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Comparative Life-cycle Assessment

INEOS Bio Ltd
Seal Sands Waste to Biofuel Initial Plant

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Disclaimer

Executive Summary

Eunomia Research & Consulting Ltd ('Eunomia') has been commissioned by INEOS Bio Ltd ('INEOS Bio') to undertake a life-cycle assessment (greenhouse gas (GHG) emissions only) of the initial INEOS Bio plant planned to be located at Seal Sands in the UK. The key objective of the study is to compare the performance of the INEOS Bio process, with the performance of alternative technologies, when processing a range of waste feedstocks.

The analysis is undertaken using two different methodologies:

1. Evaluation of the life-cycle GHG emissions reductions of biofuel produced from several key waste feedstocks using the INEOS Bio process under the Renewable Energy Directive (RED) methodology; and
2. Evaluation of the INEOS Bio process against alternative technologies for the treatment of different types of waste (the 'waste system' approach).

The feedstocks considered within the analysis are residual municipal solid waste (MSW), bio-waste (a mix of separately collected food and garden waste), garden waste alone and shredded wood waste. The analysis also considers two methods for the pre-treatment of MSW prior to its use as a feedstock for the INEOS Bio process – mechanical heat treatment (MHT) and mechanical biological treatment (MBT).

Based on the RED Methodology, Table E1 presents emissions reductions from the INEOS Bio production process in comparison with those anticipated to occur from the conventional process for petrol production. Table E1 also includes emissions reductions expected for an anaerobic digestion (AD) process where the output from that process is assumed to produce transport fuel in the form of compressed biogas. The analysis shows that all the bio-fuel systems result in emissions reductions that are in excess of 60% - the likely future minimum sustainability target for bio-fuel production stipulated in the RED.[1]

The results presented in Table E1 indicate that the INEOS Bio process performs better than the AD process for source separated bio-waste feedstocks when the sustainability of the two systems is assessed using the methodology outlined in the RED. The results suggest that, when the fuel is produced from a purely organic waste feedstock, the production and use of one litre of bio-fuel produced by the INEOS Bio process would result in an emissions saving of 3 kg CO_2 equivalent in comparison to the use of the same amount of fossil petrol. Where garden waste is used as the feedstock for the INEOS Bio process, the results suggest a saving of around 0.5 tonnes of CO_2 equivalent per tonne of garden waste treated would be achieved. In comparison, the composting of garden waste produces a soil improver but delivers no net CO_2 savings. If bio-waste from MSW was used as the feedstock, emissions savings would be slightly lower, at 2 kg CO_2 equivalent per litre of bio-fuel.

Production of bio-ethanol from an MSW feedstock results in lower emissions reductions, principally as a result of the following:

- Less bio-fuel and less electricity is produced per tonne of feedstock (reducing the associated emissions credits); and

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[1] The sustainability targets for biofuel production in the RED take the form of emissions reductions targets. The current emissions reduction target for biofuel production is 35%, but this is set to increase over time, such that new facilities producing biofuel built from 2017 onwards will be required to demonstrate emissions reductions of 60%.

- There are some fossil emissions from the non-organic material, i.e. plastics, which remains in the feedstock after pre-treatment.

For the bio-waste feedstocks, the emissions credit associated with electricity production is sufficient to offset all of the fossil emissions from the INEOS production process and pre-treatment (in the case of the bio-waste plant).

Table E1: Comparison of Process Emissions using the RED Methodology

		Biofuel system			Fossil[1 2]	Systems comparison (emissions reductions)
		Ethanol from 1 tonne to process	Emissions bio-fuel production process	Emissions per MJ of energy	Emissions per MJ of energy	
		Tonnes bio-ethanol	Tonnes CO_2eq	g CO_2eq / MJ	g CO_2eq / MJ	%
INEOS	Garden	0.145	-0.094	-19.581	83.800	123%
	Residual (MBT)	0.083	0.022	7.844	83.800	91%
	Residual (MHT)	0.112	0.050	13.637	83.800	84%
	Wood	0.172	-0.115	-20.194	83.800	124%
	Bio-waste	0.079	-0.019	-7.387	83.800	109%
AD[1]	Bio-waste	0.057		23.000	83.800	73%

Notes

1. Default data from the RED methodology are used to estimate emissions from the fossil (petrol) system and AD
2. The methodology assumes petrol has a lower heating value of 32 MJ / litre

Figure E1 presents the CO_2 equivalent emissions generated per tonne of waste for each of the waste treatment processes and feedstocks considered within the study, modelled according to the 'waste systems' approach. Results are presented excluding any biogenic CO_2 emissions, and under this approach, the INEOS Bio process outperforms the others with respect to the emissions generated per tonne of waste, for all of the feedstocks considered within the current analysis.[2]

When treating MSW with the INEOS Bio process, offset emissions from recycling are included, along with offsets associated with the energy generation. This is such that avoided emissions are sufficient to offset all of the direct emissions from the process, giving an overall negative GHG balance. When treating bio-waste, the INEOS Bio process outperforms both AD options as these convert relatively less carbon into transport fuel or electricity

Sensitivity analysis was undertaken to consider the impact upon the results of improvements in recycling rates; improvements in the fuel pre-treatment process for the MSW feedstock; variation in the carbon intensity of electricity generation; and alternative treatment routes for

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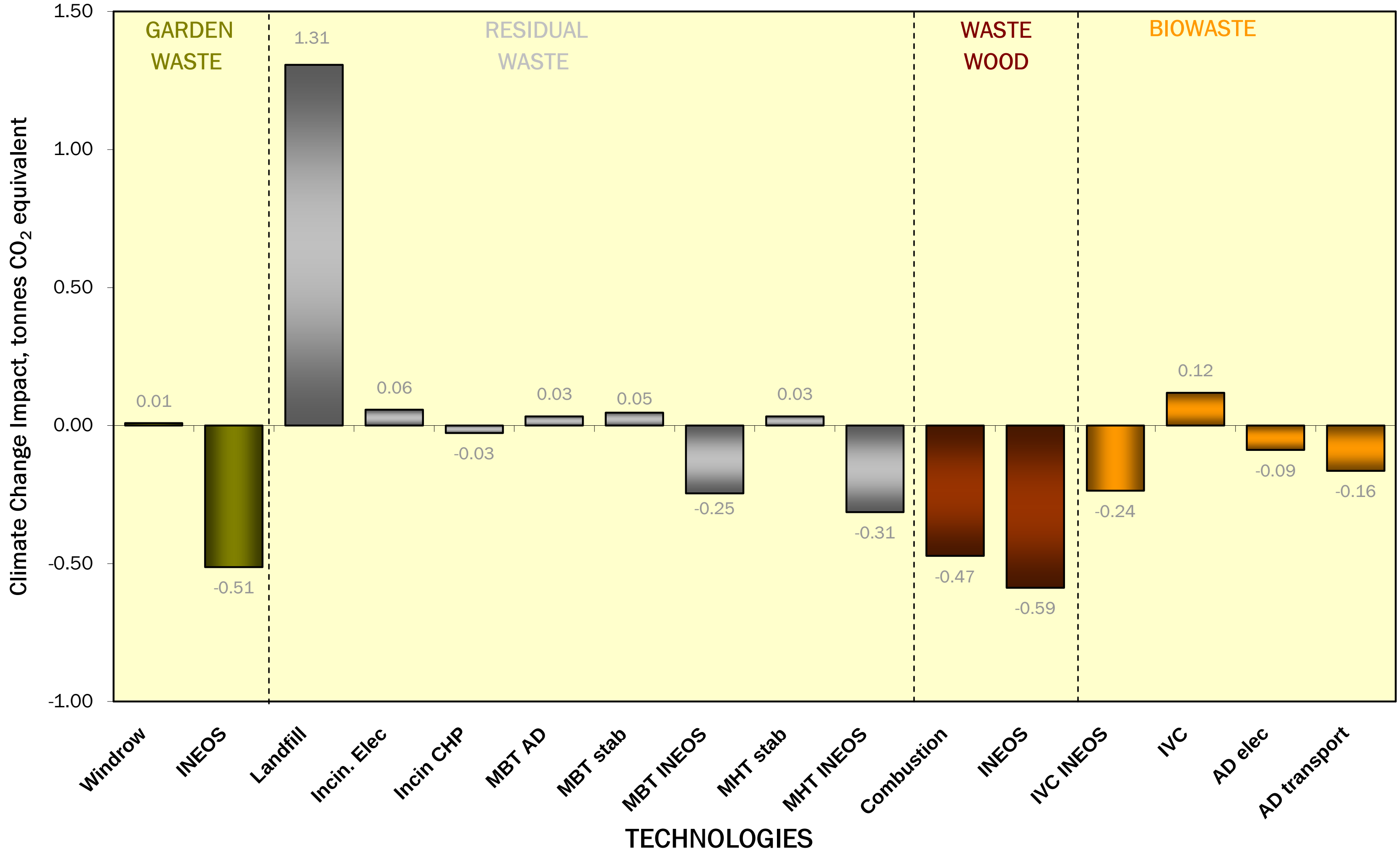
[2] When the biogenic CO_2 emissions are included, the ranking differs slightly, as presented in Appendix 2

the mixed plastic stream produced by the MSW pre-treatment processes. Variation of these elements did not have a significant impact on the results of the analysis.

Figure E1: GHG Emissions per Tonne of Waste Treated using the 'Waste Systems' Methodology



In the UK, local authority recycling targets, and associated National Indicators (NIs), are currently such that AD and composting are regarded by local authorities as preferential to the production of bio-fuels from wastes. The core goal of this study, therefore, was to consider whether this is a sound position from an environmental perspective, with regard to emissions of CO_2 equivalent.

The results presented in the study demonstrate that this position cannot be justified in the case of the INEOS Bio process. The central finding of the analysis is that under both of the assessment methodologies considered within the study, technology configurations incorporating the INEOS Bio process result in far lower emissions of CO_2 equivalent than all other alternatives. As mentioned above, this was also the case with all variations on the central assumptions tested by way of sensitivity analysis.

Eunomia believes, therefore, that on the basis of the findings of this study, INEOS Bio has a reasonable case to put forward to both Defra and the European Commission. This might be towards establishing a relevant framework such that there is *at least* equal incentive for local authorities to procure facilities (or capacity at relevant merchant facilities) designed to produce bio-fuels from waste compared to composting or anaerobic digestion of the wastes. It is understood that Defra is currently deliberating over implementation of the EU Waste Framework Directive, and will shortly issue a second consultation document. It is therefore recommended that INEOS Bio uses the information contained in this study as a contributing element to support a formal response to this forthcoming consultation.

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Appendices

1.0 Introduction and Objectives

INEOS Bio Ltd (INEOS Bio) announced in 2009 that it was to carry out a feasibility study for an advanced bio-ethanol plant in the North East of England with support from One North East and the Department of Energy and Climate Change (DECC). The aim is of this feasibility study is to lead to the construction of an initial commercial bio-ethanol-from-waste plant at Seal Sands. Subsequent expansion could turn the initial plant into a fully integrated biofuel refinery by 2015.

Eunomia Research & Consulting Ltd ('Eunomia') has been commissioned by INEOS Bio Ltd ('INEOS Bio') to undertake a life-cycle assessment (greenhouse gas (GHG) emissions only) of the initial INEOS Bio plant planned to be located at Seal Sands. The key objective of the study is to compare the performance of the INEOS Bio process, with the performance of alternative technologies, when processing a range of waste feedstocks.

The European Council of March 2007 reaffirmed the Commission's commitment to the Community-wide development of energy from renewable sources beyond 2010. It endorsed a mandatory target of a 20% share of energy from renewable sources in overall Community energy consumption by 2020, and a mandatory 10% minimum target to be achieved by all Member States for the share of biofuels in transport petrol and diesel consumption by 2020.

The 2009 Renewable Energy Directive (RED) reiterates these targets.[3] Reflecting, however, the controversy surrounding some biofuel production methods, the RED also includes mandatory related sustainability targets, and sets out a methodology for making associated comparisons between biofuels and their fossil fuel equivalents. The RED is being transposed by Member States and implementation in the UK is expected during the latter part of 2010.

The sustainability targets for biofuel production in the RED take the form of emissions reductions targets. The current emissions reduction target for biofuel production is 35%, but this is set to increase over time, such that new facilities producing biofuel built from 2017 onwards will be required to demonstrate emissions reductions of 60%.

The UK's Renewable Transport Fuels Obligation (RTFO) currently places an obligation on fuel suppliers to ensure that a certain percentage of their aggregate fuel supply comes from biofuels. The target for 2013/14 is that 5% (by volume) of all transport fuels sold on UK forecourts should come from a renewable source. Under the existing scheme, RTFO certificates are allocated to biofuel producers and these are subsequently traded between the fossil fuel producers and biofuel producers.

