Street, Barrie, Ontario, L4N 2L2, Canada
  - Web address: [www.geepglobal.com](http://www.geepglobal.com)
  - Phone: +1 7057370355.
  - Email: [poberle@barriemetals.com](mailto:poberle@barriemetals.com)

#### ■ GreenMantra Recycling Technology

- Location: ON, Canada.
- Process 'type': information not available.
- Specific feed type for system: resins 1–7.
- Feed source: independent sources.
- Feed preparation: none. Feed bought from suppliers is clean.
- Toleration of contamination: information not available.
- Products: Industrial waxes, lubricants and fuels.
- Residue: information not available.
- Acid treatment: information not available.
- Process yield: 95%.
- Operation temperature: information not available.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: information not available.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): information not available.
- Contact detail:
  - Contact person: information not available.
  - Address: MaRS Discovery District, Suite #313, 101 College Street Toronto, ON M5G 1L7, Canada.
  - Web address: [www.greenmantra.ca](http://www.greenmantra.ca)
  - Phone: +1 6473305543.
  - Email: [info@greenmantra.ca](mailto:info@greenmantra.ca)

## ■ Klean Industries Inc

- Location: BC, Canada.
- Process 'type': low temperature pyrolysis liquefaction.
- Specific feed type for system: resins 1–7; however, primarily processing polyethylene, HDPE, LDPE, polystyrene, polypropylene. Engineering grade resins and PLA. System can handle PVC and PET of up to 20% of feed volume.
- Feed source: municipal solid waste, (MRF) residual waste, auto shredder residue (ASR), agricultural scrap plastics, plastic films, post-consumer and post-industrial waste, and e-waste.
- Feed preparation: integrated material handling system.
- Toleration of contamination: can handle mixed, wet dirty feedstock because of the integrated material handling system, which is capable of removing 95% of contamination.
- Products: diesel (no gasoline) (70%), diesel/gasoline mix (70%/30%), product ready to be used by consumer; natural gas (+/-10%), monomers, proportion of the output (+/-30%).
- Residue: char (<5%), pelletised and used as a co-combustion fuel and replacement coal.
- Acid treatment: yes.
- Process yield: a tonne of plastic produces 650–950l of fuel (both gasoline and diesel).
- Operation temperature: information not available.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: 3,500tpa. Scalable up to 75,000tpa.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): 12 facilities in operation for approximately 12 years.
- Contact detail:
  - Contact person: Marc Smith.
  - Address: 349 West Georgia St., PO Box 3038, Vancouver, BC, Canada, V6B 3X5.
  - Web Address: [www.kleanindustries.com](http://www.kleanindustries.com)
  - Phone: +1 6046379609.
  - Email: [m.smith@kleanindustries.com](mailto:m.smith@kleanindustries.com)

## ■ Natural State Research

- Location: CT, USA.
- Process 'type': thermal liquefaction process.
- Specific feed type for system: resins 3 to 7 excluding PVC.
- Feed source: mixed plastic from municipal waste.
- Feed preparation: information not available.
- Toleration of contamination: system can handle contamination.
- Products: diesel and natural gas ready for use by consumer.
- Residue: char (<5%) when system is ran in batches and almost no char with a continuous system.
- Acid treatment: information not available.
- Process yield: 95–98%.
- Operation temperature: information not available.

- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: 6kg/h.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): one facility in operation.
- Contact detail:
  - Contact person: Dr Moinuddin Sarker.
  - Address: 37 Brown House Road, 2nd floor, Stamford, CT 06902, USA.
  - Web address: [www.naturalstateresearch.com](http://www.naturalstateresearch.com)
  - Phone: +1 2034060675.
  - Email: [msarker@naturalstateresearch.com](mailto:msarker@naturalstateresearch.com)

### **Niutech Energy Limited**

- Location: China.
- Process 'type': pyrolysis with distillation.
- Specific feed type for system: resins 1 to 7.
- Feed source: scrap tyre and mixed plastic.
- Feed preparation: size reduction.
- Toleration of contamination: information not available.
- Products: diesel/gasoline mix and heavy oil, which is used directly to supply fuel for furnace and steam boilers.
- Residue: less than 5%.
- Acid treatment: yes, hydrogen chloride neutralization.
- Process yield: information not available.
- Operation temperature: information not available.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: information not available.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): none reported.
- Contact detail:
  - Contact person: information not available.
  - Address: Room 507, Lanshi Business Centre, No.6 North Baotuquan Road, Lixia District, Jinan, Shandong, PRC. 250011, China.
  - Web address: [www.niutechenergy.com](http://www.niutechenergy.com)
  - Phone: +86 53186196301.
  - Email: [info@niutech-energy.com](mailto:info@niutech-energy.com)

- **Plastic Advanced Recycling Corp**

- Location: IL, USA.
- Process 'type': pyrolysis with catalyst.
- Specific feed type for system: resins 1 to 7.
- Feed source: MSW, from paper mills, after separation.
- Feed preparation: size reduction.

- Toleration of contamination: no maximum contamination level.
- Products: product similar to crude oil (50%–70%). Product can be further refined or used directly by consumer as furnace fuel for power generation. Natural gas (15–25%) which is recycled back into the reactor and used as a fuel.
- Residue: mostly carbon black (15–25%). Can be used as raw material for regenerative carbon black and bricks.
- Acid treatment: information not available.
- Process yield: 30 tonnes of plastic produces 4,605 gallons of oil and 4.5 tonnes of carbon black.
- Operation temperature: <500°C.
- Operating pressure: ambient pressure.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: 10,000tpa.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): two facilities in operation.
- Contact detail:
  - Contact person: Willy Li.
  - Address: 7884 S. Quincy Street, Willowbrook, IL 60527, USA.
  - Web address: [www.plastic2x.com](http://www.plastic2x.com)
  - Phone: +1 6306556976.
  - Email: [info@plastic2x.com](mailto:info@plastic2x.com)

#### ▪ Plastic2Oil

- Location: NY, USA.
- Process 'type': low-temperature thermal process.
- Specific feed type for system: resins 1 to 7 with 2, 4, 5 having the highest yield.
- Feed source: information not available.
- Feed preparation: information not available.
- Toleration of contamination: no maximum contamination level.
- Products: diesel/gasoline mix (70%/30%) and natural gas (8.0%). Product needs further refining.
- Residue: carbon black, which is 1–5% of yield. Residue has 10,600BTU value.
- Acid treatment: information not available.
- Process yield: 0.867.
- Operation temperature: information not available.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: 7,000tpa.
- Limits to scale up: none reported.
- Number of facilities in operation/reference plant (if any): one facility in operation.
- Contact detail:
  - Contact person: John Bordynuik.
  - Address: 1783 Allanport Road, Thorold, Ontario, L0S 1K0, Canada.
  - Web address: [www.plastic2oil.com](http://www.plastic2oil.com)
  - Phone: 9053844383 ext. 227 or 716 278 0015

- Email: [john@johnbordynuik.com](mailto:john@johnbordynuik.com)

- **PolyFlow**

- Location: OH, USA.
- Process 'type': conventional pyrolysis process.
- Specific feed type for system: resins 3 to 7, engineering grade resins, ABS, styrene acrylonitrile, polycarbonate, acetal, tyres, carpet, sheet moulding compound (70% inerts), PLA, co-polymers, films, multi-layer films, HDPE with calcium carbonate, snack bags, pouches, all thermoplastics and thermosets, e-waste polymer.
- Feed source: commercial and industrial generators, Akron Zoo, building contractors, local MRF, residential collection, MSW.
- Feed preparation: information not available.
- Toleration of contamination: system can tolerate up to 50%. To maximise product yield, acceptable level is less than 25%. Moisture should be less than 5%.
- Products: diesel/gasoline mix (33%) and monomers (33%). Product needs further refining.
- Residue: char (13% for baseline mix) consisting of the contaminants, fillers glass and metals in the feedstock. Plastic feed only produces 5–7% of char.
- Acid treatment: information not available.
- Process yield: baseline polymer waste will yield 67–72% gasoline, diesel fuel and chemical intermediates. Clean feedstock yields 78–83%. A clean non-condensable gas is also produced.
- Operation temperature: information not available.
- Operating pressure: information not available.
- Residence time: information not available.
- Precise design of process unit: information not available.
- Current system capacity: 180kg batch pilot plant. Scalable up to 150,000tpa.
- Limits to scale up: none reported.
- Number of facilities in operation/reference plant (if any): one facility in operation (batch scale).
- Contact detail:
  - Contact person: Joseph Hensel.
  - Phone: +1 3302535912.
  - Email: [henseljd@polyflowcorp.com](mailto:henseljd@polyflowcorp.com)

- **Promeco**

- Location: Italy.
- Process 'type': conventional pyrolysis process.
- Specific feed type for system: feed materials containing more than 80% plastics.
- Feed source: independent sources.
- Feed preparation: Pre-treatment such as drying.
- Toleration of contamination: can handle any contaminants up to 20%.
- Products: diesel/gasoline.
- Residue: solid carbon residue.
- Acid treatment: no.
- Process yield: 80% in oil of input plastics.

- Operation temperature: 350°C.
  - Operating pressure: information not available.
  - Residence time: from 15 to 30 minutes.
  - Precise design of process unit: information not available.
  - Current system capacity: system not scalable; developed one size only.
  - Limits to scale-up: none reported.
  - Number of facilities in operation/reference plant (if any): two facilities.
  - Contact detail:
    - Contact person: Paolo Rebai.
    - Address: Promeco spa Via Tevere 51, 22073 Fino Mornasco (CO), Italy.
    - Web address: [www.promeco.it](http://www.promeco.it)
    - Phone: +39 031267331, +39 0312286034.
    - Email: [rbai@promeco.it](mailto:rbai@promeco.it)
- 
- **Vadxx**
    - Location: OH, USA.
    - Process 'type': pyrolysis with catalyst.
    - Specific feed type for system: resins 1 to 7 with minimal plastic content from resins 1 and 3. Scrap tyre, many grades of industrial waste rubber, polymer fraction of ASR/auto fluff, e-waste polymer.
    - Feed source: municipal plastic waste from multiple waste management and recycling companies.
    - Feed preparation: information not available.
    - Toleration of contamination: moisture contaminants should be minimal, less than 10%. System is robust and can tolerate contaminants in higher levels.
    - Products: one product similar to crude oil (75%) and a second similar to natural gas (15%). Both products need further refining or purification.
    - Residue: char, which is sold to a third party.
    - Acid treatment: none reported.
    - Process yield: Not given. 15–20% of the products are used to provide energy for the process.
    - Operation temperature: can only be disclosed under NDA.
    - Operating pressure: can only be disclosed under NDA.
    - Residence time: can only be disclosed under NDA.
    - Precise design of process unit: can only be disclosed under NDA.
    - Current system capacity: 60 tonne per day, 2,000 barrels per year. Scalable up to 12,000tpa.
    - Limits to scale-up: none reported.
    - Number of facilities in operation/reference plant (if any): one facility in operation for 2 years. Footprint is 50ft by 200ft.
    - Contact detail:
      - Contact person: Russell Cooper.
      - Address: 1768 East 25th Street, Cleveland, OH 44114, USA.
      - Web address: [www.vadxx.com](http://www.vadxx.com)
      - Phone: +1 4402926192.
      - Email: [rcooper@vadxx.com](mailto:rcooper@vadxx.com)

## A.2. Catalytic depolymerisation

### ■ Alphakat

- Location: Germany.
- Specific feed type for system: all kinds of plastics and synthetic materials. Resins 1 to 7 including PVC, PET.
- Feed source: industrial plastic wastes, MSW, agricultural plastic wastes.
- Feed preparation: feedstock has to be shredded to a particle size of 12×3mm. Feed is made into sludge for easier processing.
- Catalyst used and lifespan: the catalyst is part of the continuous process producing synthetic diesel fuel. A part of the catalyst is being recovered from the plant (ca. 20%), the rest of the catalyst, which is needed for the chemical reaction, is used continuously by production of diesel fuel.
- Toleration of contamination: maximum 5% inorganics (metals, ceramics, glass, stones, sand). Maximum 20% moisture content.
- Products: diesel which requires further desulphurisation.
- Residue: solid residues, ash, char.
- Process yield: The KDV plant has an overall process efficiency of 80%. The yield depends on the calorific value of the feedstock (MJ/kg).
- Operation temperature: maximum 280 °C.
- Operating pressure: vacuum (−0.1bar).
- Current system capacity: 150, 500, 1,000, 2,000 and 5,000l/h (diesel production amount). Can be scaled up to 50,000l/h.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): eight facilities.
- Contact detail:
  - Contact person: Johannes J. Krmc.
  - Address: Schlustrasse 8, Buttenheim (96155), Germany.
  - Web address: [www.alphakat.de](http://www.alphakat.de)
  - Phone: +49 9545208.
  - Email: [mail@alphakat.de](mailto:mail@alphakat.de), [johannes.krmc@krmc.si](mailto:johannes.krmc@krmc.si)

### ■ T Technology

- Location: Poland.
- Specific feed type for system: polyolefin group plastic waste, polyethylene and polypropylene.
- Feed source: Plastic municipal waste directly from landfill.
- Feed preparation: size reduction and, if necessary, drying.
- Catalyst used and lifespan: strongly passivated aluminium (Al/Al<sub>2</sub>O<sub>3</sub>), a spongy deposit of micro-granules, the surface of which is coated with aluminium oxides, with a multi-layer bonded structure.
- Toleration of contamination: feedstock moisture content and mineral contamination up to 10%. Mineral contaminants include dust, glass, small metal elements. Only up to 50% soft-film contaminant is acceptable.
- Products: a broad hydrocarbon fraction (crude oil substitute), further processed into oil and petrol fractions in the proportion approximately 80% to 20%.
- Residue: plastics that cannot be processed and sludge containing minerals such as sand, glass.

