Greenhouse Gas and Air Quality Impacts of Incineration and Landfill

Report to ClientEarth

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Report for ClientEarth

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Contents

1.0 Introduction

This report was commissioned by ClientEarth to examine the greenhouse gas and air quality impacts of alternative approaches to the treatment of residual waste. The study considered the following:

- Landfill;
- Landfill with pre-treatment and bio-stabilisation;
- Incineration; and
- Incineration with pre-treatment.

The report focusses on the following impacts:

1) The greenhouse gas emissions produced (carbon dioxide, methane and nitrogen dioxide emitted in tonnes of carbon dioxide equivalent per tonne of waste treated).
2) The impacts on human health (monetised impacts of air pollution per tonne of waste treated).

Critically, this work takes both current and forward-looking perspectives. The impacts of current waste treatment per tonne of waste are calculated in a 'Today' scenario using Eunomia's bespoke modelling tools.

Perhaps more importantly (because EfW facilities can be in operation for up to 30 years), this study also considers environmental impacts into the future, using 2035 as the basis year for comparison.[1] This 'Expected-2035' scenario examines how the likely changes in residual waste composition and the provision of electricity and heat will affect the greenhouse gas performance of residual waste technologies.

In order to account for the urgency of climate change, and to examine whether the timeframe considered in the analysis has an impact on the conclusions drawn, a further scenario is established. Under this 'GWP20' scenario, which uses the same energy and composition assumptions as the Expected-2035' scenario, only the emissions in the first 20 years are considered, and a higher Global Warming Potential of 86 (as modelled by the International Panel on Climate Change) is used to account for methane's significantly higher potency in the shorter term.

The report compares the technologies from a UK perspective, however reference is also made to how its conclusions could be applied in countries with less advanced waste treatment options.

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[1] The term 'energy from waste' can include multiple processes, however this report focusses on incineration of waste, excluding processes like anaerobic digestion (AD).

The results of this study are compared to those in the literature, and significant differences in the conclusions drawn are explained in terms of differences in methodology and assumptions.

The report comprises the following key sections:

- Section 1.1 describes the context and motivation behind this study.
- Section 2.1 describes the residual waste treatment systems compared.
- Section 2.2 describes the scenarios examined.
- Section 2.3 compares the climate change impacts of the treatment technologies modelled.
- Section 2.4 compares the air quality impacts of the treatment technologies.
- Section 3.0 compares the climate change impacts of incineration to other electricity generation methods.
- Section 4.0 gives conclusions and recommendations based on the findings of this study.

1.1 Context

Energy from Waste (EfW) is seen by some as a technology that is key to reducing the carbon emissions from residual waste treatment into the future, through diverting waste from landfill and reducing the need to burn fossil fuels in conventional power plants. The context surrounding how this conclusion is drawn are changing, however.

Defra's "Energy from waste: A Guide to the Debate", which states that there is "a good carbon case for continuing to include EfW as a key part of the [waste] hierarchy," is still being used to guide infrastructure decisions related to EfW technology but was published in 2014. [2]

The national discourse on carbon emissions and climate change has shifted significantly since then, and the need to make substantial reductions in carbon emissions in the next decade has become clearer. This is evidenced, for example, by the 300 (74%) Councils that have declared a 'Climate Emergency' to date, with 200 of those setting net-zero target dates of 2040 or earlier.[3]

The argument that incinerating waste may not be 'climate friendly' has in fact been made for some time. A report written by Eunomia for Friends of the Earth in 2006 found that, contrary to industry and political consensus at the time, incineration should not be considered an ideal solution to reducing the carbon emissions from waste treatment. [4] The report argued that the assumptions used to arrive at that conclusion – particularly that EfW generates less carbon emissions per unit of energy produced than the technologies that it is replacing – are not entirely well-founded.