The existing system requires biofuel producers to meet sustainability targets prior to the issuance of the RTFO certificates. Once the RED is transposed into UK law, biofuel producers will be required to meet its emissions reductions targets in order to quality

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[3] European Commission (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources, Official Journal of the European Union, June 2009

for these certificates, with emissions reductions being calculated according to the methodology outlined in the RED.

In the UK, however, local authority recycling targets, and associated National Indicators (NIs), are currently such that anaerobic digestion (AD) and composting are regarded by local authorities as preferential to the production of biofuels from wastes. The core goal of this study, therefore, is to consider whether this position is justified from an environmental perspective, with regard to emissions of CO_2 equivalent.

2.0 Project Scope

Towards achieving the above core goal, the focus of this study is on the evaluation of the INEOS Bio process through a direct comparison with alternative technologies treating the same waste feedstocks. It should be noted that the INEOS Bio process is both a waste treatment process and a biofuel production process. As such, there is a need to understand its performance against different types of competing processes – both with respect to alternative methods of treating waste, and different methods of producing biofuel. As detailed further in Section 3.0, therefore, our comparative analysis is undertaken using two methods:

1. Evaluation of the life-cycle GHG emissions reductions of biofuel produced from several key waste feedstocks using the INEOS Bio process under the Renewable Energy Directive methodology (thereafter referred to as the 'biofuels system' approach); and
2. Evaluation of the INEOS Bio process against alternative technologies for the treatment of different types of waste (the 'waste system' approach).

The study considers four main scenarios associated with the possible feedstocks for the INEOS Bio process, along with a further 13 scenarios associated with alternative treatment technologies for the same feedstocks. These scenarios are summarised in Table 2-1.

Table 2-1: Summary of Scenarios for Comparison

Waste Input Scenario		Technology Configurations for Comparison
1	Residual MSW	(a) Mechanical heat treatment (MHT) to produce a refined biomass fuel (RBF) for use in the INEOS Bio process to produce a liquid biofuel for road transport and renewable power
		(b) Mechanical heat treatment (MHT) followed by aerobic composting to produce a compost like output (CLO) for land remediation[1]
		(c) MBT ('biostabilisation') to produce a tailored output for use in the INEOS Bio process to produce a liquid biofuel for road transport and renewable power
		(d) MBT('biostabilisation') to produce a compost like output (CLO) for land remediation
		(e) MBT ('splitting') to produce an organic fraction for AD (electricity only) and an SRF for combustion (CHP)
		(f) Incineration (with generation of electricity only)
		(g) Incineration (CHP)
		(h) Landfill (with generation of electricity only)
2	Separately collected food and garden waste (bio-waste)	(a) In-vessel aerobic degradation process used in bio-drying mode to produce a tailored output for use in the INEOS Bio process to produce a liquid biofuel for road transport and renewable power
		(b) In-vessel composting (IVC) to produce a compost for use on land
		(c) Anaerobic digestion (with CHP) to produce a digestate for use on land
		(d) Anaerobic digestion to produce both compressed biogas for road transport and a digestate for use on land
3	Garden waste	(a) INEOS Bio process to produce a liquid biofuel for road transport
		(b) Open-windrow composting to produce a compost for use on land
4	Shredded waste wood (e.g. chip board, laminates, furniture)[1]	(a) INEOS Bio process with no pre-treatment
		(b) Combustion in a dedicated biomass CHP facility

Notes:

1. It is also possible to compost waste wood if mixed with garden wastes, but as this is not currently undertaken at commercial scale, it has not been included within the analysis.

In addition, the sensitivity analysis detailed within Section 7.0 considers some variants to the central assumptions for these four feedstocks. These are outlined in Table 2-2.

Table 2-2: Variables Tested Through Sensitivity Analysis

	Central Assumptions	Variation tested via Sensitivity Analysis
1	Output produced from the MBT and MHT facilities produces a fuel with 90% of the carbon content from biogenic sources	Output produced from the MBT and MHT facilities produces a fuel with 100% of the carbon content from biogenic sources
2	Impacts of electricity used and generated by all facilities calculated assuming power generation from CCGT	Impacts of electricity used and generated by all facilities calculated assuming power generation from the average UK generation mix in 2009
3	Residual waste composition based on a relatively low kerbside recycling (approx 25%)	Residual waste composition based on a high degree of kerbside recycling rate (approx 55%)
4	Mixed plastic stream recovered from the MBT and MHT facilities is sent to landfill	Mixed plastic stream sent to a cement kiln, offsetting the use of coal
		Dense plastics from within the mixed plastic stream are recycled

3.0 Approach and Methodology

The two core modelling methodologies highlighted in Section 2.0 are considered in detail in Sections 3.1 and 3.2.

3.1 'Biofuels Systems' Analysis Using RED Model

The Renewable Energy Directive (RED) includes a methodology for evaluating the performance of biofuels for transport against existing methods for producing transport fuels.[4] In this section, this is referred to as the 'RED methodology'.

The methodology – in its currently published form – is clearly aimed at evaluating the GHG impact of biofuel production systems using agricultural crops and residues as the feedstock. As such, it is more appropriate for evaluating the performance of 'first generation' biofuel production systems, as opposed to 'second generation' or 'advanced biofuel' processes, such as that to be operated by INEOS Bio. The methodology provides default values that indicate the performance of a number of the more conventional biofuel production processes, including that expected from AD processes which use source-separated bio-wastes as their feedstock.

The methodology implies that the feedstock to the biofuel production process contains carbon derived entirely from biogenic sources, as it states that all emissions from the fuel are assumed to be zero. However, the published methodology contains no definition of what constitutes a biofuel, and the RED does not provide any guidance on what should be done in such cases whereby the biofuel production process uses a feedstock that contains a mixture of biogenic and fossil carbon – as might be expected to result from a process that uses an initial feedstock of MSW.

The RED methodology indicates that emissions arising from the following elements of the production system should be considered within the evaluation process:

- Those that result from the extraction or cultivation of raw materials;
- Those that result from land-use change;
- Emissions from the biofuel processing phase, including:
  - Those that result from wastes and leakages; and
  - Those originating from the production of chemicals or products used in during processing;
- Any additional energy required where this is not generated by the process itself; and
- Impacts that result from transporting the biofuel and its pre-cursors.

The methodology indicates that the GHG impacts of electricity utilisation and the offset emissions assumed to occur as a result of its generation should be calculated on the

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[4] European Commission (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources, Official Journal of the European Union, June 2009

basis of the average generation mix of a defined region or country. This differs from guidance produced in the UK by Defra which suggests that the marginal fuel source should be used. The RED does not provide any guidance with respect to emissions anticipated to arise from heat utilisation or heat generation.

The methodology further indicates that wastes used in biofuel production processes should be considered to have zero life cycle emissions up to the point of collection of those materials.

Although the methodology stipulates that impacts associated with the wastes from biofuel processing should be included within the analysis, the guidance published to date does not indicate how impacts associated with the recycling of materials - such as those removed from MSW feedstocks as part of the waste pre-treatment process - should be considered. In addition, although the methodology allows for a GHG credit to be applied to the biofuel production system where electricity or heat generation occurs as part of the process, the assessment does not consider any credit to the biofuel production process associated with the treatment of waste that might otherwise have occurred by other (less environmentally beneficial) means.[5]

Eunomia understands that the Directorate General for Energy and Transport at the European Commission (DG TREN) is to publish a Practical Implementation Guide associated with the biofuels sustainability scheme in April 2010. Ahead of this anticipated guidance, representatives of DG TREN have confirmed the following approach should be taken with respect to the impacts associated with the pre-treatment of mixed waste feedstocks where these are used in a bio-fuel production process:

1. Where the main purpose of an MBT pre-treatment process is to remove the biomass from the mixed waste, any impact associated with the recycling of materials should not be considered;
2. A proportion of the emissions associated with the pre-treatment phase is allocated to the biofuel production process, based on the proportion of biomass in the feedstock, calculated on the basis of the calorific value (or energy content) of that biomass feedstock going to the biofuel plant relative to the total calorific value of the waste pre-treated;
3. Emissions associated with the stabilisation and subsequent landfilling of rejected material from the pre-treatment process (such as those produced during the refinement of the biofuel) are not attributed to the biofuel production process; and
4. Impacts associated with residual fossil carbon remaining within the biofuel at the point of combustion should, however, be accounted for.

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[5] Work undertaken in the UK on behalf of the RFA indicates that these so-called indirect impacts can be significant for biofuels produced from residual waste and biowaste. See Ecometrica / Eunomia / Imperial College (2009) Methodology and Evidence Base on the Indirect Greenhouse Gas Effects of Using Wastes, Residues, and By-products for Biofuels and Bioenergy; Report to the RFA and DECC, November 2009

Emissions from the biofuel production system are calculated on the basis of grams of CO_2 equivalent per MJ of energy. These are compared to those that are anticipated to arise from the production of an equivalent amount of transport fuel using a fossil fuel production system. The methodology indicates that the comparisons made on the basis of the relative energy content of the two types of fuel can be modified to reflect the useful work done by that energy, provided some justification of the modifications made to the standard approach is supplied.

Our assumptions with regard to the modelling of the INEOS Bio process are outlined in Section 4.0. Assumptions regarding the pre-treatment processes for the residual and biowaste feedstocks are considered in Section 5.0 as part of the waste systems analysis.

3.2 'Waste Systems' Analysis Using the 'Atropos' Model

All modelling of residual waste treatment 'methods' carried out for this assessment is undertaken using Eunomia's proprietary Atropos tool. This model has been developed over a 6-7 year period and is based both upon data provided by technology providers, and upon peer-reviewed information in published journals. It is an iterative model, which is continually updated as new information comes to light, so that it presents the most current picture as possible. Atropos has recently been used as the key model to support evidence-based policy analysis for both Defra and the Committee on Climate Change.[6]

Eunomia's waste treatment models aim to quantify the environmental impacts of treatment processes for both residual mixed wastes and separately collected organic wastes. These models are used to analyse the effects of the pre-treatment for INEOS, as well as to evaluate the performance of the alternative systems for treating the different types of waste considered as feedstocks for the INEOS process.

Much of the literature in this area has focused upon life-cycle assessment (LCA) oriented approaches.[7] The standard approach in this type of analysis typically considers that:

- There is a cut-off for emissions, usually taken to be 100 years; and
- All CO_2 emissions originating from non-fossil (or 'biogenic') carbon should be excluded.[8]

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[6] Eunomia (2008) Development of Marginal Abatement Cost Curves for the Waste Sector, Final Report for the Committee on Climate Change, Defra and the Environment Agency, December 2008; Eunomia (2010) Landfill Bans: Feasibility Research, Draft Final Report for WRAP produced for Defra and the Devolved Administrations

[7] The life-cycle assessment approach can be used to examine the environmental impacts of a product or activity during any defined stage of its existence, from production to final disposal.

[8] Paper, textiles, food and garden waste contain non-fossil or biodegradable carbon in variable proportions, and some of this carbon is emitted in the form of CO_2 as a result of waste management processes. Such emissions are excluded by typical LCA approaches, whilst emissions of non-fossil carbon in the form of CH_4 (e.g. from landfill) are included.

Our model considers outcomes over a 150 year period, which we believe more fully accounts for behaviour of organic waste sent to landfill. The model also produces results for the climate change impacts both including and excluding the biogenic CO_2 emissions. In the main part of this study, we present results *excluding* these emissions, in line with the majority of literature published in this area. Appendix 2.0 provides further discussion on the distinction between the two approaches, and presents results *including* the biogenic CO_2 emissions for comparison purposes.

Eunomia's waste treatment models – for both residual mixed wastes and separately collected biowaste - are based upon 'first principles'. In the case of residual waste treatment processes, a proximate analysis of each element of the waste composition is generated at the beginning of each project. Both the fossil and non-fossil carbon content of each constituent of the waste is then tracked through each phase of the technology scenario to determine the extent of GHG emissions. Within the model, the biogenic carbon is broken down into lignin, cellulose, sugars, fats, and proteins so that the rapidity of degradation can be determined when waste is resident either within biological treatment processes or in landfill. A similar approach is taken with regard to the modelling of the degradation of biowaste in the organic waste treatment processes.

The Environment Agency's software tool WRATE is often used to assess the environmental impacts of waste management treatment methods. We have not used this method in the current analysis as we believe the model contains fundamental errors, both in regard to the behaviour of landfilled wastes, and with respect to its treatment of the stabilised output from MBT facilities. In the case of the latter, WRATE assumes a proportion of the carbon is degraded within the biological part of the MBT process. However, when this stabilised material is subsequently landfilled, the methane emission is assumed to be exactly the same as that of the non-stabilised material – the model only accounts for the reduction in mass which occurs in material which is biologically pre-treated (occurring as a result of moisture loss). The model, therefore, significantly underestimates the extent to which the biological component of the MBT process reduces the biological activity of material subsequently sent to landfill.