- Process yield: 50–62%. Efficiency is relative to the type of raw material and its contamination level. From 100kg of waste 550l of fuel can be produced. From 12M kilograms of waste, 7M litres of fuel per year is produced.
- Operation temperature: 390–420 °C.
- Operating pressure: close to atmospheric pressure.
- Current system capacity: 400–600 tonnes per month. System is built in modules; five modules is ideal.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): several facilities; reference plants in Poland, India, Thailand and Slovakia.
- Contact detail:
  - Contact person: Michał Tokarz.
  - Address: Bogumiłów, ul. Nowa 6, 97-410 Kleszczów Województwo Łódzkie, Polska.
  - Web address: [www.tokarz.pl](http://www.tokarz.pl)
  - Phone: +48 509837055.
  - Email [info@tokarz.pl](mailto:info@tokarz.pl)

#### ■ Ventana Cleantech

- Location: India.
- Specific feed type for system: mixed rigid plastics, 1 to 7; however, system works best with resins 2, 4, 5 and 6.
- Feed source: unwashed post-consumer and post-industrial mixed plastics from municipal waste stream, material recycling facility or an industrial source.
- Feed preparation: dry automated segregation process on front end of system.
- Catalyst used and lifespan: catalyst activity can last for days before decrease in activity. However, work on catalyst is still on-going.
- Toleration of contamination: up to 5% moisture content and other contaminants.
- Products: light fuel. Gas produced is put back into process.
- Residue: solid carbon residues.
- Process yield: 70–95% (by weight). 4.75–5.75 barrels of oil produced per tonne of mixed plastics.
- Operation temperature: 400–450 °C.
- Operating pressure: atmospheric pressure.
- Current system capacity: 7,000tpa.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): one facility.
- Contact detail:
  - Contact person: none available.
  - Address: KK-16, HSIDC Estate, Kalka (Haryana), 133302, India.
  - Web address: [www.ventanacleantech.com](http://www.ventanacleantech.com)
  - Phone: +91 9779428009.
  - Email: [info@ventanacleantech.com](mailto:info@ventanacleantech.com)

#### ■ Kemia

- Location: Vienna, Austria.

- Specific feed type for system: resins 1 to 7. Can also process carpet wastes, waste lubricant oils and shredded tyre pieces.
- Feed source: mixed, comingled or multi-layer, heterogeneous plastics from independent sources.
- Feed preparation: shredded to approximately 2cm sized pieces.
- Catalyst used and lifespan: catalyst is needed only if PVC and polyurethane proportions in processed materials are high; initially propane gas or natural gas is needed for 2 hours, otherwise the system uses its own gas for self-fuelling.
- Toleration of contamination: up to 10% is acceptable; contaminants include sand, dust. It is important to note that paints and solvent are not included as contaminants and cannot be accepted.
- Products: heavy oils and gas.
- Residue: slag containing feed contaminants.
- Process yield: 75–80% oil from thermoplastics. Process can convert also synthetic carpet wastes (50% oil approximately). 4,000 tonnes of input material produces, approximately, 3,000 tonnes of heavy oil output, 300 tonnes of slag and 700 tonnes of gas output. In case of further distillation of the 3,000 tonnes, the yield depends mainly on the quality of the input materials. Otherwise, from 3,000 tonnes of heavy oil, 2MW electricity is produced.
- Operation temperature: Approximately 500°C.
- Operating pressure: low pressure.
- Current system capacity: 2,000tpa; presently building 4,000tpa of capacity.
- Limits to scale-up: none reported. System built in 4,000-tonne modules; easy increase of capacity.
- Number of facilities in operation/reference plant (if any): two facilities.
- Contact detail:
  - Contact person: Dr Laszlo Kondor – Managing Director.
  - Address: KEMIA Handels und Projektierungs GmbH, Vienna, Austria.
  - Web address: [www.kemia.at](http://www.kemia.at)
  - Phone: +43 18770553.
  - Email: [kondor@kemia.at](mailto:kondor@kemia.at)

#### ■ Vuzeta

- Location: Italy.
- Specific feed type for system: RDF, polyethylene, polypropylene, PVC and also biomass, agricultural waste, exhausted oils, anaerobic digestion solid residuals.
- Feed source: independent sources.
- Feed preparation: crushed to <3mm particle size.
- Catalyst used and lifespan: information not available.
- Toleration of contamination: up to 10% moisture content.
- Products: clean synthetic diesel fuel and gas.
- Residue: solid residues.
- Process yield: 23,000tpa of RDF produces 2,330,000 gallons per year of synthetic fuel and 7,000tpa of solid residues.
- Operation temperature: 350°C.
- Operating pressure: vacuum.
- Current system capacity: 20,000tpa of MSW.
- Limits to scale-up: none reported.

- Number of facilities in operation/reference plant (if any): two facilities in Italy.
- Contact detail:
  - Contact person: Doug Frater.
  - Email: [dougfrater@sigmaconsult.co.uk](mailto:dougfrater@sigmaconsult.co.uk)

### A.3. Gasification to syngas

#### ▪ Enerkem

- Location: QC, Canada.
- Conversion type: ethanol.
- Specific feed type for system: MSW, RDF from sorted MSW, woody wastes from construction and demolition, used telephone poles and other wastes from industrial, commercial and institutional (ICI) sources.
- Feed source: independent sources; however, RDF contains 20% plastic and 60–70% biomass.
- Feed preparation: preparation of RDF waste includes sorting and biological treatment, followed by processing to a fluff, and shredding of feedstock to 1–3 inches.
- Toleration of contamination: the inorganic matter content of each type of feedstock is generally 15% of total weight for RDF and ICI waste, while for construction and demolition waste, wood is less than 5%.
- Products: syngas further used to produce ethanol, electricity and other green chemicals.
- Process yield: 75% conversion efficiency. Enerkem defines the conversion efficiency as the ratio of the lower heating value (LHV) of the syngas to the LHV of the input feed. An additional 5–10% conversion efficiency can be achieved with high- or low-grade heat recovery.
- Operation temperature: staged gasification, temperature varies.
- Operating pressure: can only be disclosed under NDA.
- Acid neutralization: yes.
- Current system capacity: 2 tonnes per hour. Can be scaled up to 100,000tpa.
- Limits to scale up: none reported.
- Number of facilities in operation/reference plant (if any): a demonstration plant in operation for 3 years. Two commercial-scale plants running from mid-2012.
- Contact detail:
  - Address: 375 rue de Courcellette, Suite 900, Sherbrooke, QC J1H 3X4, Canada.
  - Web address: [www.enerkem.com](http://www.enerkem.com)
  - Phone: +1 8193471111.

#### ▪ Rentech

- Location: CO, USA.
- Conversion type: F–T.
- Specific feed type for system: RDF, with up to 5% plastic content except PVC, agricultural wastes, construction waste.
- Feed source: independent sources.
- Feed preparation: size reduction.
- Toleration of contamination: depends on what contamination is; however, no more than 5% permitted.
- Products: syngas.

- Process yield: can only be disclosed under NDA.
- Operation temperature: can only be disclosed under NDA.
- Operating pressure: can only be disclosed under NDA.
- Acid neutralization: unknown.
- Current system capacity: demonstration scale, 20 tonnes per day; pilot scale, 400 tonnes per day. Can scale up to 1,000 tonnes per day.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any):
- Contact detail:
  - Address: 10877 Wilshire Blvd. Suite 600, Los Angeles, CA 90024, USA.
  - Web address: [www.rentechinc.com](http://www.rentechinc.com)
  - Phone: +1 3105719800.
  - Email: [ir@rentk.com](mailto:ir@rentk.com)
  
- **Syngas Technology**
  - Location: MN, USA.
  - Conversion type: MTG.
  - Specific feed type for system: RDF, plastic except PVC, agricultural wastes, construction waste.
  - Feed source: independent sources.
  - Feed preparation: size reduction.
  - Toleration of contamination: should be less than 5%.
  - Products: syngas.
  - Process yield: 1.4 barrels of specific fuel per tonne of feed with high-calorific value. Lower yields are expected with lower calorific materials.
  - Operation temperature: can only be disclosed under NDA.
  - Operating pressure: can only be disclosed under NDA.
  - Acid neutralization: no.
  - Current system capacity: 600 tonnes per day.
  - Limits to scale-up: none reported.
  - Number of facilities in operation/reference plant (if any): none
  - Contact detail:
    - Contact person: Duane Goetsch
    - Address: information not available
    - Web address: [www.syngastechnology.com](http://www.syngastechnology.com)
    - Phone: +1 7637179490.
    - Email: [dgoetsch@syngastechnology.com](mailto:dgoetsch@syngastechnology.com)
  
- **Thermo-chem Recovery Int'l**
  - Location: NC, USA.
  - Conversion type: F-T.
  - Specific feed type for system: RDF with up to 15% plastic content except PVC.
  - Feed source: independent sources.
  - Feed preparation: size reduction to 1 inch in two dimensions. No exorbitant pre-treatment needed.

- Toleration of contamination: up to 1% metal contaminants. Up to 10% moisture content acceptable.
- Products: syngas.
- Process yield: can only be disclosed under NDA.
- Operation temperature: can only be disclosed under NDA.
- Operating pressure: can only be disclosed under NDA.
- Acid neutralization: no.
- Current system capacity: 200 tonnes per day, dry basis. Can be scaled up to 2,000 tonnes per day, dry basis.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): two – Durham (NC) and Trenton (Ontario)
- Contact detail:
  - Contact person: Chris Doherty
  - Address: 3700 Koppers Street, Suite 405, Baltimore, MD 21227, USA.
  - Web address: [www.tri-inc.net](http://www.tri-inc.net)
  - Phone: +1 4105252400.
  - Email: [cdoherly@tri-inc.net](mailto:cdoherly@tri-inc.net)

#### A.4.Syngas fermentation

##### ■ INEOS-Bio

- Location: IL, USA.
- Specific feed type for system: all ligno-cellulosic materials and other carbon materials, which includes plastics and rubber.
- Feed source: household, commercial, industrial, agricultural wastes.
- Feed preparation: homogeneity in size is required. For plastic rubber feed, a particle size of 5cm in two dimensions is ideal; for wood chip, up to 40cm can be accepted.
- Toleration of contamination: moisture content can be reduced by drying to the desired water content using low-grade waste heat from the process. Up to 40% moisture content typically found in animal slurries and some food waste is best treated in an anaerobic digestion plant.
- Products: ethanol.
- Process yield: a metric tonne of dry, ash-free biomass produces about 400l (315kg) of bioethanol in a commercial process. Yield is dependent on feedstock used. For 90,000 tonnes of plastics, 25,000 tonnes of ethanol can be produced per year.
- Operation temperature for fermentation: fermenter at body temperature.
- Operating pressure for fermentation: low pressure.
- Current system capacity: pilot scale, 1.5 tonnes per day; commercial, 90,000tpa.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): two facilities located at Teesside and in Florida.
- Contact detail:
  - Contact person: Graham Rice
  - Address: S3030 Warrenville Road, Suite 650, Lisle, IL 60532, USA.
  - Web address: [www.ineosbio.com](http://www.ineosbio.com)
  - Phone: +44(0)7768568197.
  - Email: [graham.rice@ineos.com](mailto:graham.rice@ineos.com)

■ **LanzaTech**

- Location: New Zealand.
- Specific feed type for system: information not available. Only deals with the syngas fermentation and not gasification.
- Feed source: information not available.
- Feed preparation: information not available.
- Toleration of contamination: information not available.
- Products: information not available.
- Process yield: varies based on plant capacity and feedstock gasified. 100,000 gallons per year can be produced at a site based in China.
- Operation temperature for fermentation: low temperature.
- Operating pressure for fermentation: low pressure.
- Current system capacity: 700 tonnes per day of municipal waste located in India.
- Limits to scale-up: none reported.
- Number of facilities in operation/reference plant (if any): about three facilities, located in New Zealand and China(2).
- Contact detail:
  - Contact person: Laurel Harmon.
  - Address: 725-C E. Irving Park Road, Roselle, Illinois 60172, USA.
  - Web address: [www.lanzatech.co.nz](http://www.lanzatech.co.nz)
  - Phone: +1 7344266272.
  - Email: [laurel@lanzatech.com](mailto:laurel@lanzatech.com)

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## Appendix B: environmental impact assessment

### B.1. Background

This section reviews the environmental performance of each technology option and compares these with the current disposal routes for low-grade, contaminated plastics (landfill and incineration). Each assessment is based on the mass and energy balance models that have been completed in section 4.8.

The key parameters in each assessment are the process yield (product and energy generation) and the energy consumed in each of the conversion processes. Other variables specific to each technology, such as catalyst use and transport, are also considered and quantified. As part of the assessment it is also important to clarify the emissions associated with the displacement of other products (such as petrol or diesel production phase) and energy.

The main assessment method will be to clarify the carbon footprint emissions associated with each technology option and compare them to landfilling, which is considered to be the baseline case for the study, as the quality of plastic considered is too low for reuse or recycling (an example of this type might be plastic film contaminated with food). Incineration is also presented as an alternative baseline case.