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[2] DEFRA (2014) *Energy from Waste: A Guide to the Debate, Revised Edition*, February 2014

[3] https://www.climateemergency.uk/blog/list-of-councils/

[4] Eunomia Research & Consulting (2006) *A Changing Climate for Energy from Waste?*, 2006

The study found that “typical UK incinerators, generating only electricity, are unlikely to be emitting a lower quantity of greenhouse gases… than the average gas-fired power station in the UK,” and that the convention of ‘ignoring’ biogenic carbon dioxide – that coming from organic- as opposed to fossil-based materials – is not always appropriate for comparing incineration to landfill, as it does not take into account the time profile of GHG emissions or the sequestration effect of landfill.

Fourteen years later, the arguments put forward in that report have become even stronger. Driven by changes to waste management policy, the residual waste stream is likely to change significantly in the coming years: a 65% municipal waste recycling rate by 2035 (as targeted by the EU’s Circular Economy Package) is likely to be adopted into UK law, which will drive changes in the composition of municipal waste. The England Resources and Waste Strategy aims for no more than 10% of municipal waste to end up in landfill by this date, and no food waste to end up in landfill by 2030 (this being aided by universal separate food waste collection systems).

Accordingly, it is anticipated the fossil carbon content in the residual waste stream will increase as more food waste is recycled. Alongside this, a significant amount of plastic will remain in the waste stream even if high recycling rates are achieved, because plastic film is typically not easily recycled. These changes to the residual waste stream will have a significant impact on the carbon emissions from waste treatment.

Furthermore, as the electricity grid continues its aggressive decarbonisation, the carbon emissions ‘credit’ from displacing other forms of energy generation that is earned by incineration will decrease. The changes to the residual stream laid out above – a relative increase in the fossil carbon content of residual waste – will exacerbate this.

Other changes since 2006 may improve the picture for incineration relative to landfill. Our deeper understanding of methane’s climate-changing potential has led to an increase in the climate impacts accounted for in modelling (as approximated by its Global Warming Potential (GWP), the heat absorbed by a gas in the atmosphere divided by the heat that the same mass of carbon dioxide would have absorbed). This reduces the performance of landfill.

As well as this, the impacts of carbon dioxide and methane on global warming vary over time. Methane is extremely potent in the first couple of decades after emission but decays or is removed from the atmosphere more quickly than carbon dioxide. This means that the timescale used in the analysis has a critical impact on conclusions: from a 20-year perspective landfill is a less favourable treatment method than from a 100-year perspective. Conversely, while EfW emits carbon dioxide instantaneously, landfill emits greenhouse gases on multi-decadal timescales. This means that impacts of landfill and incinerators are not equivalent when viewed over different timescales, which is critical when considering the urgency of climate change – these points are often omitted from analyses comparing landfill and incineration.

The changing context laid out in this section reinforces the need to understand which residual waste treatment offers the lowest climate change impacts, now and in the future.

2.0 Comparing Waste Treatment Facilities

This chapter describes the methodology, assumptions and scenarios considered when comparing the climate change and air quality impacts of landfill (‘straight’ and with mechanical pre-treatment and bio-stabilisation), and incineration (‘straight’ and incineration with mechanical pre-treatment).

2.1 Treatment Systems

This section describes the residual waste treatment options modelled in this study. Each of these treatment practices is a method of disposing of *residual waste*: municipal waste from households and commercial (non-industrial) sites that is not sent to be recycled.

2.1.1 Landfill (‘straight’)

A landfill is a site dug into the ground in which residual waste is deposited into ‘cells’, smaller blocks of waste which are divided by separating structures. At the end of each day, the waste is covered with compressed soil or earth to limit material blowing away.

The breakdown of organic material that occurs in landfills releases a combination of methane and carbon dioxide, a process that occurs on a timescale of 100+ years. Cells are periodically sealed to limit the escape of gases. Some of the methane produced is oxidised into carbon dioxide by micro-organisms as it rises through the landfill. In the UK, a substantial proportion of the landfill gas is captured and either combusted to produce electricity, or ‘flared’ to convert the methane to carbon dioxide before being released into the atmosphere.