Comparisons are made on the basis of one tonne of waste to each of the different waste treatment processes. Our assumptions for each of the processes considered within the analysis are outlined in model detail in Section 5.0.

4.0 Key Assumptions for 'Biofuel Systems' Analysis

The analysis presented here is carried out following the methodology for assessing the sustainability of biofuels contained within the RED. Section 4.1 gives a description of the INEOS Bio process, whilst Section 4.2 describes the approach taken in the analysis.

4.1 Description of the INEOS Bio Process

The INEOS Bio process employs the following set of consecutive technology steps for the production of ethanol:

- **Fuel preparation.** Depending on the fuel type to be used, this will typically involve drying and sizing the input material for the gasifier, as well as (depending upon the waste stream) separation processes designed to deliver feedstock of a defined quality. Bespoke schematics for front end operations will need to be defined when details of the fuel are confirmed for a full scale plant. The fuel preparation is not be a wholly isolated process since low grade waste heat from the process will be used for fuel drying;
- **Gasification.** Thermal conversion of the solid fuel to a synthesis gas occurs in an oxygen-blown gasifier. Conversion conditions will be controlled to maximise the formation of carbon monoxide and hydrogen, but minimising production of hydrocarbons;
- **Gas clean up.** The hot syngas exits the gasifier and is quenched and cleaned. The design, operation and reducing environment of the gasifer and downstream system inhibits the production of dioxins and furans, and removes volatilised metals, acid gases and particulates. The heat captured will be used for ethanol distillation, to generate electricity from steam turbines, and for fuel drying purposes;
- **Fermentation.** Ethanol is produced through the bio-catalytic synthesis of the cleaned, cooled syngas. Our model assumes 30% of the carbon within the feedstock becomes incorporated into the bioethanol, with the remainder being emitted during the heat recovery process;
- **Off Gas Energy Recovery.** Most of the syngas is converted to ethanol. The remaining off gas is cleaned and combusted for power generation and heat recovery. Whilst the bio-ethanol process requires energy to operate, our model assumes 0.7 kWh of electricity is exported to the grid per kg of carbon in the feedstock; and
- **Ethanol Purification.** The water and other impurities are removed from the output from the fermentation unit to produce ethanol with a purity of 99.7%.

In addition to the waste feedstock, the INEOS Bio process requires significant quantities of oxygen (supplied by pipeline) and small quantities of lime. The oxygen does not have to be pure for the INEOS Bio process but as pure oxygen is available to the plant it will be used. The process produces both electricity and bio-ethanol, and the excess electricity not utilised in the bio-ethanol production process will be exported to the grid. The exact quantities of electricity and bio-ethanol produced will vary according to the carbon content of the feedstock.

It should be noted here that the INEOS Bio technology is currently in the process of being commercialised. A number of efficiency optimisations are therefore expected to be delivered following commissioning of the initial plant. It is anticipated that these will be incorporated retrospectively and into the subsequent similar plants. Such a development curve is entirely normal for new technologies of this nature.

4.2 Approach Taken for Analysis Using the RED Methodology

4.2.1 Pre-treatment of Feedstocks

Residual mixed waste and separately collected biowaste will require some pre-treatment before their utilisation as feedstocks for the INEOS process. Section 5.3 discusses the pre-treatment of residual waste, whilst Section 5.4 discusses the pre-treatment of biowaste.

4.2.2 INEOS Bio Process

Our model considers the following impacts with regard to the performance of the INEOS Bio process:

- The use of lime;[9]
- Emissions resulting from energy requirements including:
    - The energy used during pre-treatment processes for the residual waste and biowaste feedstocks;
    - That required for the Air Separation Unit (used to supply oxygen for the gasification process);[10]
- Direct emissions associated with waste pre-treatment processes (such as the fugitive emissions from biodrying);
- The avoided (or offset) emissions that result from the export of excess electricity to the grid;[11]
- CO_2 emissions associated with the remaining fossil carbon for the MSW feedstocks.

In the case of impacts associated with the pre-treatment of the residual waste feedstocks, a proportion of the total impact (with regard to energy use and direct emissions) is considered, as was discussed in Section 3.1.

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[9] Lime production is assumed to result in GHG impacts of 0.9 kg of CO_2 equivalent per kg of lime, based on data from: European Commission (2009) Draft Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries, May 2009

[10] The production of the oxygen is assumed to require 280 kWh of electricity per tonne of pure oxygen and 0.3 tonne of oxygen is assume to be required per tonne of feedstock to the INEOS Bio process

[11] These impacts are calculated on the basis of the UK's average grid mix for electricity, which is taken to be 0.540 kg CO_2 per kWh

4.2.3 Transport Impacts

Although the methodology suggests that transport impacts should be considered within the analysis, we have not included emissions associated with the collection of the waste or the transport of the biofuel output. It is assumed that the waste is supplied from the local area, and that the resulting biofuel is similarly utilised locally to minimise transport emissions. Any impact associated with this is assumed to be offset by the requirement to transport petrol.

We have adjusted the energy content of the bio-ethanol comparison so that it takes into account the useful work done by the fuel; this results in a substitution ratio of 1.32 kg of ethanol for every kg of petrol. The methodology used to develop this substitution ratio is discussed in more detail in Appendix 1.0.

4.2.4 Anaerobic Digestion

We assume that the use of biogas from an anaerobic digestion plant to produce transport fuel results in an emissions reduction of 73% when compared to an equivalent fossil fuel production system for transport fuel. This figure is the default value provided in the RED for the performance of this type of system.

4.2.5 GHG Emissions from the Fossil Fuel Production System

GHG emissions from the comparator fossil fuel production system are assumed to be 83.8 grams of CO_2 equivalent per MJ of petrol (or 2.62 kg of CO_2 equivalent per litre).[12] This figure is the default value provided in the RED for the production and combustion of petrol.

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[12] The calculation uses a lower heating value of 32 MJ per litre of petrol. This is equivalent to 3.60 kg CO_2 equivalent per kg of fuel.

5.0 Key Assumptions for 'Waste Systems' Analysis

Key assumptions in the waste systems analysis fall into two broad categories:

1. Generic parameters: these are the non-process specific assumptions and are discussed in Section 5.1;
2. Process specific assumptions: these are described for each of the waste treatment processes in Sections 5.2 to 5.6.

5.1 Generic Parameters

5.1.1 Carbon Intensity of Avoided and Used Energy

The carbon intensity of an energy source is the quantity of GHG emissions associated with generating the energy. Where emissions are avoided as a result of generating energy from waste, or where energy is used by a process, assumptions regarding which source of energy is considered to have been avoided, or utilised, are important in determining the overall GHG benefit associated with power generation.

5.1.1.1 Electricity

Defra has suggested that for the purposes of policy evaluation, the marginal source of electricity should be taken to be CCGT gas plant, representing the trend in terms of recently commissioned power generation technology.[13] The carbon intensity figure used within the waste systems analysis is based around electricity generated by a modern CCGT power station. The carbon intensity associated with electricity generation in this form is 0.387 kg CO_2 equivalent per kWh including some pre-combustion emissions.[14] Further detail on the use of this approach is provided in Appendix 2.0.

The approach suggested by Defra differs from that stipulated within the RED methodology. Sensitivity analysis therefore considers impacts associated with the different waste treatment methods assuming the average generation mix for the UK.

5.1.1.2 Heat

The carbon intensity of heat generation was estimated from the calorific value of natural gas of 39 MJ/m^3. Emissions are 0.258 kg CO_2 equivalent per kWh of heat energy generated, taking into account the efficiency of heat generation (assumed to be 90%) and the pre-combustion emissions as was the case with the electricity emissions figure.

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[13] Defra (2006) Greenhouse Gas Policy Evaluation and Appraisal in Government Departments, April 2006

[14] We have assumed an efficiency of generation of 55% and assumed natural gas has a calorific value of 39 MJ/m^3. The carbon intensity associated with electricity generation in this form is 0.330 kg CO_2 equivalent per kWh from the process itself with some 0.057 kg CO_2 equivalent per kWh from the pre-combustion process, giving a total of 0.387 kg CO_2 equivalent per kWh.

Heat generation from waste management facilities is generated continuously and would not always be capable of being utilised. We have incorporated a heat load factor into the model, and this was set at 60% for the modelling runs in this report.

5.1.1.3 Diesel

We have used a figure of 3.26 kg CO_2 equivalent per litre of diesel (including 0.46 kg CO_2 equivalent pre-combustion emissions).[15]

5.1.2 Emissions Reductions Offered by Materials Recycling / Reprocessing

The recovery of materials for recycling results in the following environmental impacts:

1. The re-processing of the recovered material requires energy and results in emissions;
2. The recycled material offsets production from primary sources and as such, emissions and energy use associated with the production of these materials are avoided;
3. Changes occur in the transport of mixed waste, separately collected recyclables and the resources used for primary material (timber, minerals, ore, etc.). Fuel use and emissions from transport are consequently affected.

In relation to item 3, the environmental impacts associated with changes in transport tend to be more marginal, and are often dwarfed by the other environmental impacts. Overall transport impacts are also likely to be dependent upon the relative location of the primary production and re-processing facilities.

A brief summary of the key environmental impacts associated with the recycling of individual materials follows.

For **aluminium** the avoided energy use in the production of primary material is significant. The total global warming potential for ingot production in Europe is identified as 9.68 tonnes CO_2 equivalent per tonne of primary aluminium. Comparable emissions for producing ingot from recycled aluminium were given as 0.51 tonnes CO_2 equivalent.[16] This suggests avoided emissions of 9.17 tonnes CO_2 equivalent per tonne of aluminium recycled.

For **glass**, the most important consideration is whether the recovered material is recycled back in to glass (closed loop recycling) or whether is it used as a secondary raw material such as aggregate (open loop recycling). We have use a closed loop recycling emissions reduction value of 0.314 tonnes of CO_2 equivalent per tonne of recycled material; this assumes that the glass is re-processed within the UK.[17] We further assume that 50% of the glass is recovered is suitable for use in a closed loop

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[15] This is very similar that assumed in the RED methodology

[16] European Aluminium Association (2008) *Environmental Profile Report for the European Aluminium Industry: Life Cycle Inventory Data for Aluminium Production and Transformation Processes in Europe*, April 2008

[17] Enviros (2003) *Glass Recycling – Life Cycle Carbon Dioxide Emissions*, internal report for the British Glass Public Affairs Committee

recycling process. The recycling of glass using an open loop process is assumed to result in no net greenhouse gas emissions benefit.

For **plastics**, the key factor is what the recovered material is used for. The literature presents us with a range of emission offsets – the low values represent the impacts associated with the use of plastic as plastic lumber whilst the high values represent the effect of displacing granulate. Within our modelling, we assume closed loop recycling processes and arrive at avoided emissions of 1.4 tonnes CO_2 equivalent per tonne of recycled dense plastic.[18]

For **steel**, we use the average value suggested by the WRAP review of the benefits associated with recycling which indicates avoided emissions of 1.34 tonnes CO_2 per tonne of steel recycled.[18]

Some MHT facilities also recover some inert materials for recycling as part of its treatment process. The recycling of this type of material is not attributed any net greenhouse gas emissions benefit.[18]

5.1.3 Emissions from Transportation

Our model assumes that with regard to the waste transport impacts, the net effect of changing from one waste treatment system to another is negligible. Emissions associated with the transportation and collection and waste are therefore considered to be zero.

5.1.4 Biogenic CO_2 Emissions

Results are presented both excluding and including the biogenic CO_2 emissions.[19]

5.1.5 Waste Input Composition

The municipal waste composition is based on data taken from a recently published Defra review of English waste composition analyses for the residual waste scenarios.[20] The national composition dataset was collected in 2006/7, and the residual composition therefore reflects the national recycling rate at that time, which was 25%. Although the UK's national recycling rate is now higher than this, our central assumption is to use the national composition dataset without modification. The current recycling rate in the North East of England is considerably lower than the current national average, and as such, the national composition from 2006/7 is taken to be representative of a likely residual waste composition generated within the area surrounding the INEOS Bio plant.

Sensitivity analysis considers the impact upon the results of future improvements in the current recycling rate in the North East. In this case the national dataset has been modified to reflect the likely residual waste composition that might be expected

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[18] WRAP (2006) *Environmental Benefits of Recycling: An International Review of Life-cycle Comparisons for Key Materials in the UK Recycling Sector*, May 2006

[19] See Appendix 2.0 for more information

[20] Defra (2010) Municipal Waste Composition: A Review of Waste Composition Analyses, Research Project Final Report, January 2010

assuming a 55% recycling rate (which includes the separate collection of food waste).[21] A more detailed discussion regarding the waste composition analysis is provided in Appendix 2.0.

For scenario 2 (biowaste), it is assumed that the input composition contains 50% food and 50% garden wastes.