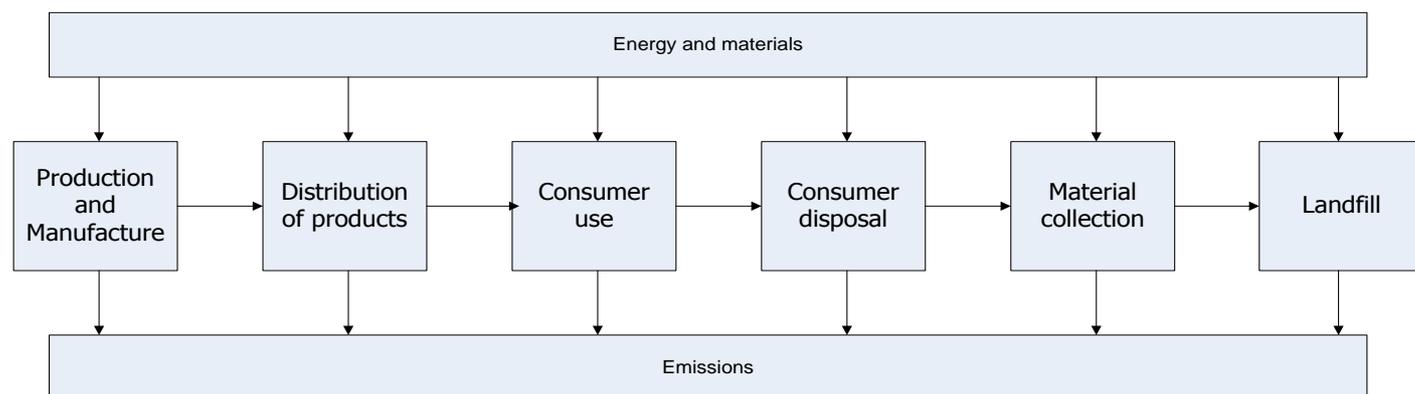
### B.2. Baseline case: mixed plastic wastes to landfill

The majority of plastics are derived from fossilised carbon in the form of crude oil. This crude oil undergoes a variety of treatment steps including distillation and polymerisation to produce a range of plastics which are manufactured into a wide variety of products including components in electrical equipment, packaging and carrier bags as well as building and construction materials. Products are purchased and used by a consumer before they come to the end of their useful life at which point they are disposed of. Whilst good-quality, relatively clean plastic can be separated and recycled cost effectively (e.g. plastic bottles), lower quality, heavily contaminated plastic is not currently reused or recycled. This material is normally disposed of either as a fuel source for energy recovery or as a landfill fraction.

Typically, rigid plastic material falls into the grouping of good-quality plastic for recycling, whereas a large fraction of flexible plastic (film and carrier bags) tends to be lower quality and more contaminated and is used as a fuel or disposed to landfill.

Currently in Scotland, this low-quality mixed plastic fraction is disposed to landfill, which is considered as the baseline case for comparison.

During each phase of the life cycle, there are energy or materials consumed, associated with the products and emissions generated. This life cycle is shown in **Figure 27**.

**Figure 27** Scenario 1: life cycle of low-quality, mixed plastic waste sent to landfill

### B.3. Alternative cases: mixed plastic waste thermal treatment to oil

The alternative cases involve diverting the material from landfill and utilising a thermal treatment technology to generate oil-rich material for upgrading into fuels or back into plastic. These technologies are:

- pyrolysis
- catalytic depolymerisation
- gasification with F-T
- gasification with MTG conversion
- gasification with biological conversion of syngas to ethanol.

Plastic films are manufactured, distributed and used in exactly the same manner as the baseline case scenario above. However, the main difference emerges after the point of material collection at which the low-quality plastic wastes are collected or extracted from the general residual waste stream. The material is transported to a thermal treatment plant and converted to diesel or gasoline.

#### *Mixed plastic wastes to oils via pyrolysis*

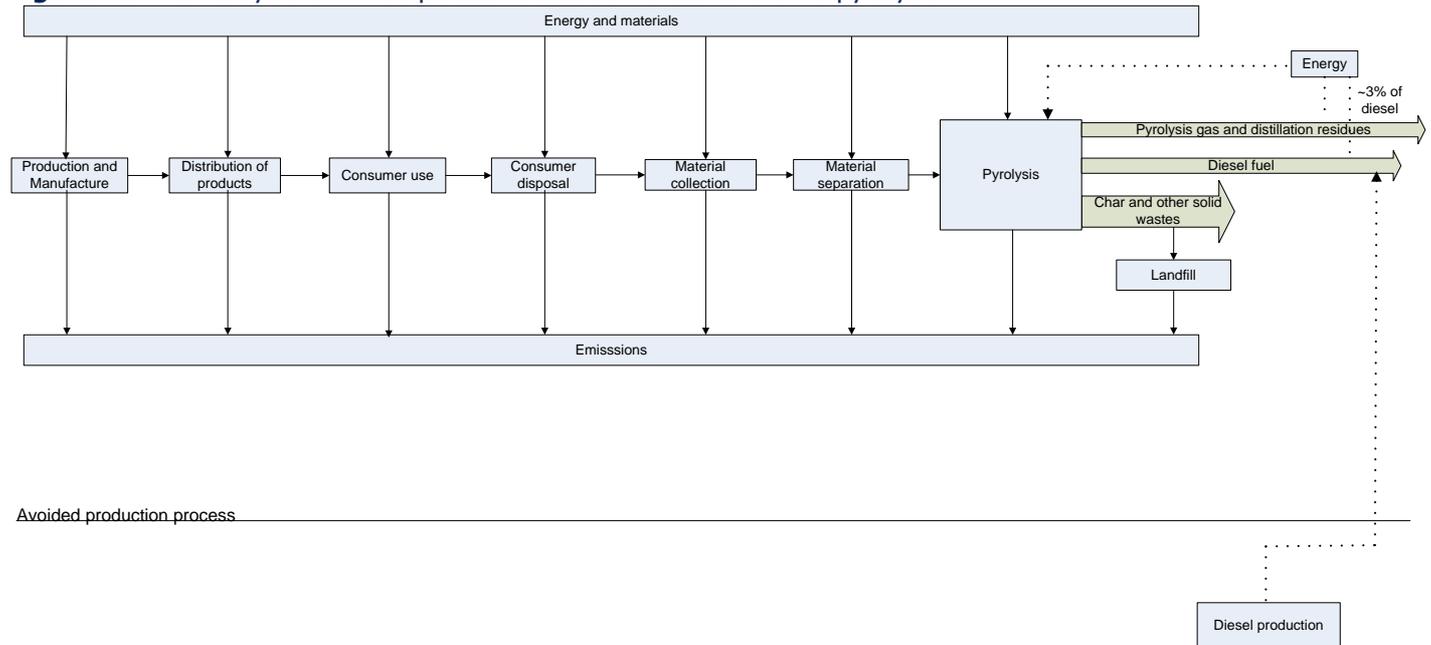
In this alternative scenario, the mixed plastic wastes are converted into oil fuels which are further refined to produce diesel for use as a fuel through a pyrolysis process.

The life cycle is shown in **Figure 28**. When plastic wastes are converted into fuel oils via pyrolysis, it is assumed that there is a displacement effect on the production phase of diesel fuel from crude oil. This means that the emissions associated with the production phase of fossil diesel via the normal processing route are avoided; they are displaced by the emissions associated with this proposed route. It is important to understand that this displacement affects only the phases associated with the production of diesel and not its use phase. Emissions associated with the use of the fuel regardless of the source (from either crude oil or plastic pyrolysed oil) will remain the same.

The pyrolysis process takes into account the downstream distillation processing required for the pyrolysed oil to be used directly as diesel. This downstream process also requires the introduction of a small amount of hydrogen to produce the desired diesel product. An assumption has also been made that the displacement effect is 100%. This implies that, for each kilogram of oil produced from waste plastic films, a kilogram of diesel fuel from a fossil source is displaced and therefore not produced.

The mixed plastic wastes obtained after the recyclables have been recovered, during the material separation stage, are transported to where they are dried and pyrolysed to produce a crude liquid, pyrolysis gas and char (and other residual solids) as waste. The char and other residual solids are transported to be landfilled and the crude liquid is further refined to diesel liquid, which can be sold and transported to be used in vehicles. During the distillation process, a small amount of hydrogen is introduced to make up for any hydrogen deficiency resulting from the upstream pyrolysis process. The residues from the downstream distillation processing and pyrolysis gas are non-condensable gases useful for the generation of heat when incinerated.

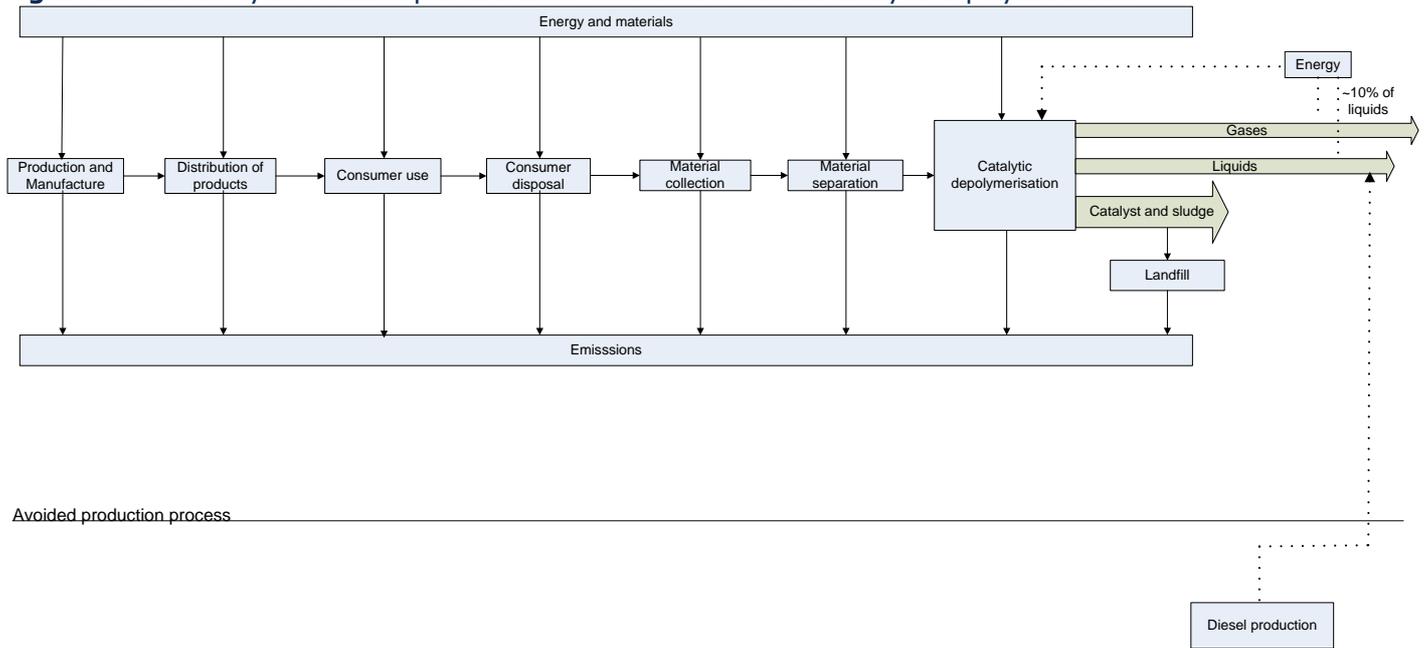
**Figure 28** The life cycle of mixed plastic wastes converted to oils via pyrolysis



#### *Alternative case: mixed plastic wastes to oils via catalytic depolymerisation*

The catalytic depolymerisation process uses catalysts to convert mixed plastic wastes to crude hydrocarbon after the initial upstream drying. A waste mixture of spent catalysts and sludge is produced also. These wastes are transported to a disposal site for landfilling, while the crude hydrocarbon is further processed in a distillation column to produce diesel liquids. During the distillation process, a small amount of hydrogen is introduced to make the desired diesel product. The diesel product can be sold and transported to be used directly in vehicles or incinerated to generate heat energy. The distillation process gives off residual gases which are incinerated to generate heat.

Diesel produced by this process leads to a 100% displacement effect on diesel fuel produced from fossil sources. The life cycle for this process is shown in **Figure 29**.

**Figure 29** The life cycle of mixed plastic wastes converted to oils via catalytic depolymerisation

### *Alternative case: mixed plastic wastes to oils via gasification with Fischer–Tropsch*

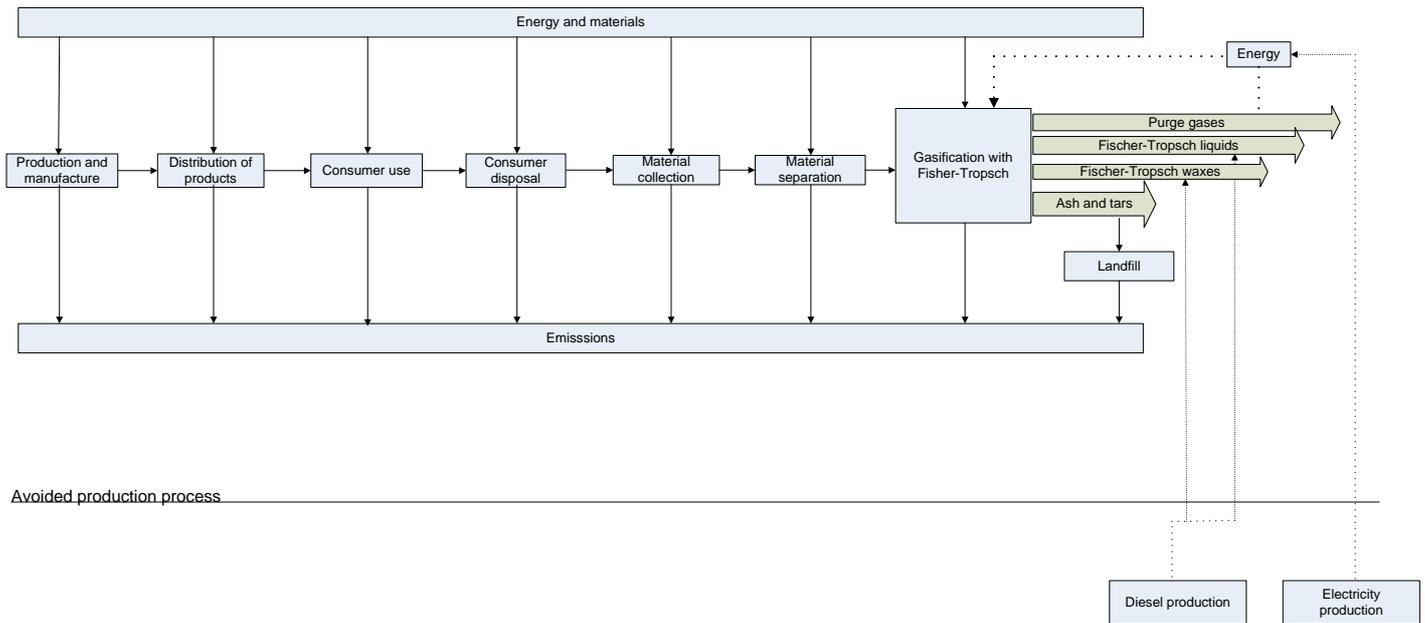
The mixed plastic wastes converted to F–T liquid predominantly displace the production of diesel from fossil sources. The mixed plastic wastes are transported to where they are dried and gasified using oxygen to produce crude syngas, which is further cooled and cleaned up. Prior to the F–T process, the syngas is processed in a water-gas shift reactor to increase the hydrogen level to that required for the production of F–T liquids and waxes. Consequently more carbon dioxide is produced, which ends up as purge gas from the F–T reactor. This purge gas also contains a fraction of combustible gases, which are incinerated to generate heat. Water is also produced from the F–T reactor, which is disposed of via mixed routes.