Not all the carbon in the material in the landfill is released as carbon dioxide within the 100-year period. While there are significant uncertainties, most analyses estimate (using the approach set out by the IPCC) that at least 50% of the biogenic carbon in the waste – that coming from organic- as opposed to fossil-based materials – in the waste remains ‘sequestered’ (see Section 2.3.2.2 for a full description of biogenic carbon emissions).[5] In addition, fossil carbon (e.g. plastics) is not subject to degradation in landfill and thus CO_2 is not emitted from such sources in landfill.

This technology considers ‘straight’ landfill: landfill without any form of pre-treatment or bio-stabilisation.

2.1.2 Incineration (‘straight’)

There are several forms of EfW technology including anaerobic digestion, pyrolysis and gasification. This report considers only incineration.

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[5] Myhre, G., Shindell, D., Bréon, F.-M., et al. (2018) *Anthropogenic and Natural Radiative Forcing (IPCC)*, 2018, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

Incineration is the controlled burning of residual waste. This waste is made up largely of molecules containing carbon atoms, and when burnt in the presence of oxygen, these carbon atoms are released as carbon dioxide alongside heat. This heat is then used to generate steam which can be used to drive a turbine to generate electricity, or as part of a Combined Heat and Power (CHP) plant, which generates electricity and subsequently uses the waste steam in a heat network to provide heat for local homes or industry. Note, however, that most incineration facilities in the UK generate only electricity.

In the UK today, where fossil fuels still provide a large amount of electricity and heat, the energy generated by incinerators reduces their net climate impact as a residual waste treatment process. This is because they reduce the amount of energy needed from other sources (other power plants or boilers, for example) which would themselves have emitted GHGs.

A given unit of heat produced by the incinerator can produce different quantities of useful electricity and heat. A high-performance incinerator can convert heat into electricity at an efficiency of 25-30%, whereas it can produce useful heat at an efficiency of about 85% (gross). This latter value is much higher because no conversion of energy is occurring.

Electricity is generated at lower efficiencies in CHP plants than electricity-only plants, because steam leaving the electricity turbine needs to be at a higher temperature to be able to provide useful heat. However, because the heat in this steam is then used (at a high efficiency), the overall thermal efficiency is higher.

As noted above, the emission of greenhouse gases is near-instantaneous in an incinerator. Landfills, conversely, emit carbon dioxide and methane over several decades.

This technology considers ‘straight’ incineration: incineration without any form of pre-treatment.

2.1.3 Advanced mechanical pre-treatment and incineration

Advanced mechanical pre-treatment systems use a series of mechanical processes to remove more of the recyclable materials from the residual waste stream. This includes the targeting of dense plastics and plastic film, which is poorly targeted by kerbside collection systems due to its low density. These systems thereby reduce fossil carbon content of the residual stream and increase the material going to recycling, improving the overall ‘climate performance’ of the system. This report examines advanced mechanical pre-treatment in conjunction with incinerators, whereby the final residual stream is combusted to produce energy.

2.1.4 Advanced mechanical pre-treatment combined with aerobic bio-stabilisation and landfill

This treatment system combines advanced mechanical pre-treatment systems, designed to remove recyclables from the residual stream as above, with aerobic bio-stabilisation of the residue from the pre-treatment system. The bio-stabilised residue is then sent to landfill.

The bio-stabilisation process allows the aerobic degradation of organic material in the residual stream to take place under controlled conditions, releasing biogenic carbon dioxide. This reduces the biogenic carbon content of the stream sent to landfill, thereby reducing methane emissions from the waste once in landfill.

2.2 Scenarios

The modelling behind this report considers, alongside the different treatment options, variations in:

- the composition of residual waste;
- the marginal source of electricity and heat production; and
- the timescale of the analysis.