For scenario 4 (wood waste) it is assumed that waste wood is shredded to 50 mm.

5.2 INEOS Bio Process for Producing Bio-ethanol

Key assumptions used in the modelling of the INEOS Bio process are detailed in Section 4.1. Where impacts associated with different waste treatments are concerned, the assessment of impact is made on the basis of one tonne of waste to the treatment facility.

5.3 Technologies Treating Residual Waste

5.3.1 Aerobic MBT Process

Aerobic degradation processes can be used to dry the waste or to reduce its biodegradability. The system can therefore be configured either to produce an output for INEOS process or to produce a stabilised output that can be used for land remediation. In either case, a refinement process is used to remove non-organic items from the output after the initial aerobic degradation phase has taken place.

The release of biogenic CO_2 is the most significant environmental impact resulting from the stabilisation process. The approach for modelling the impacts of MBT stabilisation processes draws upon work by Eunomia on behalf of WRAP, which was based upon a raft of published research.[22]

We assume that the system uses a scrubber as well as a biofilter to reduce the impact of nitrogenous emissions (of NH_3 and N_2O) to air. A review of the literature suggests that some emission of CH_4 usually occurs at enclosed aerobic treatment facilities, but that effective process management should substantially reduce these emissions.[23] We have assumed a relatively low emission of CH_4 for the aerobic process operating under

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[21] This will result in a greater proportion of organic material being present in the residual waste stream

[22] Schleiss K (1999) Grüngutbewirtschaftung im Kanton Zürich aus betriebswirtschlaftlicher und ökologischer Sicht: Situationsanalyse, Szenarioanalyse, ökonomische und ökologische Bewertung sowie Synthese mit MAUT, Dissertation ETH No 13,746, 1999; Eunomia Research & Consulting, Scuola Agraria del Parco di Monza, HDRA Consultants, ZREU and LDK ECO on behalf of ECOTEC Research & Consulting (2002) *Economic Analysis of Options for Managing Biodegradable Municipal Waste*, Final Report to the European Commission; Komilis D P and Ham R K (2004) Life-Cycle Inventory of Municipal Solid Waste and Yard Waste Windrow Composting in the United States, Journal of Environmental Engineering, 130(11), pp.1390-1400; Baky A and Eriksson O (2003) Systems Analysis of Organic Waste Management in Denmark, Environmental Project No. 822, Copenhagen: Danish EPA; Sonesson U (1996) Modelling of the Compost and Transport Process in the ORWARE Simulation Model, Report 214, Swedish University of Agricultural Sciences (SLU), Department of Agricultural Engineering, Uppsala Sweden

[23] Amlinger F, Peyr S and Cuhls C (2008) Greenhouse Gas Emissions from Composting and Mechanical Biological Treatment, Waste Management and Research, 26, pp47-60

either configuration, which we assume to be representative of a well managed process.

Both configurations of the system involve the recovery of materials for recycling. Dense plastics are recovered but this fraction is currently landfilled.

Assumptions for the landfill of stabilised material are described in Section 5.3.6, whilst emissions assumed to be offset as a result of the recovery of materials for recycling are considered in Section 5.1.2.

5.3.1.1 Stabilised Output Used for Land Remediation

Where the organic output is used for land remediation purposes, it is assumed that a proportion of the biogenic carbon contained within the material becomes sequestered in the soil, thus forming part of the soil carbon content.

After the aerobic degradation phase has taken place, the refining process removes the inert elements (such as grit, stones, and small pieces of glass and plastic film) from the fraction to further increase its biomass content.

Table 5-1: Aerobic Stabilisation Process (Output to Land Remediation)

Parameter	Assumption
Removal of materials for recycling during process	
Dense plastic[1]	50%
Ferrous metal	60%
Non-ferrous metal	65%
Energy use by process	
Electricity	30 kWh / t
Diesel	1 litre / t
CH_4 emissions from process	0.01 kg / t
N_2O emissions from process	0.04 kg / t
% organic matter from stabilised material becoming humus[2]	25%

Notes

1. The central case assumes that the recovered plastic fraction is sent to landfill.
2. The amount of stabilised output produced per tonne of waste will vary, depending on the composition of the waste being treated.

5.3.1.2 Output to INEOS Bio System

The central aim of Biodrying processes is to produce a fuel. Biodrying systems involve the use of the heat from the process of biodegradation to reduce the moisture content of waste prior to its being mechanically refined (including using material separation technologies). During this process degradation of some of the carbon fractions will occur, but the amount of degradation is relatively limited in comparison that occurring during aerobic decomposition (stabilisation) processes. Our model of biodrying treatment systems is based on data supplied by facilities currently operating in the UK.

Biodrying processes involve the separation of the treated waste into fractions, usually on the basis of the particle size of the feedstock. The fuel fraction from biodrying is typically comprised of the large fraction from the separated waste, as this material is usually of a higher calorific value. When linked to the INEOS Bio process, however, the fuel is comprised of the small fraction, as this maximises the biomass content of the fuel. As waste is separated after the biodrying process has occurred, the fuel fraction also contains a significant proportion of the partially degraded paper and card in addition to most of the food and garden waste. The refining process removes the inert elements from the fuel fraction, with the aim here being to further increase both the biomass content and calorific value of the fuel.

We have assumed that the fuel output from the aerobic degradation process has a carbon content of more than 90% from biogenic sources. This degree of purity with respect to carbon content is higher than that typically seen in other facilities of this nature that are currently operating. However, trials undertaken with other MBT processes indicate that it is possible to produce an output stream with a plastics content of less than 0.5%.[24] The degree of purity with respect to carbon content is in part determined by the requirements of the fuel consumer. INEOS Bio has confirmed that they would seek an assurance from their pre-treatment partner that the performance of their plant would achieve a biogenic carbon content of at least 90%. We have therefore modelled the performance of the aerobic degradation process based on what INEOS Bio expects to achieve as a result of this performance guarantee.

The central case also assumes that the larger fraction (containing, for example, the plastics, textiles and the larger inert items) is landfilled after undergoing a stabilisation process in order to reduce its biodegradability and thus its impact in landfill.[25]

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[24] ADAS (2007) Biowaste Materials: Quality and Suitability for Land Recycling, Report to the Environment Agency, June 2007

[25] Sensitivity analysis considers the impact of the plastics being used as fuel in a cement kiln or recycled

Table 5-2: Assumptions for Aerobic Biodrying Process

Parameter	Assumption
Removal of materials for recycling during process	
Dense plastic[1]	50%
Ferrous metal	60%
Non-ferrous metal	65%
Energy used by process	
Electricity	30 kWh / t
Diesel	1 litre / t
CH_4 emissions from process	0.01 kg / t
N_2O emissions from process	0.04 kg / t
Fuel parameters[2]	
Moisture content	20%
Proportion of biogenic carbon (of total carbon) by weight	90%

Notes:

1. The central case assumes that the recovered plastic fraction is sent to landfill.
2. The amount of fuel produced will vary, depending on the composition of the waste being treated and the organic carbon of the fuel output.

5.3.2 MHT Process

Mechanical Heat Treatment (MHT) facilities use either steam or direct heat to treat waste. Where the heat treatment is carried out under pressure, the technology is referred to as autoclaving. The aim is to produce a fraction of dry recyclables, a fuel fraction (sometimes called 'floc') that is rich in biomass, and a residue fraction which is usually landfilled.[26]

The floc that is produced can either be used in the INEOS Bio process, or as a CLO output in a similar way to that described for the aerobic MBT process. In either case, an aerobic degradation process is used to stabilise the non-floc fraction.

Energy requirements are more substantial than those of comparable MBT facilities, as an external energy source is typically required to heat the waste. For the purpose of this study, we assume that the MHT process uses 18 m^3 of gas is required per tonne of waste to the facility for heating purposes as well as 27 kWh of electricity.

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[26] This is assumed to be stabilised prior to landfill, using the process described in Section 5.3.1

Assumptions for the landfill of stabilised material are described in Section 5.3.6, whilst emissions assumed to be offset as a result of the recovery of materials for recycling are considered in Section 5.1.2.

5.3.2.1 MHT Process with Output to Land Application

In this case the floc is refined to produce a compost-like material (CLO) which can be used to remediate land or as landfill cover material. Our model assumes both the CLO fraction and the residue fraction undergo a stabilisation process following the initial MHT treatment process. The central aim of aerobic stabilisation processes is to produce an output which has a reduced biodegradability thereby decreasing the environmental impacts associated with this material.

Assumptions used in our model of this process are presented in Table 5-3.

Table 5-3: Assumptions for MHT Process with Output to Land Application

Parameter	Assumption
Removal of materials for recycling during process	
Dense plastics[1]	60%
Glass[2]	70%
Ferrous metal	70%
Non-ferrous metal	70%
Miscellaneous inert material (e.g. stones and grit, crockery)	50%
Energy use by process	
Electricity	27 kWh / t
Heat	147 kWh / t
% organic matter from compost becoming humus[3]	25%

Notes

1. The central case assumes that the recovered plastic fraction is sent to landfill.
2. 50% of the recovered glass is assumed to be suitable feedstock for a closed loop recycling process.
3. The amount of stabilised output produced per tonne of waste will vary, depending on the composition of the waste being treated.

5.3.2.2 Output to INEOS Bio System

Our model of the MHT pre-treatment system assumes a similar fuel refinement to that described for the aerobic MBT process. As is the case for the latter process, the model assumes the MHT pre-treatment process consistently achieves the performance as stipulated in the guarantee provided to INEOS Bio with respect to the biogenic carbon content of the fuel. In comparison to fuel produced from the MBT pre-treatment process, more of the biogenic carbon is retained within the fuel fraction, as no significant degradation of the waste materials takes place during the heating process.

Assumptions used in our model of the MHT system with output to INEOS Bio are presented in Table 5-4.

Table 5-4: Assumptions for MHT / INEOS Bio System

Parameter	Assumption
Removal of materials for recycling during process	
Dense plastics[1]	60%
Glass[2]	70%
Ferrous metal	70%
Non-ferrous metal	70%
Miscellaneous inert material (e.g. stones and grit; crockery)	50%
Energy use by process	
Electricity	27 kWh / t
Heat	147 kWh / t
Fuel parameters[3]	
Moisture content	20%
Proportion of biogenic carbon (of total carbon) by weight	90%

Notes

1. The central case assumes that the recovered plastic fraction is sent to landfill.
2. 50% of the recovered glass is assumed to be suitable feedstock for a closed loop recycling process.
3. The amount of fuel produced per tonne of waste will vary, depending on the composition of the waste being treated and the organic carbon content of the fuel output.

5.3.3 MBT 'Splitting' Process

The MBT ('splitting') and AD process is similar to the 5 facilities being developed by Viridor-Laing under the Greater Manchester Waste contract, whereby the SRF will be sent for combustion (CHP) at INEOS Chlor's Runcorn facility.

In this type of MBT facility, a splitting process produces a large and small fraction from the input waste materials. The small fraction contains most of the organic material and is used as a feedstock for the AD element of the process. The large fraction is shredded and forms the SRF fraction. The process also recovers materials for recycling, with metals being recovered both from the MBT process and the subsequent incineration process.

Assumptions used in our model of the MBT AD Splitting process are shown in Table 5-5.

Table 5-5: Assumptions Used for MBT AD Splitting Process

Parameter[1]	Assumption
Removal of materials for recycling during MBT process	
Dense plastics	60%
Ferrous metal[2]	65%
Non-ferrous metal	60%
Total energy use by process (including demand for incineration)	
Electricity	82 kWh / t
Diesel	3 litres / t
Gross generation efficiency – gas engine in AD facility[3]	
Electricity	40%
Gross generation efficiency – incinerator[3]	
Electricity	12%
Heat[3]	56%

Notes

1. The amount of fuel produced per tonne of waste will vary, depending on the composition of the waste being treated.
2. Some additional metal is recovered from the bottom ash at the incinerator (see Section 5.3.4)
3. Gross generation efficiencies are calculated on the basis of the proportion of the total energy content of the feedstock that is subsequently converted into electricity and heat (excluding any energy that is used in the treatment process).
4. We assume that 60% of the heat generated can be used (see Section 5.1.1.2).

The assumptions used to model the performance of the incinerator are discussed in more detail in Section 5.3.4.

5.3.4 Incineration

Greenhouse gas emissions from incineration facilities are related to the carbon content of the combusted waste materials. However, the generation of electricity also leads to a reduction in generation from other sources and an associated reduction in associated emissions. There is also a small emissions offset resulting from the recovery of metals for recycling.

Energy demands for incineration processes are relatively high, partly as a result of the requirement for complex pollution control systems. For every tonne of waste to the facility we assume an electricity requirement of 78 kWh and a diesel requirement of 4.7 litres.[27]

For incinerators producing only electricity we assume a *gross* generation efficiency of 27%.[28] Where incineration facilities operate in CHP mode to produce both heat and electricity, the electrical generation capacity is reduced as the amount of heat recovered increases. The performance of this type of facility is based on the ratio of heat to electrical production determined from European survey data (our methodology is discussed in more detail in Appendix 2).