The F–T liquids produced fall within the diesel hydrocarbon range, and the F–T waxes can undergo further refining to produce more diesel. This diesel product can be sold and transported to be used directly in vehicles.

Ash and tar solid wastes are produced from gasification and syngas cooling and clean-up processes. These wastes are transported to a disposal site for landfilling.

The life cycle for this process is shown in **Figure 30**.

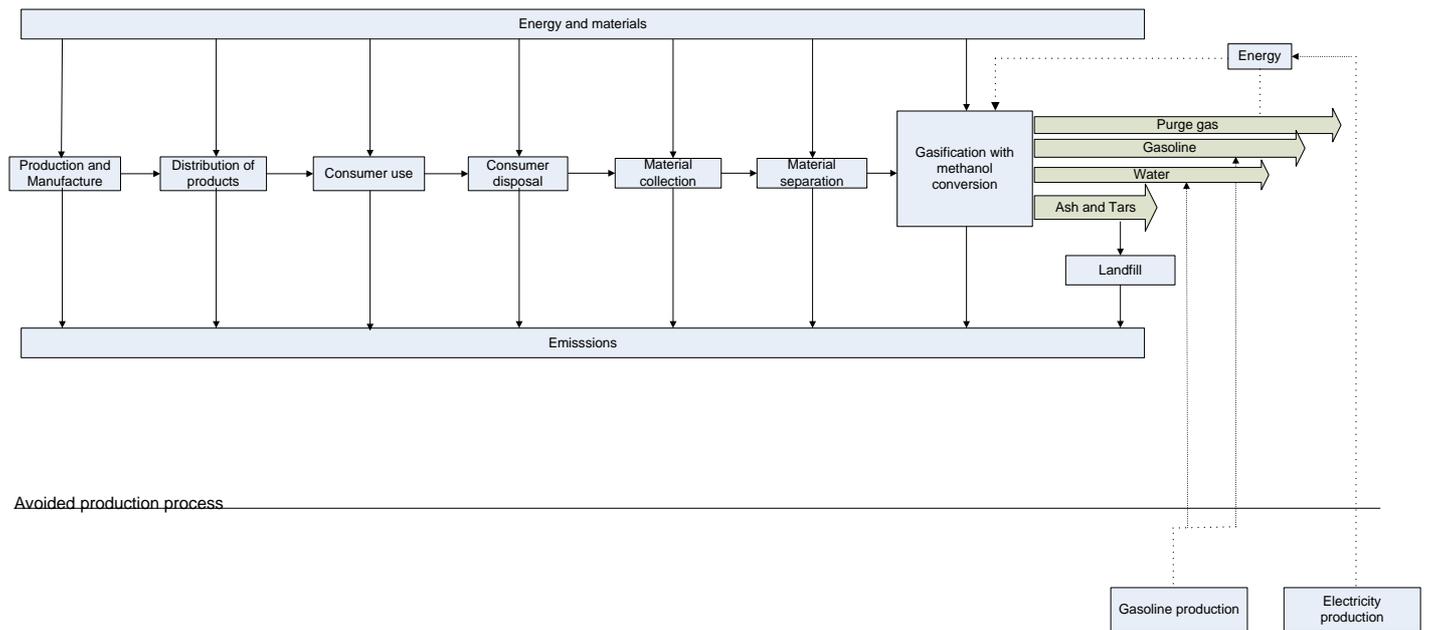
**Figure 30** The life cycle of mixed plastic wastes converted to oils via gasification with F–T



*Alternative case: mixed plastic wastes to oils via gasification with methanol conversion to gasoline*  
 The mixed plastic wastes are transported to where they are dried and gasified using oxygen to produce crude syngas and char. The crude syngas is cooled and cleaned up, producing tar as waste. Both the tar and char produced are transported to a disposal site for landfilling. The clean syngas, which is hydrogen and carbon monoxide, is converted in a water–gas shift reactor to produce carbon dioxide and more hydrogen. These gases are further used for the production of methanol, giving off a ‘purge gas’ and water as by-products. The methanol produced is subsequently converted to gasoline, giving off more purge gas and water. The purge gas is predominantly carbon dioxide with small amounts of hydrogen and carbon monoxide and some hydrocarbon molecules. The purge gas is incinerated to generate heat energy. The gasoline can be sold and transported to be used as petrol fuel in vehicles.

The conversion of syngas to methanol displaces the production of gasoline by fossil sources. Methanol produced from the process is converted to gasoline. The life cycle for the process is shown in **Figure 31**.

**Figure 31** The life cycle of mixed plastic wastes converted to oils via gasification with methanol conversion to gasoline

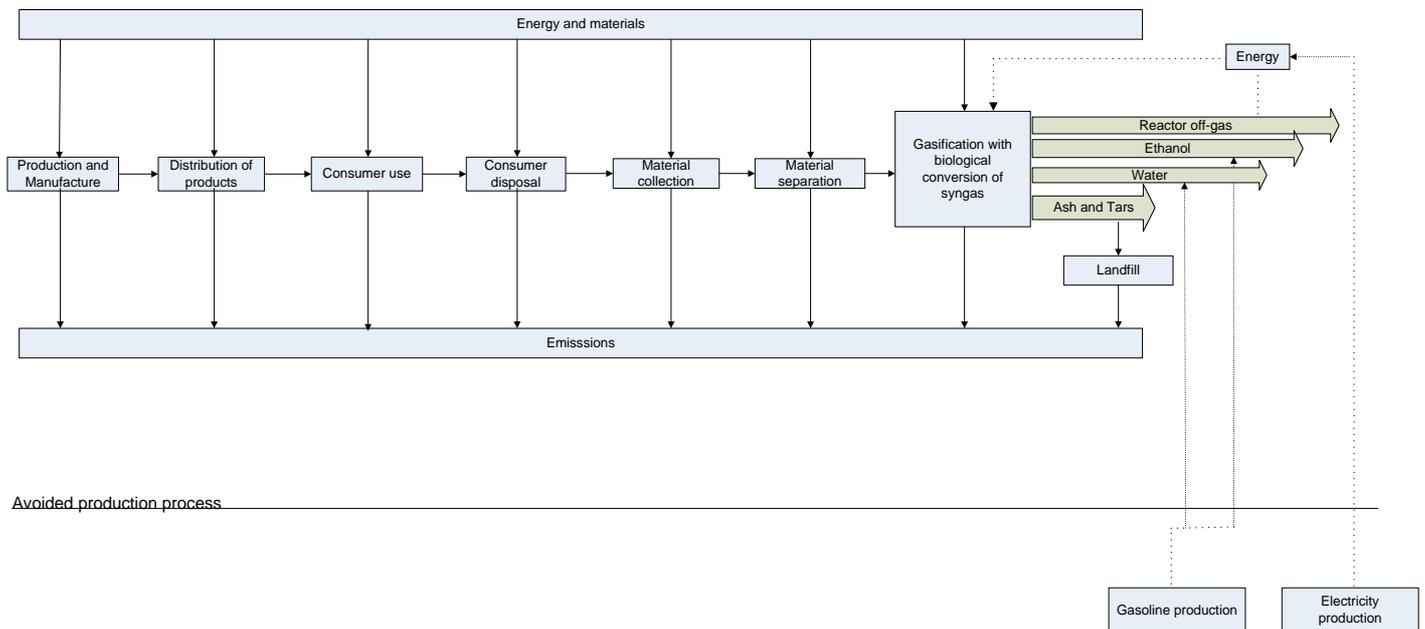


*Alternative case: mixed plastic wastes to oils via gasification with biological conversion of syngas to ethanol*

Ethanol produced from syngas fermentation is blended preferably with gasoline, displacing the production of gasoline via the traditional route. The life cycle diagram is shown in **Figure 32**.

Gasification with syngas fermentation converts clean syngas to dilute ethanol, giving off a reactor gas rich in carbon dioxide. Crude syngas is initially produced from gasifying dried mixed plastic wastes transported from a material separation facility to a drier. This crude syngas is cooled and cleaned up, producing tar as waste. The tar and char wastes produced from gasification are transported to a disposal site for landfilling. The dilute ethanol is further distilled to produce a more concentrated ethanol product and water as a by-product. The ethanol product is transported to be blended with petrol used directly in cars and the water disposed of.

**Figure 32** The life cycle of mixed plastic wastes converted to oils via gasification with biological conversion of syngas to ethanol



Avoided production process

## B.4. The environmental assessment study

### *Purpose*

This preliminary assessment aims to quantify and evaluate the GHG emissions of a number of mixed waste plastic thermal treatment technologies. The purpose is to quantify the environmental burdens or benefits that may arise as a result of commercialising the conversion technologies as an alternative to the current 'business-as-usual case' of landfill.

A further aim is to highlight the key variables that influence the potential environmental impact of each conversion technology.

The assessment reviews the impacts from each treatment/conversion process described above and compares them with those associated with the current landfill disposal route. Additionally, when oil-based product or power is generated, the emissions associated with product or power replacement are also considered.

### *Functional units*

The basis for comparison between the various options is 1,000kg of wet mixed plastic waste as feed to the conversion to oil process. The composition of the wet mixed plastic waste is 77% mixed plastic materials, 13% contaminants and 10% moisture content. The contaminants are cellulosic materials such as paper. These mixed waste plastics and cellulosic materials are residual waste after the recyclables have been recovered. This unit is used to ensure that a 'like-for-like' comparison is used in the review.

### *Scope*

Whilst a full environmental impact assessment may be useful, at this initial stage, at which technical feasibility is being reviewed, global emissions are more important than local or regional emissions. Therefore, the assessment will concentrate on the global warming potential by reviewing the GHG

emissions associated with the processes that will change or arise as a result of any of these technologies being implemented; the life cycle changes will occur downstream of consumer disposal (this is covered in detail in the **System Boundaries** section.)

For each thermal treatment technology, GHG emissions associated with the following must be considered:

- Material manufacture of any consumables: this includes emissions resulting from the manufacture of other material input to the process for the production of the desired output product.
- Material transport: this includes emissions from the transportation of the feed material and other materials required for the process.
- Site utilities: this includes the utility consumption in running the plant and emissions associated with the production of the utility.
- Site emissions: this includes emissions created on site owing to the process.
- Waste transport: this includes emissions arising from the transportation of waste materials from the process.
- Product transport: this includes emissions arising from the transportation of the product.
- Displacement of fuel production from fossil sources.
- Material transport to disposal (baseline case): this includes emissions arising from the transportation of the mixed plastic waste.
- Disposal emissions (baseline case).

The following are excluded from the study on the basis that their impact is negligible:

- production or maintenance of the vehicles used for transport;
- production or maintenance of machinery/equipment used in the process;
- manufacture and maintenance of buildings associated with the process;
- emissions associated with human labour and office energy consumption; and
- miscellaneous materials used in small quantities on the plant (e.g. cleaning fluids or antifreeze).

It is important to note that emissions associated with the manufacture of buildings, vehicles and industrial machinery/equipment are normally negligible when spread across a ~25-year lifetime of a plant processing large tonnages on a daily basis.

### *System boundaries*

To keep each assessment and the comparisons consistent, the boundary of the assessment has been limited to a 'gate-to-grave' or 'gate-to-gate' approach, rather than a full life cycle assessment. The initial stages for each scenario, which are production and manufacture, distribution, consumer use, consumer disposal, and material collection and separation, are assumed to be the same for each case and are thus not considered within the boundary limits of the study.

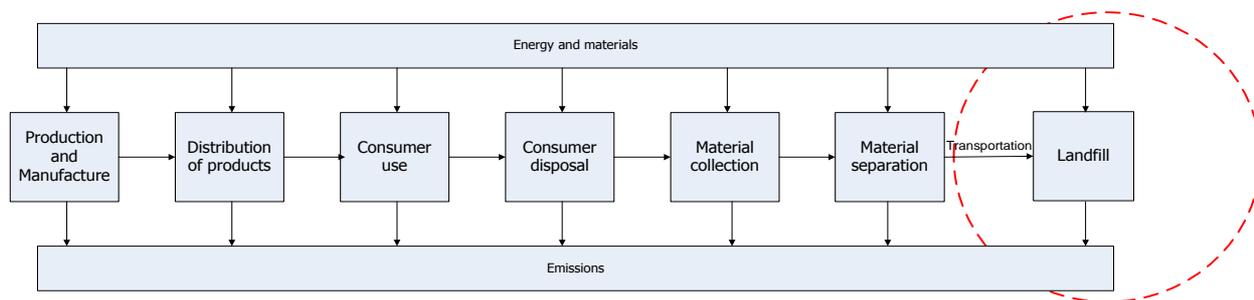
This assessment compares the emissions from mixed plastic waste from the point of material collection to landfill versus emissions associated with thermal conversion technologies off-set against displacement from production of oil-based material from other sources.