The development of these scenarios is explained in this Section. Four scenarios are explored (shown in Table 2-1). Two primary scenarios are explained in Section 2.2.1, ‘Today’ and ‘Expected-2035’, which account for current and expected developments in residual waste composition and the carbon intensity of electricity and heat provision. Two further sensitivities to the ‘Expected-2035’ scenario are explored in Sections 2.2.2 and 2.2.3 respectively: the timeframe used in the analysis (in the scenario entitled ‘GWP20’), and the marginal source of heat production (in the ‘Low heat decarbonisation’ scenario).

Table 2-1: The scenarios explored in the analysis

Scenario	Composition	GWP of methane	Marginal carbon intensity (kgCO2e/kWh)	
			Electricity	Heat
Today	Current composition	100-year GWP	0.270	0.23
Expected-2035	Circular Economy	100-year GWP	0.066	0.15
GWP20	Circular Economy	20-year GWP	0.066	0.15
Low heat decarbonisation	Circular Economy	100-year GWP	0.066	0.23

2.2.1 Composition

The effect of different compositions on the overall impact of waste treatment was modelled. These composition scenarios are explained in Sections 2.2.1.1 and 2.2.1.2, and are shown in Table 2-2.

Table 2-2 Municipal residual waste compositions in 'Today' and 'Expected-2035' (65% overall municipal recycling rate) scenarios.

Material stream	Scenario	
	Today	Expected-2035
Paper	14.7%	11.7%
Card	6.3%	4.9%
Plastic Film	8.3%	9.4%
Dense Plastic	7.9%	7.7%
Textiles	5.5%	8.4%
Wood	2.3%	3.5%
Nappies & sanitary	4.0%	6.5%
Other misc. combustible	5.3%	8.4%
Other misc. non-combustible	3.8%	5.4%
Glass	2.8%	3.3%
Ferrous	2.4%	3.7%
Aluminium	1.2%	0.7%
WEEE	1.1%	1.3%
Potentially hazardous	0.5%	0.8%
Garden waste	2.7%	3.1%
Kitchen waste	26.4%	15.1%
Other putrescibles	2.5%	3.7%
Fines	2.3%	2.3%

2.2.1.1 Today scenario

This scenario involves today's residual waste composition. The current composition of household and commercial residual and recycling waste streams are taken from WRAP's 2017 National Household Waste Composition and National Commercial Waste Composition reports. [6,7] Recycling capture rates[8] are inferred from these data.

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[6] WRAP (2020) *National household waste composition 2017*, accessed 19 October 2020, https://wrap.org.uk/sites/files/wrap/National%20household%20waste%20composition%202017.pdf

[7] WRAP (2020) *National municipal commercial waste composition, England 2017*, January 2020, https://wrap.org.uk/sites/files/wrap/National%20municipal%20commercial%20waste%20composition_%20England%202017.pdf

[8] The proportion of materials captured for recycling

2.2.1.2 Expected-2035 scenario

This scenario models the changes in residual waste composition that would be observed if the UK implemented the policies put forward in the EU's Circular Economy Package – specifically the aim of reaching a municipal recycling rate of 65% by 2035.[9]

Improvements in recycling rate will not be uniform across materials because some streams are harder to separate, reprocess or sell than others. It is therefore necessary to make assumptions about the individual improvements in recycling rate across streams that would meet a 65% overall recycling rate. These assumptions, shown in the Technical Appendix (Table 4-3), were made based on technological considerations, current recycling rates and projections about the recycling markets. This was done by Eunomia's recycling technology and markets experts.

2.2.2 Global Warming Potentials of methane (GWP20 scenario)

Carbon dioxide and methane are the two most impactful key greenhouse gases (GHG) considered in this report. Methane warms the atmosphere more powerfully than carbon dioxide; as the time period considered decreases, this discrepancy increases. Some therefore make the argument that, as climate change is such a pressing issue in the short term, carbon dioxide emissions are 'preferable' to methane emissions. Clearly, the timeframe considered in analysis can hugely impact its conclusions. These considerations are discussed further and accounted for here.