Assumptions used in our model of incineration are shown in Table 5-6.

Table 5-6: Assumptions for Incineration

Parameter	Assumption
Removal of materials for recycling from bottom ash	
Ferrous metal	70%
Non-ferrous metal	30%
Total energy use by process	
Electricity	78 kWh / t
Diesel	4.8 litres / t
Gross generation efficiency – electricity only option[1]	
Electricity	27%
Gross generation efficiency –CHP option[1]	
Electricity	10%
Heat[3]	56%

Notes:

1. Gross generation efficiencies are calculated on the basis of the proportion of the total energy content of the feedstock that is subsequently converted into electricity and heat (excluding any energy that is used in the treatment process).
2. We assume that 60% of the heat generated can be used (see Section 5.1.1.2).

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[27] VITO (2000) *Vergelijking van Verwerkingsscenario's voor Restfractie van HHA en Niet-specifiek Categorie II Bedrijfsafval*, Final Report

[28] Based on the best performing incinerators in Europe - see Riemann I (2006) *CEWEP Energy Report (Status 2001-2004): Results of Specific Data for Energy, Efficiency Rates and Coefficients, Plant Efficiency Factors and NCV of 97 European W-t-E Plants and Determination of the Main Energy Results*, updated July 2006

5.3.5 Landfill

5.3.5.1 Landfill of Un-treated Wastes

The most significant environmental impacts associated with landfill are caused by the generation of landfill gas from biodegradable materials as they degrade in the absence of air. Biodegradable carbon in paper, card, plant matter, food and other organic waste is broken down through a series of microbiological processes to form the greenhouse gases CO_2 and methane. Although a proportion of the landfill gas is captured and used for energy generation (thereby offsetting energy production from other sources) the net greenhouse gas impact remains significant.

The generation of landfill gas is widely held to follow an exponential decay function, i.e. after an initial peak, gas production drops off at a continually reducing rate. Our model quantifies these emissions though the lifetime of a typical landfill using first-order decay functions. This modelling accounts for the capture of gas for flaring and energy generation as well as the oxidisation of methane as it passes through the organic surface layer of the landfill. Our model also includes the impact of offset emissions associated with the generation of electricity from the captured landfill gas.

The efficiency with which landfill gas can be captured over the lifetime of the landfill has been the subject of considerable debate in recent years. Our model assumes a lifetime landfill gas capture rate of 50%. Whilst this is relatively low in comparison to the 75% capture rate assumed by ERM and Golders in their work for the Defra, it is much higher than that assumed by the IPCC and the European Environment Agency who assume lifetime capture rates of 20%.[29]

5.3.6 Landfill of Pre-treated Wastes

Our model assumes that waste which has been pre-treated (e.g. through an aerobic stabilisation process) will behave differently in landfill with respect to the generation of landfill gas, and that pre-treated wastes will therefore ultimately require a different form of gas management in landfill. In this case the methane flux from the landfill is much lower, no electricity production is possible and it is assumed that 90% of the methane generated is oxidised to CO_2.

5.4 Technologies Treating Biowaste

5.4.1 Conventional In-vessel Composting Process

Composting processes involve the use of micro-organisms to degrade the organic material contained in waste under controlled, aerobic conditions. In-vessel composting

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[29] ERM (2006) Impact of Energy from Waste and Recycling Policy on UK Greenhouse Gas Emissions, Final Report for Defra, January 2006; Golder Associates (2005) Report on UK Landfill Methane Emissions: Evaluation and Appraisal of Waste Policies and Projections to 2050, report for Defra, November 2005; IPCC (2007) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Metz B, Davidson O R, Bosch PR, Dave R, and Meyer L A (eds)), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp 600; Skovgaard M, Hedal N, Villanueva A, Andersen F and Larsen H (2008) Municipal Waste Management and Greenhouse Gases, ETC/RWM Working Paper 2008/1, January 2008

(IVC) processes are those whereby the composting process takes place in an enclosed environment within so-called 'vessels'.[30]

For composting processes, the quantity of emissions to the atmosphere of any given gas is related to the degree to which the process is allowed to proceed towards a theoretical 'final' point at which all the carbon dissimilable in the composting process has been degraded. Depending upon the nature of the input materials and the market outlets, compost producers may seek to produce more or less mature products. Although the production of a less mature product is likely to produce fewer process emissions, overall climate change impacts are likely to be more significant when immature compost is applied to land. Our model assumes that the composting facility incorporates a sufficient maturation period. The application of compost to land is assumed to displace the requirement for fertiliser and peat, resulting in avoided emissions of 0.06 tonnes CO_2 equivalent per tonne of green waste composted.[31]

Assumptions used in our model of incineration are shown in Table 5-7.

Table 5-7: Assumptions for In-vessel Composting Process

Parameter	Assumption
CH_4 emissions from process	0.56 kg / t input
N_2O emissions from process[1]	0.12 kg / t input
Non-degraded carbon (retained in microbial biomass)[2]	30%
Electricity requirement	40 kWh / t input
Diesel use by process	0.3 l / t input
Mineralisation rate of readily available organic matter[3]	20%
Mineralisation rate of stable humus[3]	1%
% of organic matter from compost becoming humus	25%

Notes:

1. Assumes that a biofilter converts 95% of the available NH_3 to N_2O. 88% of the total nitrogen is assumed to be released as NH_3, whilst 10% is assumed to be released as N_2O without the action of the biofilter.
2. This carbon is assumed to be used for cell reproduction and growth of the microbiological organisms carrying out the degradation process.
3. The mineralisation rate is the rate at which carbon contained within the organic matter (or humus) is assumed to become atmospheric CO_2.

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[30] In the UK, all food waste must be composted using an in-vessel process in order to meet the requirements of the Animal By-products Regulations

[31] Principally avoided N_2O emissions that would otherwise arise when nitrate fertiliser is converted to atmospheric N_2O, and avoided fossil CO_2 emissions caused by the removal of peat from peat bogs. We also include the avoided energy requirement resulting from a reduction in fertiliser manufacture.

5.4.2 In-vessel Pre-treatment Process for INEOS Bio

In contrast to the process described in Section 5.4.1, the aim here is to produce a dried output that still contains most of the carbon of the original feedstock. The model in this case is therefore based on what we know of biodrying processes for MSW, rather than that of a conventional composting process – the latter aiming to stabilise the material and reduce the further degradation of the compost. In this case no compost is produced, as all of the dried biomass is sent to the INEOS Bio process to produce bioethanol.

As is the case for the aerobic MBT process, we assume the use of a scrubber before the biofilter to reduce nitrogenous emissions including N_2O.

Table 5-8: Assumptions for In-vessel Pre-treatment Process for INEOS

Parameter	Assumption
CH_4 emissions from process	0.01 kg / t input
N_2O emissions from process[1] [2]	0.07 kg / t input
Biogenic carbon loss through biodrying	25%
Electricity requirement	40 kWh / t input
Diesel use by process	0.3 l / t input

Notes:

1. Assumes that a biofilter converts 95% of the available NH_3 to N_2O. 88% of the total nitrogen is assumed to be released as NH_3, whilst 10% is assumed to be released as N_2O without the action of the biofilter.
2. N_2O emissions are higher than those seen from MSW due to the greater organic nitrogen content of the feedstock.

5.4.3 Anaerobic Digestion of Bio-waste

The residence time and the type of organic carbon contained within the feedstock are key functions for how much of the total carbon content is converted to CO_2 and methane within the facility. Whilst the sugars, fats and proteins decompose fairly readily, the lignin-based materials are resistant to degradation. As such, biogas generation typically decreases as the proportion of garden waste in the feedstock increases.

A small amount of methane is emitted as fugitive emissions, though these tend to be fairly low as the process is fully enclosed. Beneficial offsets are again achieved through applying the stabilised output from AD to land thereby reducing the requirement for fertiliser and peat.

Beyond these factors, the most significant environmental impacts are associated with how the biogas is utilised. The current analysis considers two options for the use of the biogas:

4. Gas engine combustion generating both heat and electricity; and
5. The use of compressed biogas for road transport where it is assumed to substitute an equivalent amount (in terms of useful work done) of diesel.

As is the case with the INEOS Bio process, AD processes generate energy - some of which is required by the treatment process itself. Typically a third of the heat energy generated is required to heat the waste to achieve the temperatures required for the digestion process. Energy generation efficiencies are however higher than those seen in steam cycle processes (i.e. waste incineration facilities).

The gas upgrading process typically results in more fugitive emissions of methane in comparison to energy generation using the gas in an engine. Fugitive emissions during the upgrade process may be as high as 2% of the total amount of gas upgraded. We assume a 15% reduction in greenhouse gas emissions as a result of the use of biogas in a vehicle as opposed to diesel.[32]

Assumptions used in our model of AD for source-separated organic waste are shown in Table 5-9.

Table 5-9: Assumptions for AD (Bio-waste)

Parameter	Assumption
Methane content of biogas	60%
Gross generation efficiency – onsite generation[1]	
Electricity[2]	40%
Additional fugitive CH_4 emissions during biogas upgrading process	2%
GHG emissions reductions through use of gas in vehicle	15%

Notes

1. Gross generation efficiencies are calculated on the basis of the proportion of the total energy content of the feedstock that is subsequently converted into electricity and heat (excluding any energy that is used in the treatment process).
2. The net electrical efficiency is 36% taking into account the parasitic load of the facility.

5.5 Technologies Treating Garden Wastes

5.5.1 Open Air Windrow Composting

The principal climate change impacts are associated with release of biogenic CO_2 emissions which are not reported in the majority of life-cycle assessment studies.

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[32] Emissions reductions based on the use of CNG in Finnish buses. See N. Nylund, K. Erkkilä, M. Lappi, and M. Ikonen (2004) *Transit Bus Emission Study: Comparison of Emissions from Diesel and Natural Gas Buses*, VTT Processes, October 2004

Since these processes are not enclosed, it is not possible to reduce the nitrogenous emissions through the use of abatement equipment (as is the case with the in-vessel systems).

The application of compost to land is assumed to displace the requirement for fertiliser and peat, resulting in avoided emissions of 0.06 tonnes CO_2 equivalent per tonne of green waste composted.[33]

Assumptions for the modelling of windrow composting are shown in Table 5-10.

Table 5-10: Assumptions for Windrow Composting

Parameter	Assumption
CH_4 emissions from process	0.04 kg / t input
N_2O emissions from process[1]	0.12 kg / t input
Electricity requirement	40 kWh / t input
Diesel use by process	0.3 l / t input
Mineralisation rate of readily available organic matter[2]	20%
Mineralisation rate of stable humus[2]	1%
% of organic matter from compost becoming humus	25%

Notes:

1. Assumes that a biofilter converts 95% of the available NH_3 to N_2O. 88% of the total nitrogen is assumed to be released as NH_3, whilst 10% is assumed to be released as N_2O without the action of the biofilter.
2. The mineralisation rate is the rate at which carbon contained within the organic matter (or humus) is assumed to become atmospheric CO_2.

5.5.2 Pre-treatment for INEOS Process

We assume that garden waste is shredded prior to its use in the INEOS Bio process.

5.6 Technologies Treating Waste Wood

5.6.1 Industrial CHP

Wood waste may be used as a feedstock to generate heat energy through combustion in a dedicated biomass combustion facility. Key assumptions used to model this treatment method are outlined in Table 5-11.

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[33] Principally avoided N_2O emissions that would otherwise arise when nitrate fertiliser is converted to atmospheric N_2O, and avoided fossil CO_2 emissions caused by the removal of peat from peat bogs. We also include the avoided energy requirement resulting from a reduction in fertiliser manufacture.

Table 5-11: Key Assumptions Used to Model the Combustion of Wood Waste

Parameter	Assumption
Carbon content of ash	1%
Calorific value (dry lower heating value)	11.5 MJ / kg input
CH_4 emissions from process	0.07 kg / t input
N_2O emissions from process	0.01 kg / t input
Diesel usage in process	0.5 l / t input
Electricity usage in process	0.1 kWh / t input
Gross generation efficiency Electricity Heat	 12% 56%[1]

Notes:

1. We assume that 60% of this heat generated can be used (see Section 5.1.1.2).

5.6.2 Pre-treatment for INEOS Process

Waste wood is assumed to be dried and shredded prior to its use in the INEOS process. The moisture content of the wood waste after the drying process is 15% as the material is typically drier at the start of the process than other organic wastes.