### *Baseline case: mixed plastic wastes to landfill*

For the baseline case, the system boundary takes into account the following stages:

- the transportation of the mixed waste plastic after all recyclables have been recovered; and
- landfill.

The boundaries for the baseline case assessment are shown in **Figure 33**.

**Figure 33** Flow diagram showing the boundary of the baseline scenario

#### *Alternative cases: mixed plastic waste thermal treatment to oil (general)*

It is assumed that the initial municipal solid waste collection, transfer and mechanical separation upstream of the proposed conversion processes will be the same for each technology type reviewed. During this initial material separation stage, it is assumed that most of the high-value and easy-to-recover material will be removed, leaving a residue stream rich in mixed plastic.

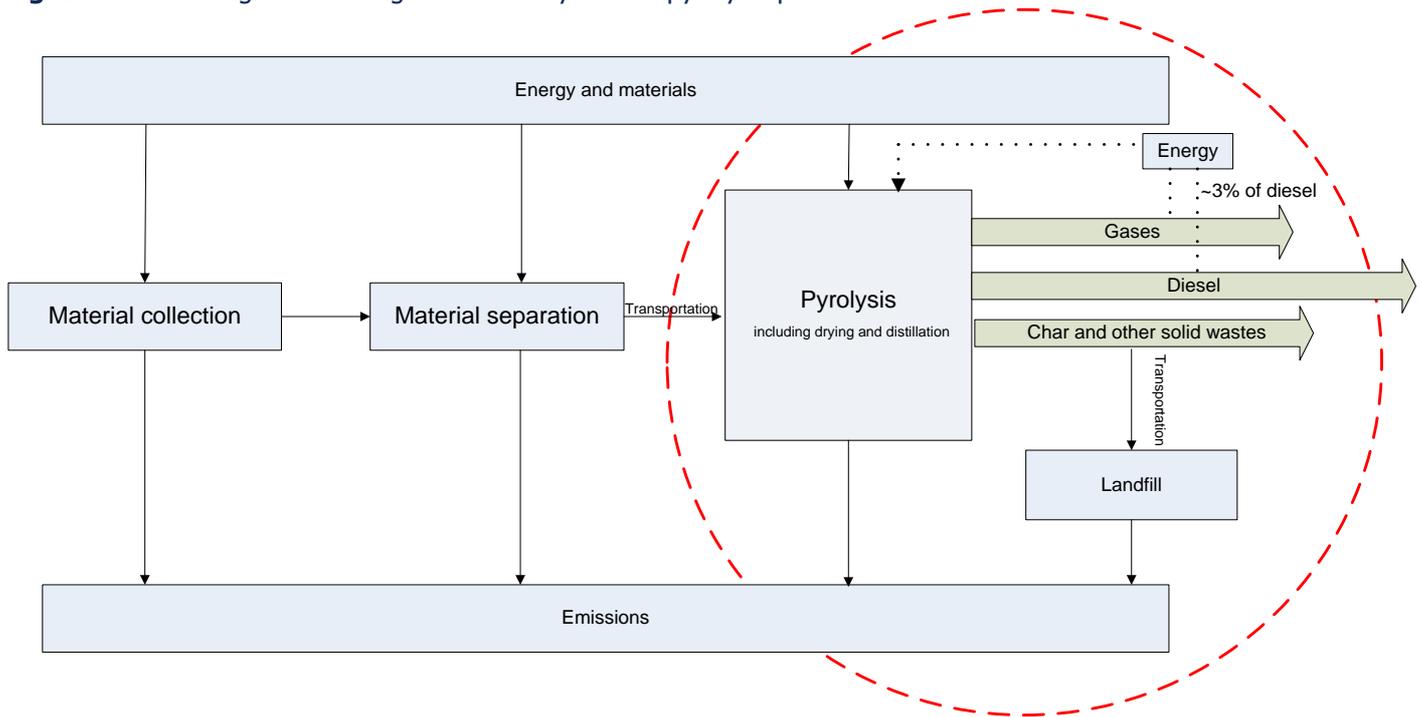
For the alternative cases, the system boundary takes into account the following stages:

- transportation of the mixed plastic waste, collected from an MRF after material separation of recyclables, to a thermal treatment facility;
- treatment site;
- thermal treatment to produce oil;
- transport of products and wastes generated from thermal treatment process; and
- disposal of wastes generated from thermal treatment process.

Generating an oil-based product from plastic wastes will mean that fuel generated from crude oil is displaced. In situations in which displacement of fuel from fossil sources occurs, only the production phase is considered. The use phase is not considered as the emissions associated with either source will be the same, as the fuel is initially sourced from fossilised carbon.

The scope and boundary for each conversion technology are based on the technology type and process flow diagram in section 4. Each process flow diagram shows the process steps, material and energy inputs and outputs for each option.

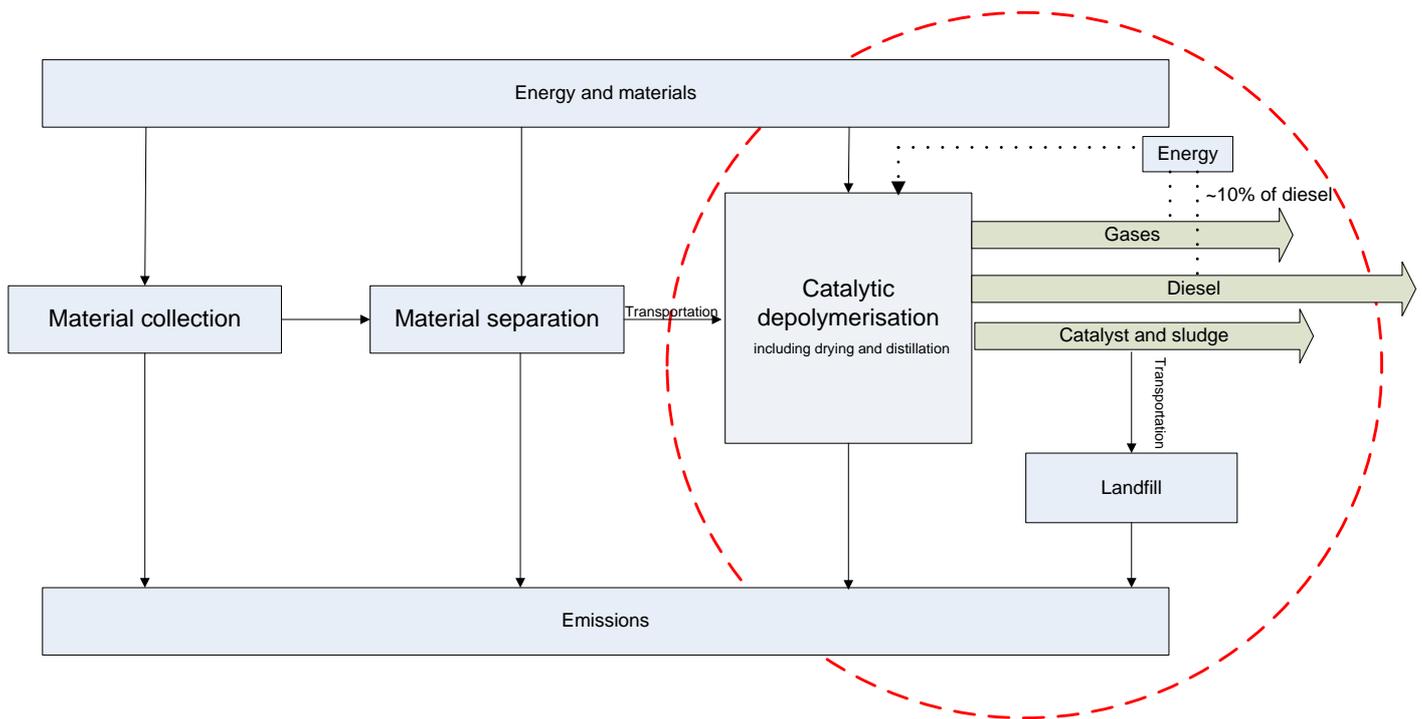
The boundaries for the alternative case assessment are shown in **Figure 34** to **Figure 38**.

**Figure 34** Flow diagram showing the boundary for the pyrolysis process

The system boundary for the pyrolysis process accounts for the transportation of a wet mixed plastic waste, which is dried to remove some moisture before being pyrolysed. The pyrolysed oil is further distilled to recover diesel, which is transported both locally and nationally. The manufacture of a small amount of hydrogen introduced in the downstream distillation process is included. The carbon residues from the pyrolysis process are transported to a local disposal site.

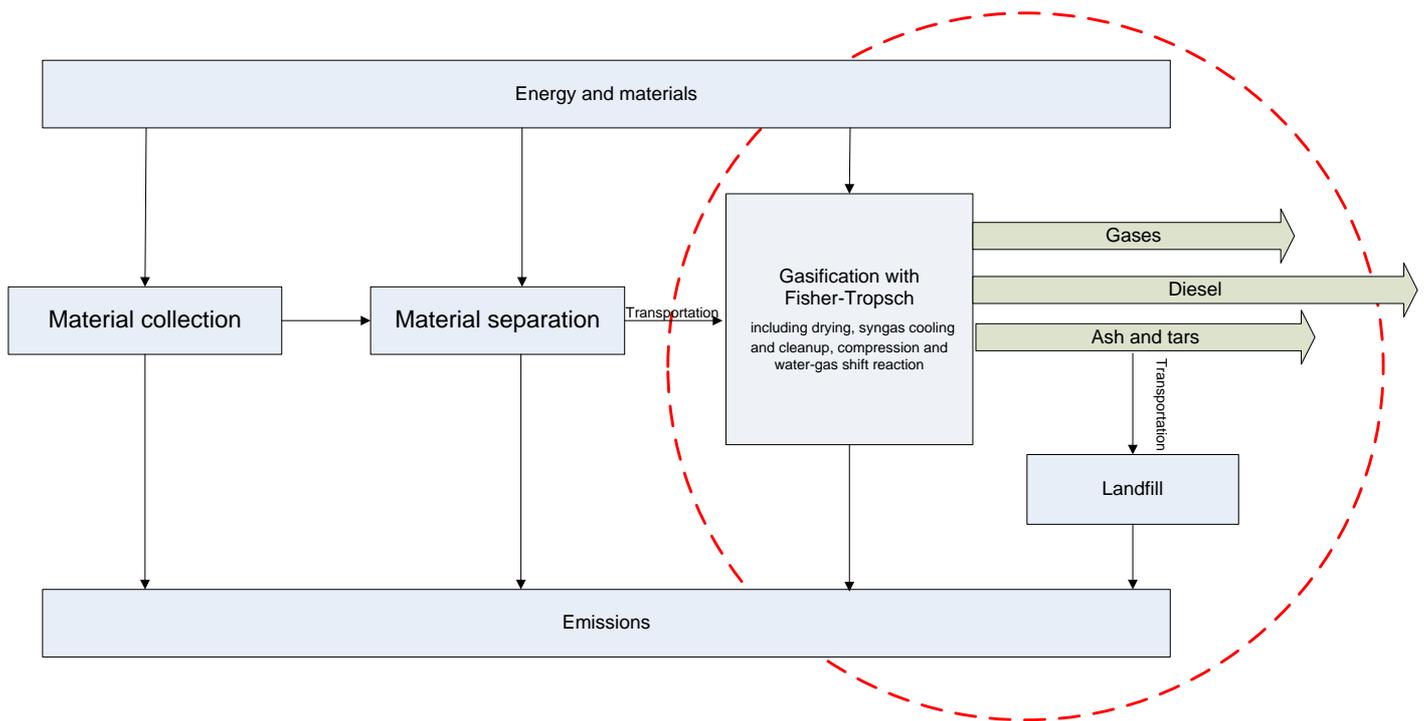
The boundary for the pyrolysis system accounts for:

- The transportation of wet mixed plastics to the pyrolysing system, which includes an upstream drier, a pyrolysis reactor and a downstream distillation column.
- The manufacture of a small amount hydrogen, which is introduced to the distillation column in order to produce the desired diesel product.
- The on-site processes of drying, pyrolysis and the downstream distillation processing. The drying process releases water vapour to the atmosphere, the pyrolysis process produces a crude liquid, pyrolysis gas and char. The distillation processing refines the crude liquid to a diesel product, giving off residues. Both the pyrolysis gas and distillation residues are incinerated for heat energy generation.
- The transportation of char (and other solid wastes) to a disposal site for landfilling.
- The transportation of the diesel product for use.