6.0 Presentation of Results

6.1 Biofuels Systems Analysis Using RED Methodology

Table 6-1 presents emissions reductions from the INEOS Bio production process in comparison with those anticipated to occur from the conventional process for petrol production. Table 6-1 also includes emissions reductions expected for an AD process where the output from that process is assumed to produce transport fuel. All the biofuel options result in emissions reductions that are in excess of 60%.[34]

Table 6-1: Comparison of Emissions – Biofuel and Fossil Fuel Production Processes

		Biofuel system			Fossil[1][2]	Systems comparison (emissions reductions)
		Ethanol from 1 tonne to process	Emissions bio-fuel production process	Emissions per MJ of energy	Emissions per MJ of energy	
		Tonnes bio-ethanol	Tonnes CO_2eq	g CO_2eq / MJ	g CO_2eq / MJ	%
INEOS	Garden	0.145	-0.094	-19.581	83.800	123%
	Residual (MBT)	0.083	0.022	7.844	83.800	91%
	Residual (MHT)	0.112	0.050	13.637	83.800	84%
	Wood	0.172	-0.115	-20.194	83.800	124%
	Bio-waste	0.079	-0.019	-7.387	83.800	109%
AD[1]	Bio-waste	0.057		23.000	83.800	73%

Notes:

1. Default data from the RED methodology are used to estimate emissions from the fossil (petrol) system and AD
2. The methodology assumes petrol has a lower heating value of 32 MJ / litre

Production of bio-ethanol from a MSW feedstock results in lower emissions reductions, principally as a result of the following:

- Less biofuel is produced per tonne of feedstock, and less electricity produced (reducing the emissions credit associated with this); and
- There are also some fossil emissions from the non-organic material that remains in the feedstock after processing.

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[34] This is the emissions reduction target from the RED for the production of biofuel from new facilities operating from 2017 onwards

For the bio-waste feedstocks, the emissions credit associated with electricity production is sufficient to offset all of the fossil emissions from the INEOS production process and pre-treatment (in the case of the bio-waste plant).

The results presented in Table 6-1 indicate that the INEOS Bio process performs better than the AD process for source separated bio-waste feedstocks when the sustainability of the two systems is assessed using the methodology outlined in the RED.

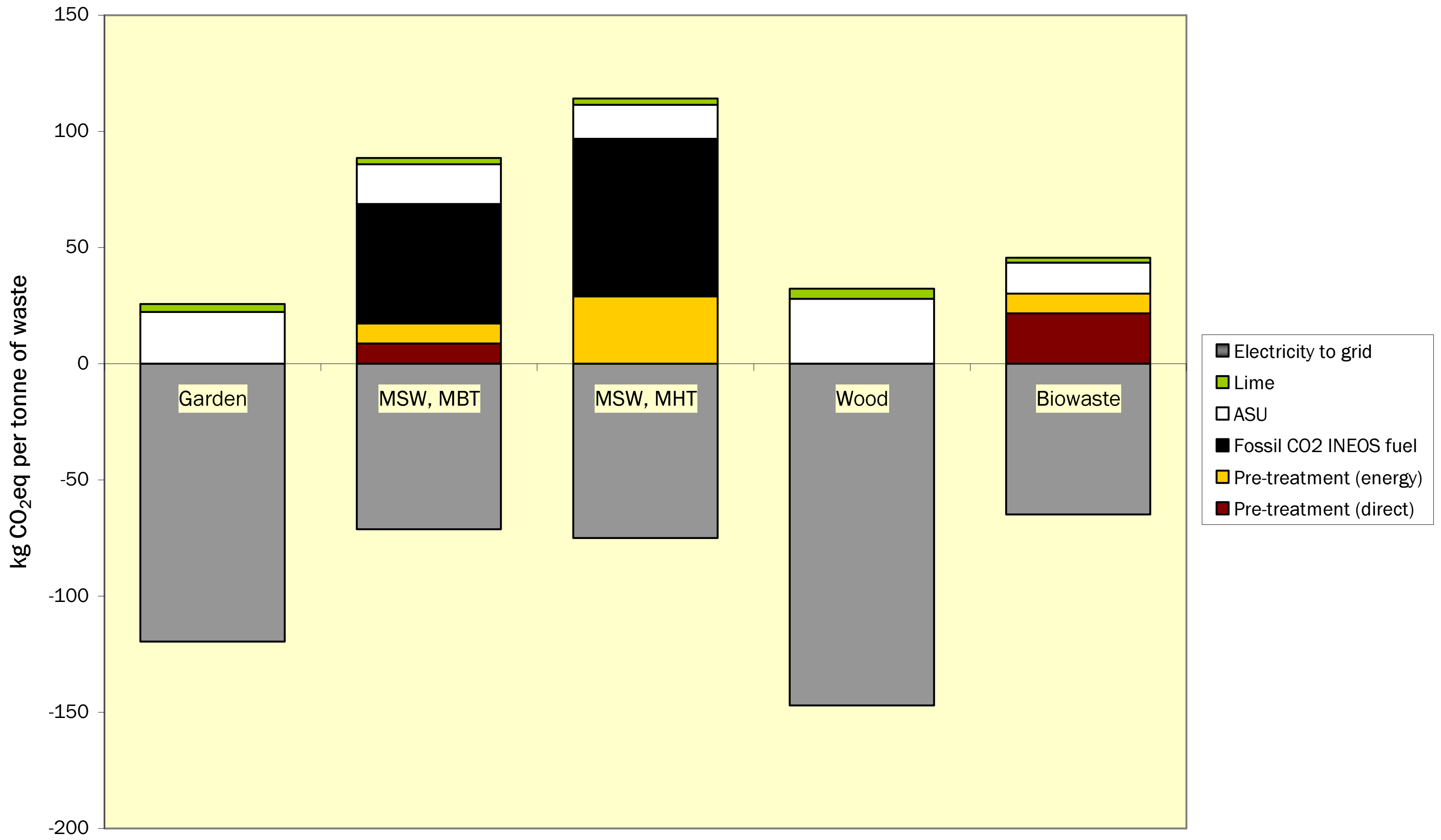
The results suggest that the use of one litre of biofuel produced by the INEOS process would result in an emissions saving of 3 kg CO_2 equivalent in comparison to the use of the same amount of fossil petrol where the fuel was produced from a purely organic waste feedstock. If bio-waste from MSW was used as the feedstock, emissions savings would be slightly lower, at 2 kg CO_2 equivalent per litre of biofuel.

Table 6-2 provides the breakdown of the emissions from the bio-fuel production process. The same information is presented graphically in Figure 6-1. These results confirm that the main difference between the two MSW processes relates to the additional emissions associated with the energy required to heat the waste during the MHT pre-treatment phase. However, the MBT process produces slightly less biofuel and electricity in comparison to the MHT system as some of the biogenic carbon within the feedstock is lost during the degradation process. The direct emissions from the MBT and the bio-waste pre-treatment process principally relate to N_2O emissions, produced as a result of the degradation of organic nitrogen in the feedstock. These emissions are more significant where bio-ethanol is produced from biowaste as a result of the feedstock's higher organic nitrogen content. The biowaste feedstock produces less bio-ethanol per tonne of feedstock in comparison to the other options as a result of its high moisture content (50% of the input material is assumed to be food waste, which has a moisture content of 70%).

Table 6-2: Breakdown of Emissions from the INEOS Bio Process (kg / t waste)

	Garden	MSW, MBT	MSW, MHT	Wood	Biowaste
Pre-treatment (direct)		8.71			21.70
Pre-treatment (energy)		8.54	28.99		8.53
Fossil CO_2 INEOS fuel		51.42	67.87		
ASU	22.28	17.16	14.54	27.95	13.32
Lime	3.44	2.65	2.81	4.31	2.06
Electricity to grid	-119.58	-71.25	-75.06	-147.07	-64.78

Figure 6-1: Breakdown of Emissions from the INEOS Bio Ethanol Production Process



6.2 Waste Systems Analysis

This section presents the CO_2 equivalent emissions generated per tonne of waste to each of the processes considered within the analysis.

Figure 6-2 presents the results of the analysis and shows that the INEOS Bio process outperforms the others with respect to the emissions generated per tonne of waste, for all of the feedstocks considered within the analysis.

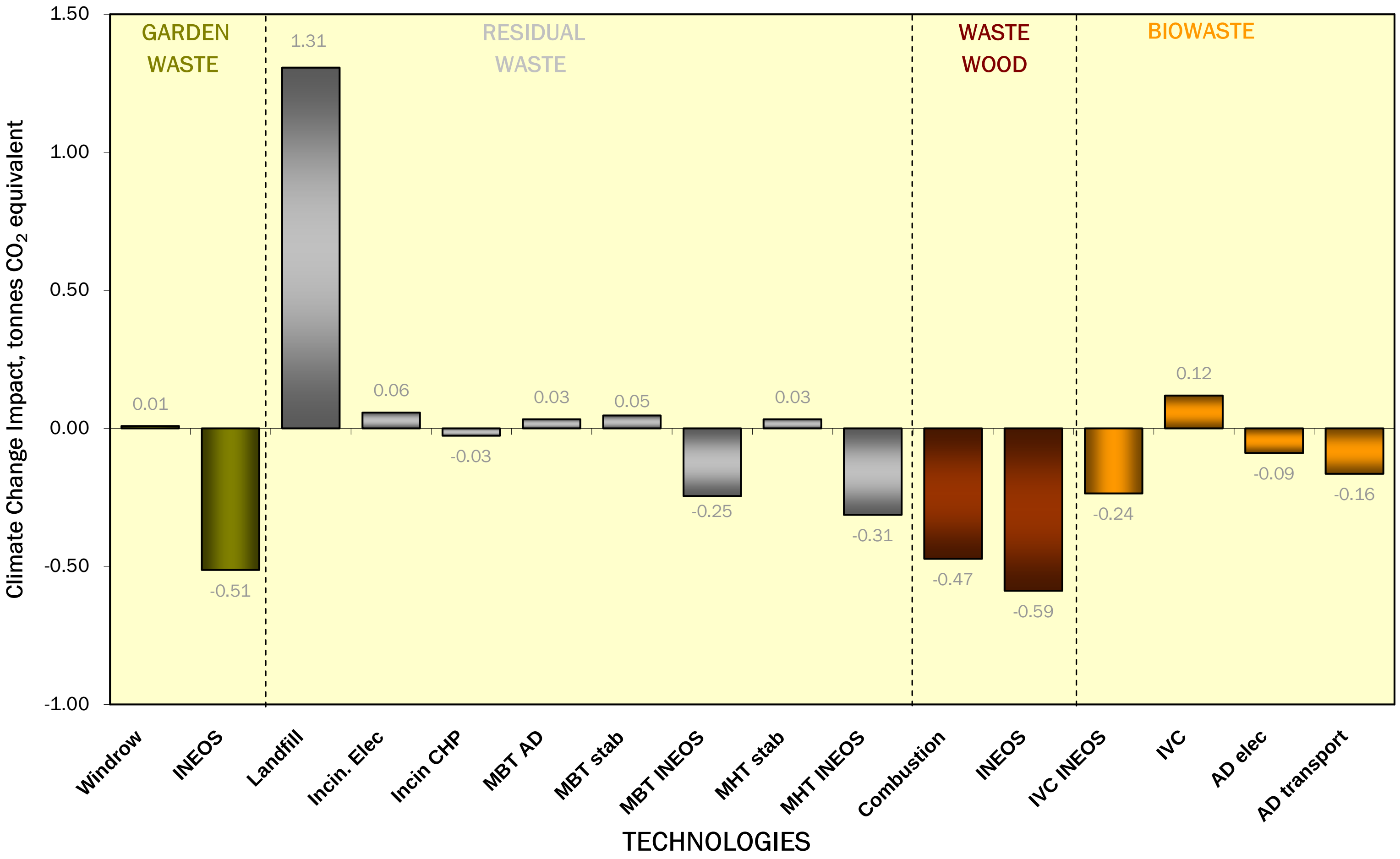
For the MSW INEOS options, offset emissions from recycling are included, along with offsets associated with the energy generation. In this case, avoided emissions are sufficient to offset all of the direct emissions from the process, giving an overall negative GHG balance. For biowaste, the INEOS Bio process outperforms the AD options as in the case of the latter, relatively less of the carbon is converted to transport fuel or electricity.

Where garden waste is used as the feedstock for the INEOS Bio process, the results suggest a saving of around 0.5 tonnes of CO_2 equivalent per tonne of garden waste treated would be achieved. In comparison, the composting of garden waste produces a soil improver but delivers no net CO_2 savings.

The use of wood waste as the feedstock for the INEOS Bio process results in the greatest net CO_2 savings, equal to 0.59 tonnes of CO_2 equivalent saved per tonne of feedstock to the process when biogenic CO_2 emissions are excluded from the analysis.

It should be noted, however, that the INEOS Bio process effectively converts the biogenic carbon contained within the waste materials into biofuel and electricity, resulting in the production of biogenic CO_2 emissions. As explored in more detail in Appendix 2.0, the relative performance of the INEOS Bio process against the competing technologies is different for some feedstocks when biogenic CO_2 emissions are included within the analysis.