**Figure 35** Flow diagram showing the boundary for the catalytic depolymerisation process

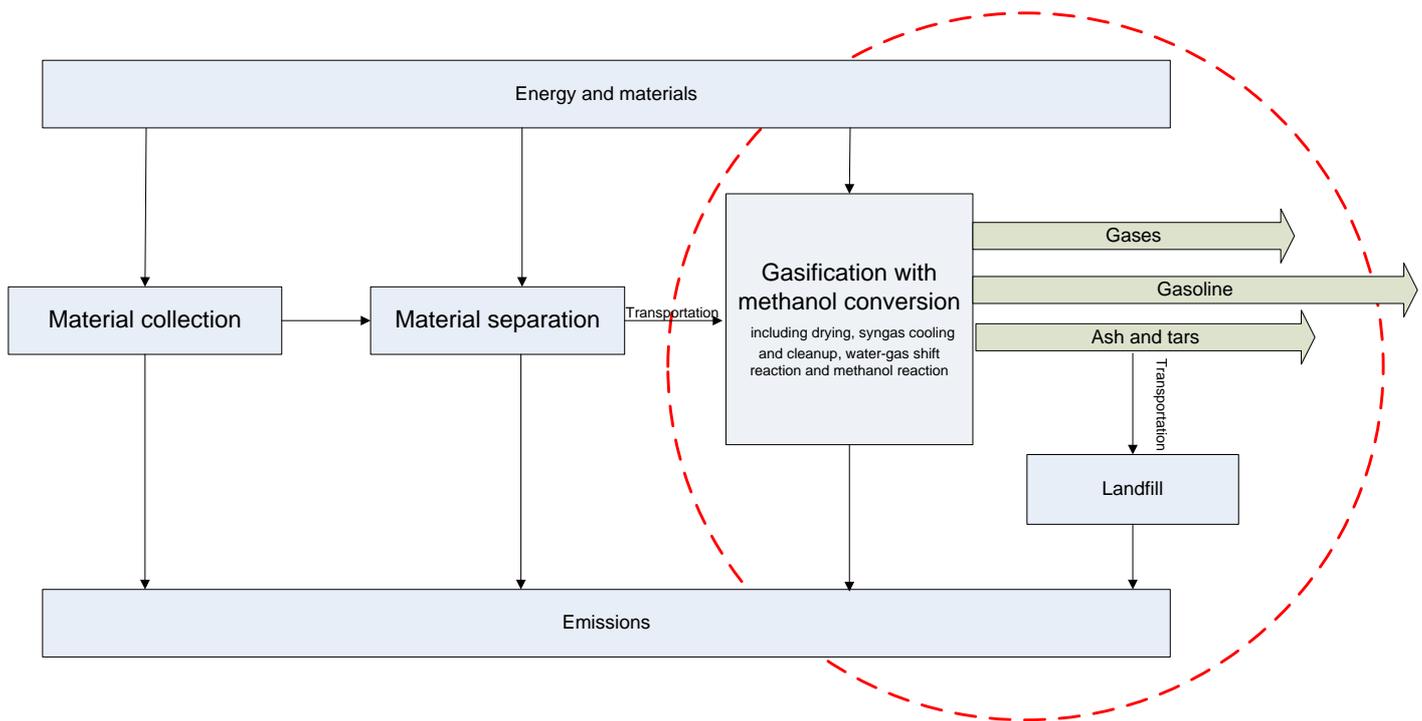
The boundary for the catalytic depolymerisation system accounts for:

- The transportation of wet mixed plastics to the depolymerisation system, which includes an upstream drier, a depolymerisation reactor and a downstream distillation column.
- The manufacture and transportation of the catalyst employed continuously in the depolymerisation process.
- The manufacture of a small amount of hydrogen, which is introduced to the distillation column to make up for the hydrogen deficiency resulting from the previous reaction and to ensure that the desired diesel product is made.
- The on-site processes of drying, depolymerisation and the downstream distillation processing. The drying process releases water vapour to the atmosphere, the depolymerisation process produces a crude hydrocarbon and spent catalyst and sludge as waste. The distillation process refines the hydrocarbon to the desired diesel product, giving off gases which are incinerated for heat energy generation.
- The transportation of the spent catalyst and sludge to a disposal site for landfilling.
- The transportation of the diesel product for use.

**Figure 36** Flow diagram showing the boundary for the gasification with F–T process

The boundary for the gasification with F–T system accounts for:

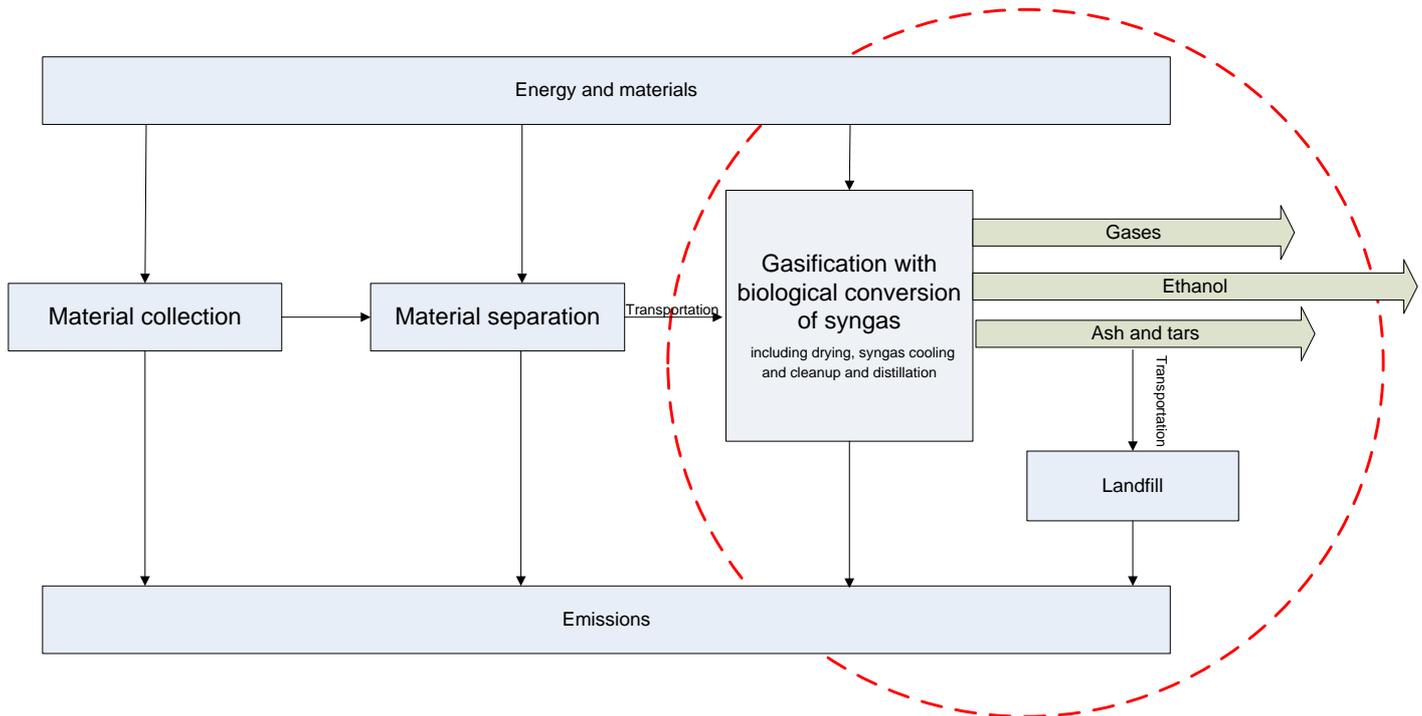
- The transportation of wet mixed plastics to the gasification with F–T system, which includes an upstream drier, gasifier, syngas cooler, compressor, water–gas shift reactor and F–T reactor.
- The manufacture of oxygen used for gasifying the mixed plastic wastes.
- The on-site production of steam input for the water–gas shift reaction and steam output for electricity generation or directly as heat energy.
- The on-site processes of drying, gasifying, syngas cooling, compressing, water–gas shift reaction and F–T reaction. The drying process releases water vapour to the atmosphere; the gasifier process produces a crude syngas and char, and the crude syngas is cleaned up and compressed. The compressed syngas is reacted in the water–gas shift reactor before it is fed into the F–T reactor, where water, F–T liquid, F–T waxes and purge gas are produced. The F–T liquid is diesel and the F–T waxes are further processed to produce more diesel. The purge gas is incinerated to generate heat energy.
- The transportation of the char waste from the gasifier and tar waste from the syngas cooling and clean-up process to a disposal site for landfilling.
- The transportation of the diesel product for use.

**Figure 37** Flow diagram showing the boundary for the process of gasification with methanol conversion to gasoline

The boundary for the system of gasification with methanol conversion accounts for:

- The transportation of wet mixed plastics to the gasification with methanol system, which includes an upstream drier, gasifier, syngas cooler, compressor, water–gas shift reactor, methanol reactor and MTG reactor.
- The manufacture of oxygen used for gasifying the mixed plastic wastes.
- The on-site production of steam input for the water–gas shift reaction and steam output for electricity generation or directly as heat energy.
- The on-site processes of drying, gasifying, syngas cooling, compressing, the water–gas shift reaction and the methanol reaction and the MTG reaction. The drying process releases water vapour to the atmosphere; the gasifier process produces a crude syngas, which is cleaned up and compressed, and char. The compressed syngas is reacted in the water–gas shift reactor prior to it being fed into the methanol reactor, where water, methanol and purge gas are produced. Subsequently, the methanol is converted to gasoline in the MTG reactor producing water, gasoline and purge gas. The purge gas from the methanol reactor and MTG reactor are incinerated to generate heat energy.
- The transportation of the char waste from the gasifier and tar waste from the syngas cooling and clean-up process to a disposal site for landfilling.
- The transportation of the gasoline product for use.

**Figure 38** Flow diagram showing the boundary for the process of gasification with biological conversion of syngas to ethanol



The boundary for the system of gasification with biological conversion of syngas accounts for:

- The transportation of wet mixed plastics to the gasification with syngas fermentation system, which includes an upstream drier, gasifier, syngas cooler, bioethanol reactor and distillation column.
- The manufacture of oxygen used for gasifying the mixed plastic wastes.
- The on-site production of steam output for electricity generation or directly as heat energy.
- The on-site processes of drying, gasifying, syngas cooling, fermentation and distillation. The drying process releases water vapour to the atmosphere; the gasifier process produces a crude syngas, which is cooled and cleaned up producing tars as waste, and char. The clean syngas is fermented in a bioethanol reactor producing a reactor off-gas, water and dilute ethanol. Subsequently, the dilute ethanol is distilled to produce a more concentrated ethanol product and water as a by-product. The reactor off-gas is incinerated to generate heat energy and the water is disposed of.
- The transportation of the char waste from the gasifier and tar waste from the syngas cooling and clean-up process to a disposal site for landfilling.
- The transportation of the ethanol product for use.

#### *Data and assumptions*

Data were collected from a number of sources to quantify the relevant inputs and outputs for each technology option.

In general, the construction of each model considers the additional impacts, in terms of carbon emissions, of the new technology and the reduction in impacts associated with the previous methods of disposal, as well as any impact from product substitution.

***Baseline case: mixed plastic wastes to landfill***

- For the baseline case, whereby 1,000kg of wet mixed plastic waste are disposed of to landfill, the Carbon Trust Footprint Expert Database<sup>19</sup> has been used to calculate the emissions associated with the collection and transportation of the materials and landfill emissions. The basis of the composition is 77% mixed plastic materials, 13% contaminants and 10% moisture content.

***Alternative case: mixed plastic wastes to oils***

For the thermal treatment processes that convert mixed plastic waste to diesel, gasoline or ethanol – considered as a stand-alone technology – there is a number of environmental emissions that need to be quantified. Additionally, by converting the waste plastic to fuel oil or blending liquid (ethanol), there is also a reduction in the amount of waste plastic material disposed of to landfill as well as a displacement effect on the emissions associated with diesel or gasoline production from crude oil.

- For all the thermal treatment cases, whereby mixed plastics are converted to fuel or a liquid for blending with fuel, the Carbon Trust Footprint Expert Database<sup>19</sup> has been used to calculate the emissions associated with the transportation of the input materials, the transportation of the product, on-site processes, downstream distillation processing when required, and waste generated and its transportation to disposal sites for landfilling.
- For the manufacture of hydrogen input to the pyrolysis and catalytic depolymerisation processes, data from the Carbon Trust Footprint Expert Database have been used.
- Data from the US Environmental Protection Agency (EPA)<sup>20</sup> have been used to quantify the percentage of carbon emissions associated with the production of diesel and gasoline fuels from a more standard petrochemical refining route. The Carbon Trust reference database value has been used to calculate the emissions associated with diesel and gasoline production from fossil sources including the use phase.
- For the three gasification options, which require oxygen, data have been used for oxygen production and sourced from the Carbon Trust Footprint Expert Database.

***General assumptions and notes***

General assumptions made in this study are given below.

***Transport***

Composition of feedstock is assumed to be a wet mixed plastic-rich material that is unsuitable for reuse or recycling. The basis of the composition is 77% mixed plastic materials, 13% contaminants and 10% moisture content.

Whilst material will be sourced across the country and distances are dependent on location, it is fair to say most material will be sourced from MRFs along the M8 corridor that links Glasgow and Edinburgh. It has been assumed that any plant would be located in this area and 70% of the waste would be sourced within a 100km radius of the plant, whilst the remaining 30% would travel 350km to the site.

Whilst it is recognised that there are other potential sources of low-grade waste plastics that may be suitable for advanced thermal treatment technologies, these are not specifically included in this assessment and would need to be considered separately.

***Current disposal route***

The current distance waste from MRFs is transported to landfill is assumed to be 25km. This figure has also been used as the distance for solids disposal of any material arising from any new facility.

### *Material and energy off-sets*

In all possible cases, site consumption of any heat and power generated will be assumed in preference to supplying external third parties or the National Grid. When an excess of power is generated, this will be exported to the National Grid. The displaced fossil fuel will be based upon the UK specific grid mix for 2012.

### *Case-Specific assumptions*

#### *Baseline case*

- For emissions from landfilling, 1,000kg of wet mixed plastic waste containing 13% contaminant (sand, stone, glass and metals) and 10% moisture was assumed. The average emission values are based on modelling carried out by the Carbon Trust in 2008.

#### *Pyrolysis*

- Hydrogen is produced on site by an independent supplier. The hydrogen required is 1%, by weight, of the feed input on a water-free basis. The emission factor used for hydrogen production includes all the process steps involved in producing hydrogen from the natural gas production/processing stage to the hydrogen product.
- With regards to on-site emissions, water vapour from the drying of feed materials has zero carbon impact. All the carbon residues produced from the process are burnt to generate energy. Emissions associated with this process are included.
- 1721kW of input energy is required in the form of heat for the dryer, pyrolyser and distillation plant.
- All the heat energy for the plant is provided self-sufficiently by combustion of the pyrolysis off-gas, distillation residue and 3% of the product oil. Emissions from incineration to generate heat have been accounted for in the on-site emissions.
- A net value of 660kg of diesel is produced, displacing the production of 660kg of diesel from the normal petroleum-based route. For clarity, it is important to highlight that the emissions associated with this are for the production process only and do not include the use phase (that is, combustion). The main reason for this allowance is that the pyrolysis diesel is also from fossilised carbon and so will produce an equivalent quantity of GHG emissions from combustion.