Figure 6-2: GHG Emissions per Tonne of Waste



7.0 Sensitivity Analysis

7.1 Alternative Input Waste Composition (High Recycling Scenario)

The sensitivity analysis in this section investigates the impact on the results of improvements in the recycling rate for households in the North East. This results in less organic material being left in the residual waste stream, leading to a reduction in energy generation and biofuel production.

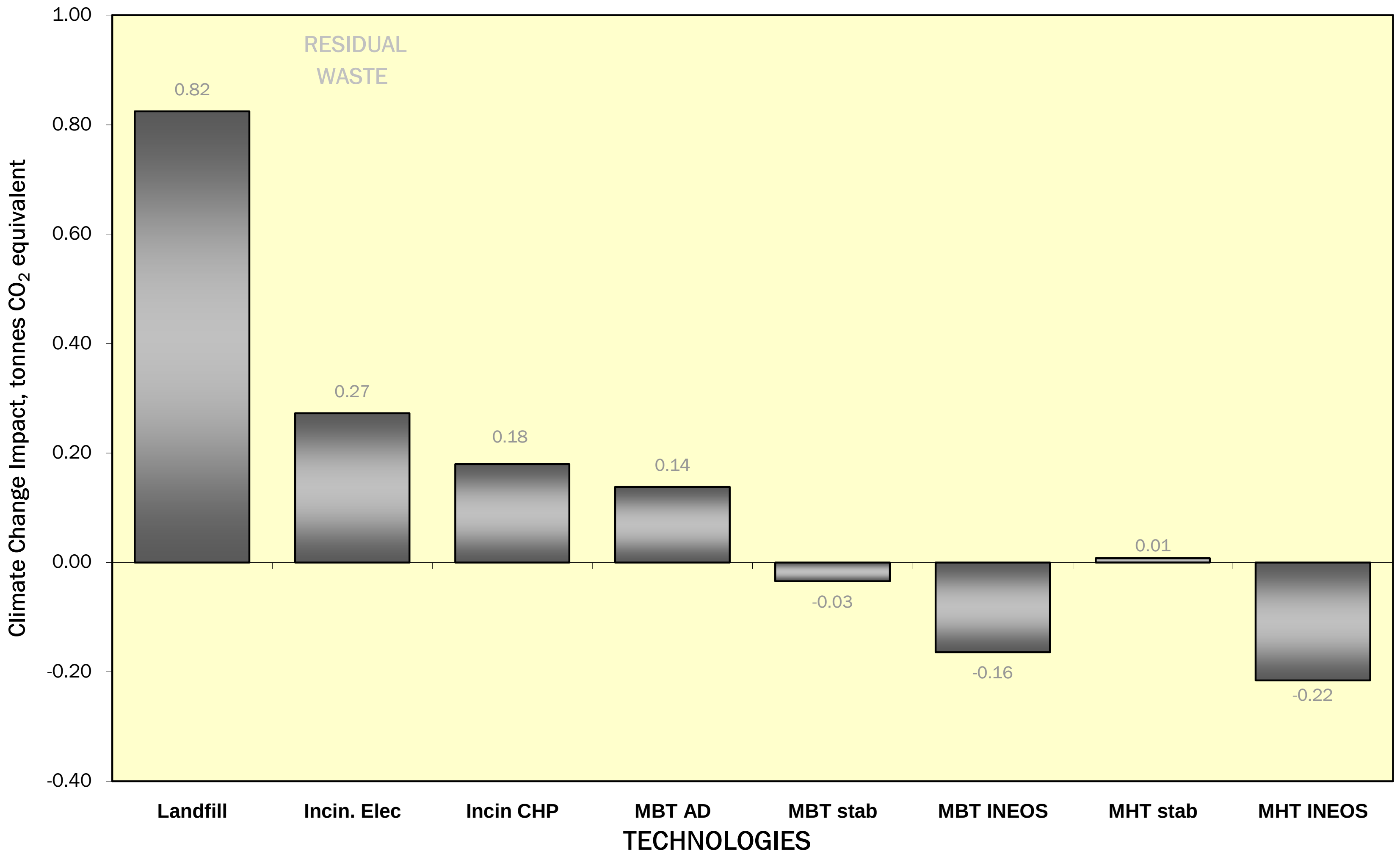
The impact with regard to the RED methodology is indicated in Table 7-1 which shows the results for the two MSW options. These results show that whilst the performance is reduced for the MBT system, the MHT achieves similar emissions reductions to that seen under the central scenario. This is because the lower biogenic carbon content leads to lower pre-treatment emissions. These are relatively more significant for the MHT system, and are sufficient to offset the impacts associated with the decrease in biofuel and energy production.

Table 7-1: Results for Biofuel Systems Analysis – High Recycling Scenario

		Biofuel system			Fossil	Systems comparison (emissions reductions)
		Ethanol from 1 tonne to process	Emissions bio-fuel production process	Emissions per MJ of energy	Emissions per MJ of energy	
		Tonnes bio-ethanol	Tonnes CO_2eq	g CO_2eq / MJ	g CO_2eq / MJ	%
INEOS	Residual (MBT)	0.044	0.019	13.437	83.800	84%
	Residual (MHT)	0.061	0.025	12.573	83.800	85%

The impact of this changed assumption under the 'waste systems' analysis is shown in Figure 7-1 .Whilst emissions associated with landfill and the MHT and MBT processes are reduced as a result of the reduction in organic matter, impacts associated with treating one tonne of waste through incineration are increased.

Figure 7-1: Results for Waste Systems Analysis – High Recycling Scenario



7.2 Alternative Fuel Composition (100% Biomass Fraction)

This section considers the impact upon the results of the removal of all of the fossil carbon from the fuel output to the INEOS Bio process. Trials undertaken with other MBT processes indicate that it is possible to produce an MBT output stream with a plastics content of less than 0.5%.[35] This will however result in less fuel being produced, and in the production of a fuel with a lower calorific value.

Indicative results for the biofuel system analysis using these assumptions in the RED methodology assessment are shown in Table 7-2, which confirms that the relative performance of the two INEOS Bio processes is improved. Given that very little mass balance data is available with respect to the production of this type of highly purified output from existing MBT or MHT processes, the results shown in this table provide a theoretical indication of the potential best performance associated with this type of system.

Table 7-2: Results for Biofuel Systems Analysis – Pure Biomass Fuel Scenario

		Biofuel system			Fossil	Systems comparison (emissions reductions)
		Ethanol from 1 tonne to process	Emissions bio-fuel production process	Emissions per MJ of energy	Emissions per MJ of energy	
		Tonnes bio-ethanol	Tonnes CO_2eq	g CO_2eq / MJ	g CO_2eq / MJ	%
INEOS	Residual (MBT)	0.068	-0.028	-12.628	83.800	115%
	Residual (MHT)	0.096	-0.022	-6.876	83.800	108%

Corresponding results for the ‘waste systems’ analysis are shown in Figure 7-2. The graph shows that this assumption has only a minor impact on the waste systems analysis.

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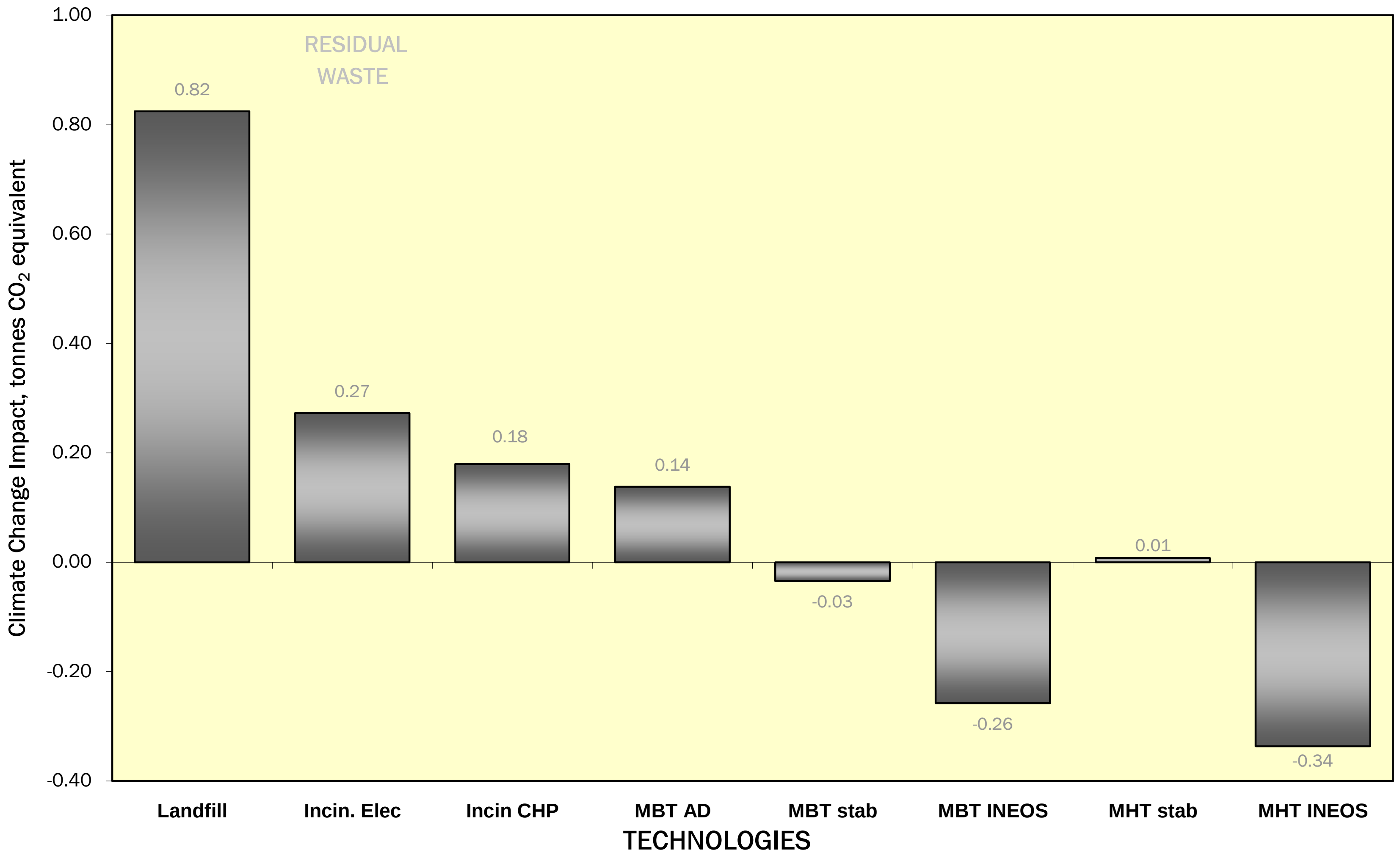
[35] ADAS (2007) Biowaste Materials: Quality and Suitability for Land Recycling, Report to the Environment Agency, June 2007

Figure 7-2: Results for Waste Systems Analysis – Pure Biomass Fuel Scenario



7.3 Variation in Carbon Intensity of Electricity

This section considers the impact on the results associated with the waste systems analysis of assuming the carbon intensity of electricity production is equal to the average UK grid mix.[36] These results are presented in Figure 7-3.

Impacts associated with the two stabilisation processes increase slightly, as neither process generates any energy. Impacts associated with all the other treatment options decrease, with those technologies that generate more energy (such as the incineration and INEOS processes) being reduced to a greater extent.

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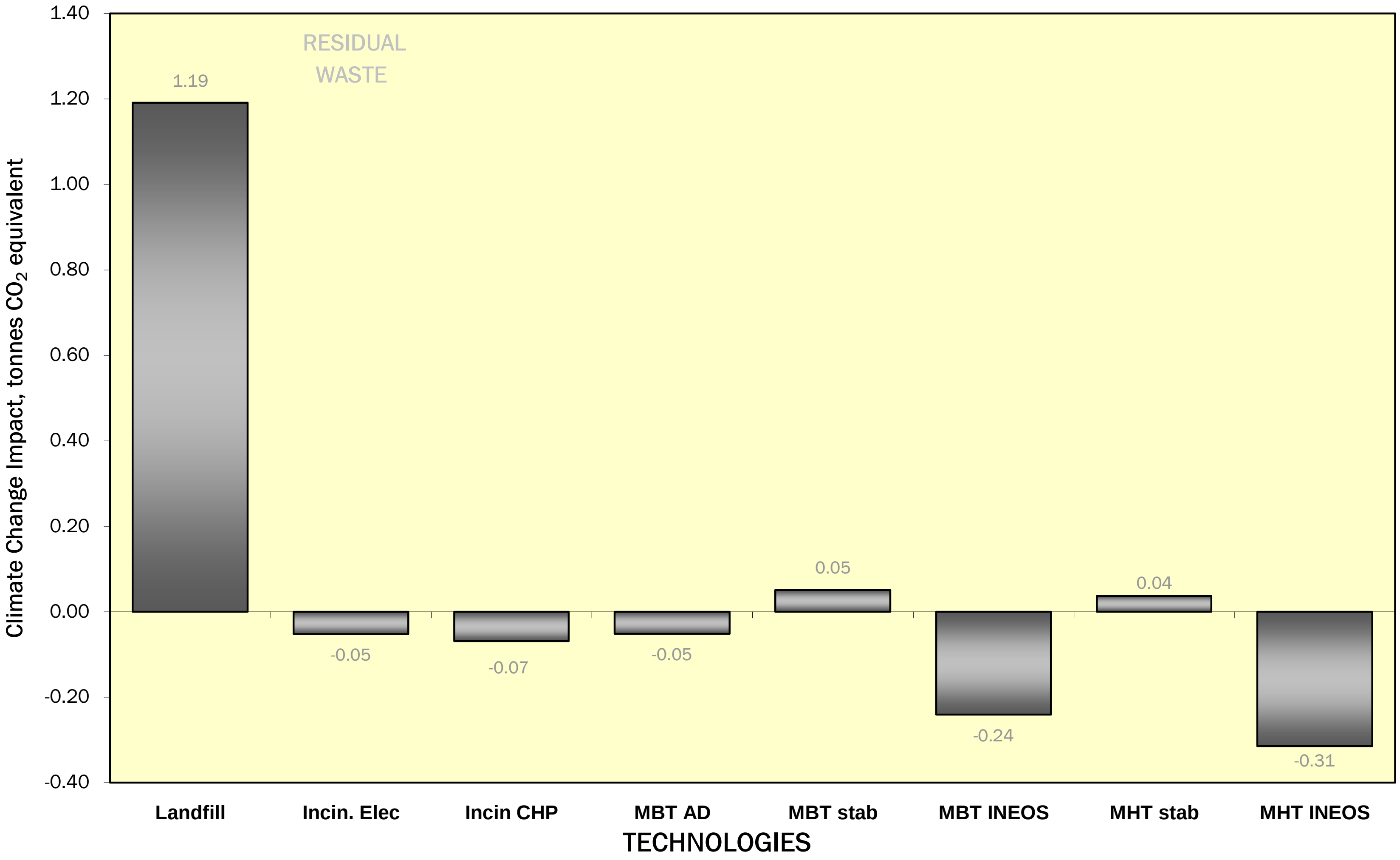
[36] The RED stipulates that this assumption must be used and this is therefore taken as the central case for the biofuel systems analysis

Figure 7-3: Results for Waste Systems Analysis – Average Grid Mix Scenario



7.4 Destination of Plastics Stream

Results for the sensitivity analysis presented in this section consider two alternative routes for the mixed plastic stream produced by the MBT and MHT processes. Whilst the central case assumes that this stream is landfilled, the analysis here considers the impact of:

1. The mixed plastic stream being sent to a cement kiln where it is assumed to offset the use of coal for heat generation at the kiln; and
2. The dense plastic stream being sent for re-processing as part of a closed loop recycling process.

The first of these options is assumed to produce a mixed film stream that is recovered along with the dense plastic. However, in the second option, no benefit is attributed to the recycling of this mixed film stream due to the relatively low quality of the recovered material.

Results for these two options are shown in Figure 7-4 and Figure 7-5 respectively. The graphs show that the first of these options results in a more significant improvement in the performance of the two INEOS processes. The MHT process is assumed to recover slightly more plastic than the MBT system, and as such shows a greater improvement in performance relative to the MBT process for both options.

Figure 7-4: Results for Waste Systems Analysis – Plastics Sent to Cement Kiln Scenario

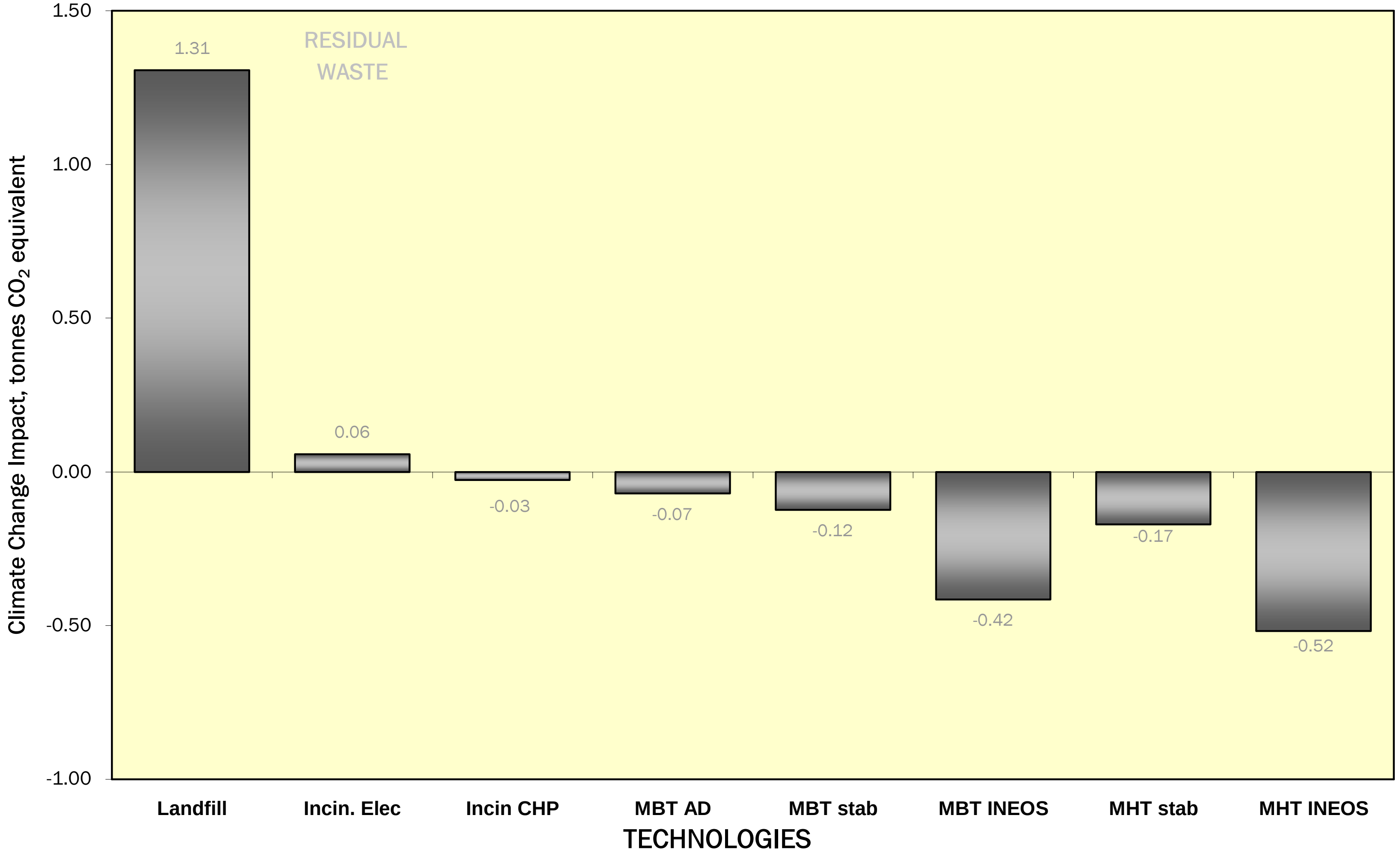
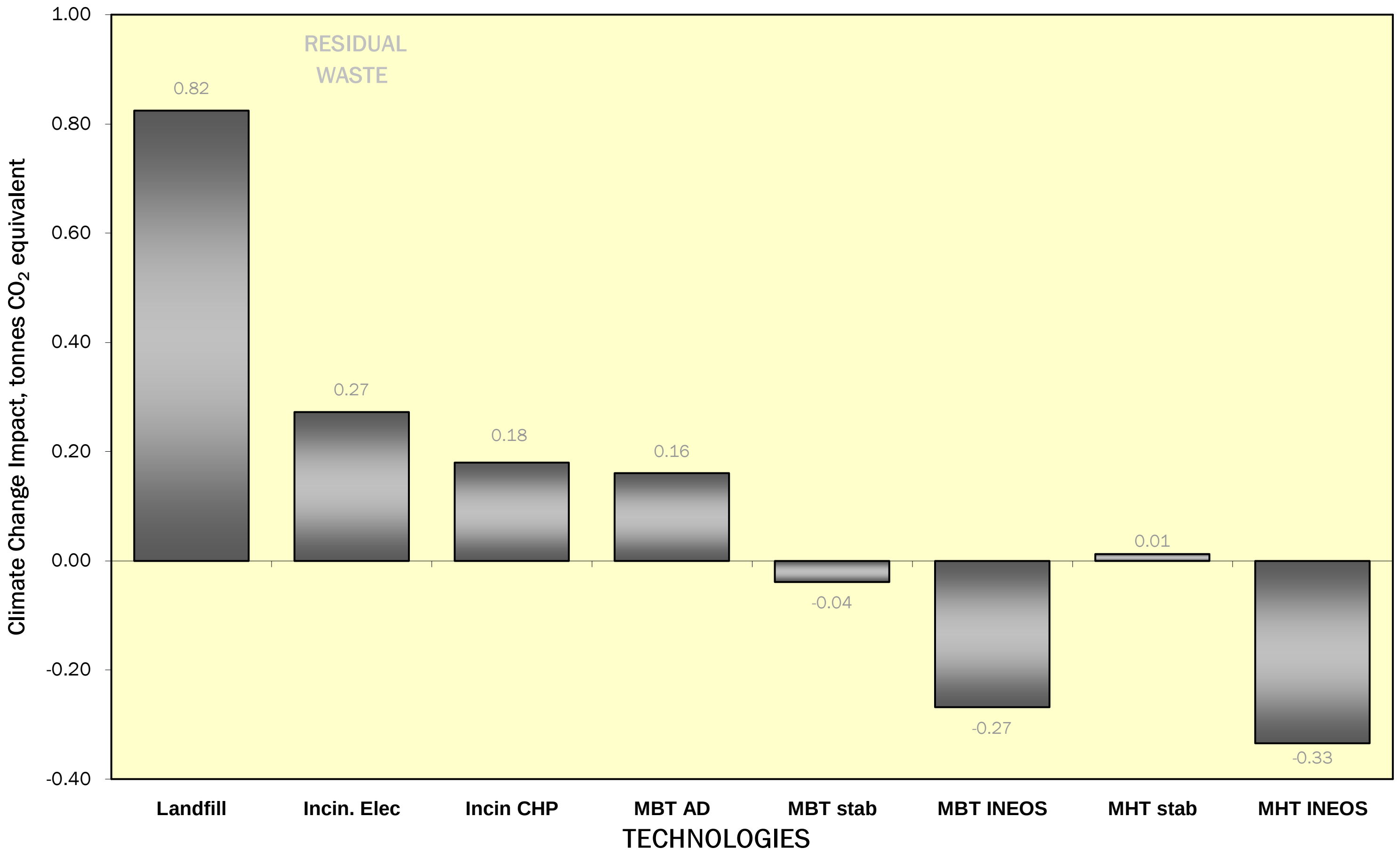


Figure 7-5: Results for Waste Systems Analysis – Plastics Sent for Re-processing Scenario



8.0 Conclusions and Recommendations

As discussed in Section 1.0, in the UK, local authority recycling targets, and associated National Indicators (NIs), are currently such that anaerobic digestion (AD) and composting are seen as preferential by local authorities to the production of biofuels from wastes. The core goal of this study, therefore, was to consider whether this is a sound position from an environmental perspective, with regard to emissions of CO_2 equivalent.

The results presented in Section 6.0 demonstrate that this position cannot be justified in the case of the INEOS Bio process. The central finding of the study is that under both the ‘Biofuels Systems’ and ‘Waste Systems’ methodologies, technology configurations incorporating the INEOS Bio process to produce a liquid biofuel results in far lower emissions of CO_2 equivalent than all other alternatives. As detailed in Section 7.0 this was also the case with all variations on the central assumptions tested as part of the sensitivity analysis undertaken for the study.

Eunomia believes, therefore, that on the basis of the findings of this study, INEOS Bio has a reasonable case to put forward to both Defra and the European Commission. This might be towards establishing a relevant framework such that there is *at least* equal incentive for local authorities to procure facilities (or capacity at relevant merchant facilities) designed to produce bio-fuels from waste compared to composting or anaerobic digestion of the wastes. It is understood that Defra is currently deliberating over implementation of the EU Waste Framework Directive, and will shortly issue a second consultation document. It is therefore recommended that INEOS Bio uses the information contained in this study as a contributing element to support a formal response to this forthcoming consultation.