#### *Catalytic depolymerisation*

- Similar to pyrolysis, hydrogen is produced on site and not in excess. The water vapour from drying the feed material has a negligible carbon impact. Only about 25% of the materials in the catalyst and sludge mix have a negligible carbon impact.
- The typical catalyst used in a catalytic depolymerisation process is alumina silicate zeolite. However, in the absence of emissions data being available for this product, emissions data from the manufacture of calcium silicate have been used.
- The input energy required for the catalytic depolymerisation process, including the drying and the distillation phase, is 944kW. All the energy needed for the process is provided by incineration of 10% of the product oils and emissions from this have been accounted for. Thus, a net diesel product of 616kg is produced from the process.

#### *Gasification with Fischer-Tropsch*

- Water vapour emitted during the drying phase has zero emissions associated with it.
- The waste ash and tars are landfilled. This waste is assumed to be inert and have zero emissions.

- The waste water from the F–T reactor is disposed of. The density of the water from the process is 1kg/l and emissions associated with the delivery of clean water to the plant and effluent treatment of the waste water are accounted for.
- 1457kW of input energy is required in the form of heat for the dryer, electricity for the compressor and steam for the water–gas shift reactor. All the heat energy needed is provided through the generation of steam from the process and the incineration of the purge gas.
- The remaining excess 2216kW of heat is used to generate electricity at 35% efficiency (that is, the site is self-supporting and can provide a minimal amount of electricity back to the grid).
- 228kg of diesel is produced, displacing the production of 228kg of diesel from the normal petroleum-based route.

#### *Gasification with methanol conversion to gasoline*

- Water vapour emitted during the drying phase has zero emissions associated with it.
- Waste water from both the methanol reactor and the MTG reactor is disposed of. The density of the water from the process is 1kg/l and emissions associated with the delivery of clean water to the plant and effluent treatment of the waste water are accounted for.
- 2221kW of input energy is required in the form of heat for the dryer, electricity for the compressor and steam for the water–gas shift reactor. All the heat energy needed is provided through the generation of steam from the process and the incineration of the purge gas.
- The remaining excess 2201kW of heat is used to generate electricity at 35% efficiency (that is, the site is self-supporting and can provide a minimal amount of electricity back to the grid).
- 336kg of gasoline is produced, displacing the production of 336kg of gasoline from the normal petroleum-based route.

#### *Gasification with biological conversion of syngas to ethanol*

- Water vapour emitted during the drying phase has zero emissions associated with it.
- Waste water from the distillation column is disposed of. The density of the water from the process is 1kg/l and emissions associated with the delivery of clean water to the plant and effluent treatment of the waste water are accounted for.
- 906kW of input energy is required in the form of heat for the dryer and distillation column. All the heat energy needed is provided through the generation of steam from the process and the incineration of the reactor off-gas.
- The remaining excess 1987kW of heat is used to generate electricity at 35% efficiency (that is, the site is self-supporting and can provide a minimal amount of electricity back to the grid).
- 584kg of ethanol is produced, displacing the production of 584kg of gasoline from the normal petroleum-based route.

## B.5. Impact assessment

Carbon emissions are expressed as kg of CO<sub>2</sub>(e) per 1,000kg of wet mixed plastic waste for landfill disposal.

### *Baseline case: mixed plastic waste to landfill*

The carbon footprint associated with the transport to disposal site and landfill emissions of 1,000kg of wet mixed plastic waste is 70.8kgCO<sub>2</sub>(e). This value includes emissions from the cellulosic contaminants present in the material. The GHG emissions associated with landfill are shown in **Table 48**.

**Table 48** GHG emissions for landfill

Description	Quantities	CO <sub>2</sub> emission factor	CO <sub>2</sub> emission per functional unit
<b>Material transport: 1,000kg MSW plastic-rich residue sourced locally</b>			
· Road transport (local)	50.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	15.1kg CO <sub>2</sub> (e)
<b>Total</b>			<b>15.1kg CO<sub>2</sub> (e)</b>
<b>Site emissions (landfill disposal)</b>			
· Mixed plastic	766.0kg	0.0219kg CO <sub>2</sub> (e)/kg	16.8kg CO <sub>2</sub> (e)
· Contamination	134.0kg	0.2902kg CO <sub>2</sub> (e)/kg	38.9kg CO <sub>2</sub> (e)
· Water	100.0kg	0.0000kg CO <sub>2</sub> (e)/kg	0.0kg CO <sub>2</sub> (e)
<b>Total</b>			<b>55.7kg CO<sub>2</sub> (e)</b>
<b>Grand total emissions</b>			<b>70.8kg CO<sub>2</sub> (e)</b>
<b>Displacement</b>			
· Diesel production	0.0kg	3.7948kg CO <sub>2</sub> (e)/kg	0.0kg CO <sub>2</sub> (e)
<b>Total</b>			<b>0.0kg CO<sub>2</sub> (e)</b>
<b>Emissions less displacement</b>			<b>70.8kg CO<sub>2</sub> (e)</b>

Landfill GHG emissions are calculated at 71 kgCO<sub>2</sub>(e).

*Alternative baseline case: mixed plastic wastes to oils*

As an alternative baseline case, incineration was considered instead of landfill. The GHG emissions associated with incineration are shown in **Table 49**.

**Table 49** GHG emissions for incineration

Description	Quantities	CO <sub>2</sub> emission factor	CO <sub>2</sub> emission per functional unit
<b>Material transport: 1,000kg MSW plastic rich residue sourced locally</b>			
· Road transport (local)	50.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	15.1kg CO <sub>2</sub> (e)
<b>Total</b>			<b>15.1kg CO<sub>2</sub> (e)</b>
<b>Site emissions (incineration)</b>			
· Mixed plastic waste	1,000.0kg	2.4080kg CO <sub>2</sub> (e)/kg	2,408.0kg CO <sub>2</sub> (e)
<b>Total</b>			<b>2,408.0kg CO<sub>2</sub> (e)</b>
<b>Grand total emissions</b>			<b>2,423.1kg CO<sub>2</sub> (e)</b>
<b>Displacement</b>			
· Electrical energy (UK average)	900.0kWh	0.6283kg CO <sub>2</sub> (e)/kWh	565.5kg CO <sub>2</sub> (e)
<b>Total</b>			<b>565.5kg CO<sub>2</sub> (e)</b>
<b>Emissions less displacement</b>			<b>1,857.6kg CO<sub>2</sub> (e)</b>

Incineration GHG emissions are calculated at 1,858 kgCO<sub>2</sub>(e).

*Alternative case: mixed plastic wastes to oils*

The GHG emissions associated with each alternative process are considered in more detail below.

### *Alternative case: mixed plastic wastes to oils via pyrolysis*

A breakdown of the CO<sub>2</sub> emissions associated with pyrolysis is given in **Table 50**.

**Table 50** GHG emissions for pyrolysis including displacement of diesel fuel production

Description	Quantities	CO <sub>2</sub> emission factor	CO <sub>2</sub> emission per functional unit
<b>Material manufacture</b>			
· Hydrogen	7.66kg	1.70kg CO <sub>2</sub> e/kg	13.0kg CO <sub>2</sub> (e)
<b>Total</b>			<b>13.0kg CO<sub>2</sub> (e)</b>
<b>Material transport: 700kg MSW plastic-rich residue sourced locally, 300kg MSW plastic-rich residue sourced nationally</b>			
· Road transport (local)	200.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	42.4kg CO <sub>2</sub> (e)
· Road transport (national)	700.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	63.5kg CO <sub>2</sub> (e)
<b>Total</b>			<b>105.9kg CO<sub>2</sub> (e)</b>
<b>Site emissions</b>			
· Water vapour from drying	53.0kg	0.0000kg CO <sub>2</sub> (e) /kg	0.0kg CO <sub>2</sub> (e)
· Pyrolysis gas	95.0kg	0.2904kg CO <sub>2</sub> (e) /kg	27.6kg CO <sub>2</sub> (e)
· Char	97.0kg	0.0000kg CO <sub>2</sub> (e) /kg	0.0kg CO <sub>2</sub> (e)
· Distillation residues	76.0kg	0.2904kg CO <sub>2</sub> (e) /kg	22.1kg CO <sub>2</sub> (e)
· Product used for CHP generation	20.4kg	0.2904kg CO <sub>2</sub> (e) /kg	5.9kg CO <sub>2</sub> (e)
<b>Total</b>			<b>55.6kg CO<sub>2</sub> (e)</b>
<b>Waste transport: 97.0kg char</b>			
· Road transport (local)	50.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	1.5kg CO <sub>2</sub> (e)
<b>Total</b>			<b>1.5kg CO<sub>2</sub> (e)</b>
<b>Product transport: 329.8kg diesel product transported locally, 329.8kg diesel product transported nationally</b>			
· Road transport (local)	200.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	20.0kg CO <sub>2</sub> (e)
· Road transport (national)	700.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	69.9kg CO <sub>2</sub> (e)
<b>Total</b>			<b>89.8kg CO<sub>2</sub> (e)</b>
<b>Grand total emissions</b>			
<b>Displacement</b>			
· Diesel production (% attributed to production phase)	659.6kg (17.0%)	3.7948kg CO <sub>2</sub> (e) /kg	425.5kg CO <sub>2</sub> (e)
<b>Total</b>			<b>425.5kg CO<sub>2</sub> (e)</b>
<b>Emissions less displacement</b>			<b>-159.7kg CO<sub>2</sub> (e)</b>

The emissions associated with the manufacture of other raw materials (excluding the waste plastic stream) are 13.0kgCO<sub>2</sub>(e). For the case of pyrolysis, these are a result of the hydrogen that is consumed within the process.

Site emissions from the incineration of pyrolysis gases, distillation residues and 3% of the diesel product generated are 56kgCO<sub>2</sub>(e). The emissions associated with all elements of transport (products and wastes) are 197kgCO<sub>2</sub>(e).

Based on these figures the emissions associated with pyrolysis are 266kgCO<sub>2</sub>(e) and the displacement savings associated with replacing fossilised diesel production are 426kgCO<sub>2</sub>(e).

Overall, the net emissions for pyrolysis are -160kgCO<sub>2</sub>(e).

When considering the option of converting waste plastic to diesel via pyrolysis, about 39% of the GHG emissions produced in processing the material are attributed to transport. This is a significant increase over the current transport emissions and is a result of waste material needing to be sourced from a wider area (an allowance has been made for supply from locally and nationally based MRFs), thereby increasing transportation distances, and the diesel product needing to be transported to a main depot for redistribution. Ideally the pyrolysis plant would be located close to either a large quantity of feed material or a fuel distribution terminal, and in either case the emissions would be reduced significantly.

The emissions associated with the technology are 34% of the overall emissions from production. Once running, the site will be able to supply its own heat and power by combustion of pyrolysis gas and distillation residue. The char fraction will be disposed of via landfill; GHG emissions associated with this material will be negligible as the material will be predominantly non-biodegradable.

Overall, conversion of wet mixed plastic waste to oil via pyrolysis offers savings in GHG emissions when compared with the current disposal-to-landfill or incineration scenarios. This is mainly a result of the emissions savings from product displacement.

#### *Alternative case: mixed plastic wastes to oils via catalytic depolymerisation*

A breakdown of the CO<sub>2</sub> emissions associated with catalytic depolymerisation is given in **Table 51**.

**Table 51** GHG emissions for catalytic depolymerisation including displacement of diesel fuel production

Description	Quantities	CO <sub>2</sub> emission factor	CO <sub>2</sub> emission per functional unit
<b>Material manufacture</b>			
· Catalyst	23.0kg	0.1300kg CO <sub>2</sub> (e)/kg	3.0
· Hydrogen	7.7kg	1.70kg CO <sub>2</sub> (e)/kg	13.0kg CO <sub>2</sub> (e)
<b>Total</b>			<b>13.0kg CO<sub>2</sub>(e)</b>
<b>Material transport: 700.0kg MSW plastic-rich residue sourced locally, 300.0kg MSW plastic-rich residue sourced nationally</b>			
· Road transport (local)	200.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	42.4kg CO <sub>2</sub> (e)
· Road transport (national)	700.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	63.5kg CO <sub>2</sub> (e)
<b>Total</b>			<b>105.9kg CO<sub>2</sub>(e)</b>
<b>Material transport: 23.0kg catalyst sourced nationally</b>			
· Road transport (national)	700.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	4.9kg CO <sub>2</sub> (e)
<b>Total</b>			<b>4.9kg CO<sub>2</sub>(e)</b>
<b>Site emissions</b>			
· Water vapour from drying	53.0kg	0.0000kg CO <sub>2</sub> (e)/kg	0.0kg CO <sub>2</sub> (e)
· Catalysts and sludge	189.0kg	0.0165kg CO <sub>2</sub> (e)/kg	3.1kg CO <sub>2</sub> (e)
· Distillation gas	97.0kg	0.2904kg CO <sub>2</sub> (e)/kg	28.2kg CO <sub>2</sub> (e)
· Product used for CHP generation	68.0kg	0.2904kg CO <sub>2</sub> (e)/kg	19.7kg CO <sub>2</sub> (e)
<b>Total</b>			<b>51.0kg CO<sub>2</sub>(e)</b>
<b>Waste transport: 189.0kg char</b>			
· Road transport (local)	50.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	2.9kg CO <sub>2</sub> (e)
<b>Total</b>			<b>2.9kg CO<sub>2</sub>(e)</b>
<b>Product transport: 308.0kg diesel product transported locally, 308.0kg diesel product transported nationally</b>			
· Road transport (local)	200.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	18.6kg CO <sub>2</sub> (e)
· Road transport (national)	700.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	65.2kg CO <sub>2</sub> (e)
<b>Total</b>			<b>83.9kg CO<sub>2</sub>(e)</b>
<b>Grand total emissions</b>			
<b>Displacement</b>			
· Gasoline production (% attributed to production phase)	616.0kg (17.0%)	3.7948kg CO <sub>2</sub> (e)/kg	397.4kg CO <sub>2</sub> (e)
<b>Total</b>			<b>397.4kg CO<sub>2</sub>(e)</b>
<b>Emissions less displacement</b>			<b>-132.8kg CO<sub>2</sub>(e)</b>

The emissions associated with the manufacture of other raw materials (excluding the waste plastic stream) are 16kgCO<sub>2</sub>(e). For the case of catalytic depolymerisation, these are a result of the hydrogen that is consumed within the process and the catalyst.

Site emissions from the incineration of off-gases, distillation residues and diesel required to produce power are 51kgCO<sub>2</sub>(e). The emissions associated with all elements of transport (products and wastes) are 198kgCO<sub>2</sub>(e).

Based on these figures the emissions associated with catalytic depolymerisation are 265kgCO<sub>2</sub>(e) and the displacement savings associated with replacing fossilised diesel production are 397kgCO<sub>2</sub>(e).

Overall, the net emissions for catalytic depolymerisation are  $-133\text{kgCO}_2(\text{e})$ .

Overall, conversion of wet mixed plastic waste to oil via catalytic depolymerisation offers savings in GHG emissions when compared with the current disposal-to-landfill or incineration scenarios. This is mainly a result of the emissions savings from product displacement.

### *Alternative case: mixed plastic wastes to oils via gasification with Fischer–Tropsch*

A breakdown of the  $\text{CO}_2$  emissions associated with gasification with F–T is given in **Table 52**.

**Table 52** GHG emissions for gasification with F–T including displacement of diesel fuel production

Description	Quantities	$\text{CO}_2$ emission factor	$\text{CO}_2$ emission per functional unit
<b>Material manufacture</b>			
· Oxygen for gasification	1044.0kg	0.1472kg $\text{CO}_2(\text{e})/\text{kg}$	153.7kg $\text{CO}_2(\text{e})$
<b>Total</b>			<b>153.7kg <math>\text{CO}_2(\text{e})</math></b>
<b>Material transport: 700kg MSW plastic-rich residue sourced locally, 300kg MSW plastic-rich residue sourced nationally</b>			
· Road transport (local)	200.0km	0.3026kg $\text{CO}_2(\text{e})/\text{tonne}/\text{km}$	42.4kg $\text{CO}_2(\text{e})$
· Road transport (national)	700.0km	0.3026kg $\text{CO}_2(\text{e})/\text{tonne}/\text{km}$	63.5kg $\text{CO}_2(\text{e})$
<b>Total</b>			<b>105.9kg <math>\text{CO}_2(\text{e})</math></b>
<b>Site emissions</b>			
· Water vapour from drying	53.0kg	0.0000kg $\text{CO}_2(\text{e})/\text{kg}$	0.0kg $\text{CO}_2(\text{e})$
· Water from F–T process	640.0kg	0.0005kg $\text{CO}_2(\text{e})/\text{kg}$	0.3kg $\text{CO}_2(\text{e})$
· Purge gas	981.1kg	0.2904kg $\text{CO}_2(\text{e})/\text{kg}$	284.9kg $\text{CO}_2(\text{e})$
· Ash and tar	153.0kg	0.0000kg $\text{CO}_2(\text{e})/\text{kg}$	0.0kg $\text{CO}_2(\text{e})$
<b>Total</b>			<b>285.2kg <math>\text{CO}_2(\text{e})</math></b>
<b>Waste transport: 153.0kg ashes and tars</b>			
· Road transport (local)	50.0km	0.3026kg $\text{CO}_2(\text{e})/\text{tonne}/\text{km}$	2.3kg $\text{CO}_2(\text{e})$
<b>Total</b>			<b>2.3kg <math>\text{CO}_2(\text{e})</math></b>
<b>Product transport: 114.0kg diesel product transported locally, 114.0kg diesel product transported nationally</b>			
· Road transport (local)	200.0km	0.3026kg $\text{CO}_2(\text{e})/\text{tonne}/\text{km}$	6.9kg $\text{CO}_2(\text{e})$
· Road transport (national)	700.0km	0.3026kg $\text{CO}_2(\text{e})/\text{tonne}/\text{km}$	24.1kg $\text{CO}_2(\text{e})$
<b>Total</b>			<b>31.0kg <math>\text{CO}_2(\text{e})</math></b>
<b>Grand total emissions</b>			<b>578.2kg <math>\text{CO}_2(\text{e})</math></b>
<b>Displacement</b>			
· Gasoline production (% attributed to production)	336.0kg (21.0%)	3.7088kg $\text{CO}_2(\text{e})/\text{kg}$	147.1kg $\text{CO}_2(\text{e})$
<b>Total</b>			<b>147.1kg <math>\text{CO}_2(\text{e})</math></b>
<b>Emissions less displacement</b>			<b>431.1kg <math>\text{CO}_2(\text{e})</math></b>

The emissions associated with the manufacture of other raw materials (excluding the waste plastic stream) are  $154\text{kgCO}_2(\text{e})$ . For the case of gasification with F–T, these are a result of the oxygen consumed within the process.

Site emissions from the incineration of off-gases are  $285\text{kgCO}_2(\text{e})$ . The emissions associated with all elements of transport (products and wastes) are  $139\text{kgCO}_2(\text{e})$ .

Based on these figures the emissions associated with gasification with F–T are  $578\text{kgCO}_2(\text{e})$  and the displacement savings associated with replacing fossilised gasoline production are  $147\text{kgCO}_2(\text{e})$ .

Overall, the net emissions for gasification with F–T are  $431\text{kgCO}_2(\text{e})$ .

Overall, conversion of wet mixed plastic waste to oil via gasification with F–T offers a net increase in GHG emissions when compared with the current disposal-to-landfill or incineration scenarios. This is a result of the emissions from production being greater than the emission savings from product displacement.

*Alternative case: mixed plastic wastes to oils via gasification with methanol conversion to gasoline*

A breakdown of the CO<sub>2</sub> emissions associated with gasification with methanol conversion to gasoline is given in **Table 53**.

**Table 53** GHG emissions for gasification with methanol conversion to gasoline including displacement of gasoline fuel production

Description	Quantities	CO <sub>2</sub> emission factor	CO <sub>2</sub> emission per functional unit
<b>Material manufacture</b>			
· Oxygen for gasification	1044.0kg	0.1472kg CO <sub>2</sub> (e)/kg	153.7kg CO <sub>2</sub> (e)
<b>Total</b>			<b>153.7kg CO<sub>2</sub>(e)</b>
<b>Material transport: 700kg MSW plastic-rich residue sourced locally, 300kg MSW plastic-rich residue sourced nationally</b>			
· Road transport (local)	200.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	42.4kg CO <sub>2</sub> (e)
· Road transport (national)	700.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	63.5kg CO <sub>2</sub> (e)
<b>Total</b>			<b>105.9kg CO<sub>2</sub>(e)</b>
<b>Site emissions</b>			
· Water vapour, methanol reactors	610.0kg	0.0005kg CO <sub>2</sub> (e)/kg	0.3kg CO <sub>2</sub> (e)
· Purge gas	1216.0kg	0.8185kg CO <sub>2</sub> (e)/kg	995.2kg CO <sub>2</sub> (e)
· Ash and tars	153.0kg	0.0000kg CO <sub>2</sub> (e)/kg	0.0kg CO <sub>2</sub> (e)
· Water vapour, drying	53.0kg	0.0000kg CO <sub>2</sub> (e)/kg	0.0kg CO <sub>2</sub> (e)
<b>Total</b>			<b>995.5kg CO<sub>2</sub>(e)</b>
<b>Waste transport: 153.0kg ashes and tars</b>			
· Road transport (local)	50.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	2.3kg CO <sub>2</sub> (e)
<b>Total</b>			<b>2.3kg CO<sub>2</sub>(e)</b>
<b>Product transport: 329.8kg diesel product transported locally, 329.8kg diesel product transported nationally</b>			
· Road transport (local)	200.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	10.2kg CO <sub>2</sub> (e)
· Road transport (national)	700.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	35.6kg CO <sub>2</sub> (e)
<b>Total</b>			<b>45.8kg CO<sub>2</sub>(e)</b>
<b>Grand total emissions</b>			<b>1,303.2kg CO<sub>2</sub>(e)</b>
<b>Displacement</b>			
· Gasoline production (% attributed to production)	336.0kg (21.0%)	3.7088kgCO <sub>2</sub> (e)/kg	261.7kg CO <sub>2</sub> (e)
<b>Total</b>			<b>261.7kg CO<sub>2</sub>(e)</b>
<b>Emissions less displacement</b>			<b>1,041.5kg CO<sub>2</sub>(e)</b>

The emissions associated with the manufacture of other raw materials (excluding the waste plastic stream) are 154kgCO<sub>2</sub>(e). For the case of gasification with methanol conversion, this is a result of the oxygen consumed within the process.

Site emissions from off-gases are 996kgCO<sub>2</sub>(e). The emissions associated with all elements of transport (products and wastes) are 154kgCO<sub>2</sub>(e).

Based on these figures the emissions associated with gasification with methanol conversion to gasoline are 1,303kgCO<sub>2</sub>(e) and the displacement savings associated with replacing fossilised gasoline production are 262kgCO<sub>2</sub>(e).

Overall, the net emissions for gasification with methanol conversion to gasoline are 1,042kgCO<sub>2</sub>(e).

Overall, conversion of wet mixed plastic to gasoline via gasification offers a net increase in GHG emissions when compared with the current disposal scenarios of landfill or incineration. This is a result of the emissions from production being greater than the emissions savings from product displacement.

**Alternative case: mixed plastic wastes to oils via gasification with biological conversion of syngas to ethanol**

A breakdown of the CO<sub>2</sub> emissions associated with gasification with biological conversion of syngas to ethanol is given in **Table 54**.

**Table 54** GHG emissions for gasification with biological conversion of syngas to ethanol including displacement of gasoline fuel production

Description	Quantities	CO <sub>2</sub> emission factor	CO <sub>2</sub> emission per functional unit
<b>Material manufacture</b>			
· Oxygen for gasification	1,044.0kg	0.1472kg CO <sub>2</sub> (e)/kg	153.7kg CO <sub>2</sub> (e)
<b>Total</b>			<b>153.7kg CO<sub>2</sub>(e)</b>
<b>Material transport: 700kg MSW plastic-rich residue sourced locally, 300kg MSW plastic-rich residue sourced nationally</b>			
· Road transport (local)	200.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	42.4kg CO <sub>2</sub> (e)
· Road transport (national)	700.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	63.5kg CO <sub>2</sub> (e)
<b>Total</b>			<b>105.9kg CO<sub>2</sub>(e)</b>
<b>Site emissions</b>			
· Water vapour, distillation process	5,195.0kg	0.0005kg CO <sub>2</sub> (e)/kg	2.5kg CO <sub>2</sub> (e)
· Reactor off-gas	1,391.7kg	0.8727kg CO <sub>2</sub> (e)/kg	1,214.6kg CO <sub>2</sub> (e)
· Ash and tars	153.0kg	0.0000kg CO <sub>2</sub> (e)/kg	0.0kg CO <sub>2</sub> (e)
· Water vapour, drying	53.0kg	0.0000kg CO <sub>2</sub> (e)/kg	0.0kg CO <sub>2</sub> (e)
<b>Total</b>			<b>1,217.1kg CO<sub>2</sub>(e)</b>
<b>Waste transport: 153.0kg ashes and tars</b>			
· Road transport (local)	50.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	2.3kg CO <sub>2</sub> (e)
<b>Total</b>			<b>2.3kg CO<sub>2</sub>(e)</b>
<b>Product transport: 292.0kg diesel product transported locally, 292.0kg diesel product transported nationally</b>			
· Road transport (local)	200.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	17.7kg CO <sub>2</sub> (e)
· Road transport (national)	700.0km	0.3026kg CO <sub>2</sub> (e)/tonne/km	61.9kg CO <sub>2</sub> (e)
<b>Total</b>			<b>45.8kg CO<sub>2</sub>(e)</b>
<b>Grand total emissions</b>			<b>1,558.5kg CO<sub>2</sub>(e)</b>
<b>Displacement</b>			
· Gasoline production (% attributed to production)	584.0kg (21.0%)	3.7088kg CO <sub>2</sub> (e)/kg	454.9kg CO <sub>2</sub> (e)
<b>Total</b>			<b>454.9kg CO<sub>2</sub>(e)</b>
<b>Emissions less displacement</b>			<b>1,103.6kg CO<sub>2</sub>(e)</b>

The emissions associated with the manufacture of other raw materials (excluding the waste plastic stream) are 154kgCO<sub>2</sub>(e). For the case of gasification with biological conversion of syngas to ethanol, this is a result of the oxygen consumed within the process.

Site emissions from off-gases are 1,217kgCO<sub>2</sub>(e). The emissions associated with all elements of transport (products and wastes) are 188kgCO<sub>2</sub>(e).

Based on these figures the emissions associated with gasification with biological conversion of syngas to ethanol are 1,559kgCO<sub>2</sub>(e) and the displacement savings associated with replacing fossilised gasoline production are 455kgCO<sub>2</sub>(e).

Overall, the net emissions for gasification with methanol conversion to gasoline are 1,104kgCO<sub>2</sub>(e).