The Global Warming Potential (GWP) of a gas is the heat absorbed by that gas divided by the heat that the same mass of carbon dioxide would have absorbed. The GWP of methane over a 20-year period is 86, but over 100 years is 28 or 34 (the higher value includes the effects of feedback loops).[10] As noted in the introduction, estimates of methane's 20 and 100-year GWP have been revised upwards in recent years by the Intergovernmental Panel on Climate Change (IPCC) from 72 (20-year) and 25 (100-year, without feedback loops), due to greater understanding of the gas's physical effects on the atmosphere.

Using 100-year timescales (and GWP values) is problematic because it does not capture the short-term heating effect of methane, which is important in the context of the urgency of climate change. However, a 20-year analysis ignores the longer lifetime of carbon dioxide in the atmosphere and its longer-term warming effect, as well as the

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[9] UK Government (2020) *Circular Economy Package policy statement*, July 2020, https://www.gov.uk/government/publications/circular-economy-package-policy-statement/circular-economy-package-policy-statement

[10] Myhre, G., Shindell, D., Bréon, F.-M., et al. (2018) *Anthropogenic and Natural Radiative Forcing (IPCC)*, 2018, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

ability of landfill to delay and effectively sequester emissions. In considering these impacts, recent research by Balcombe *et al.* indicated that:[11]

> *It is not advisable or conservative to use only a short time horizon, e.g. 20 years, which disregards the long-term impacts of CO_2 emissions and is thus detrimental to achieving eventual climate stabilisation.*

Both of these timescales reveal important results, particularly in the analysis of landfill, where the 100+ year emissions profile means the *timing* of emissions is relevant.

The Expected-2035 scenario models the effects of waste treatment over 100 years. In order to adhere to the 'precautionary principal' and given the increasing importance of action to tackle climate change, a GWP100 value for methane of 34 has been used.

A variant of the Expected-2035 scenario, the 'GWP20 scenario', was modelled to account for the above considerations using methane's 20-year GWP value. In this scenario, only methane emissions occurring in the first 20 years are considered, with the rest considered to be sequestered. As in all landfill analyses in this report (and in adherence with IPCC recommendations), biogenic carbon dioxide emissions are ignored (see Section 2.3.2.2 for a full description of assumptions surrounding the treatment of biogenic carbon emissions). [12]

2.2.3 Carbon intensity of energy systems

The energy emissions credit (i.e. a negative emissions contribution) that can be claimed by incineration and landfill gas is based on the source of energy that is being 'displaced': the source whose output is reduced as a result of an incinerator's production.

Historically, analyses have assumed that displaced electricity generation, also known as the marginal source of generation, is a Combined Cycle Gas Turbine (CCGT). This assumption is not unreasonable as this technology was for the last 15 years the most likely plant to be built in response to changes in electricity demand, and was also the technology most likely to be operating 'at the margin' (i.e. responding to small changes in demand).[13] In the case of heat provision, the counterfactual source tends to be natural gas, which meets a large majority of UK buildings' heat demand.[14]

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[11] Balcombe P, Spiers J, Brandon N and Hawkes A (2018) Methane emissions: choosing the right climate metric and time horizon, Environ. Sci.: Processes Impacts, 20, pp1323

[12] IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories - Chapter 3 Waste*, 2019, https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/5_Volume5/19R_V5_3_Ch03_SWDS.pdf

[13] Department for Business, Energy and Industrial Strategy (2019) *Valuation of energy use and greenhouse gas: background documentation*, April 2019, https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[14] Department for Business, Energy & Industrial Strategy (2018) *Clean Growth - Transforming Heating - Overview of Current Evidence*, December 2018, https://www.gov.uk/government/publications/heat-decarbonisation-overview-of-current-evidence-base

These assumptions will no longer be applicable in the future however, due to a rapidly decarbonising, renewables-fed grid and the need to decarbonise heat production to meet net-zero targets.

2.2.3.1 Electricity

The sources of electricity generation which supply the grid are chosen, largely through the wholesale electricity markets, to meet a given level of demand. The cheapest source of generation is selected, then the next cheapest etc., until selected generation equals demand. The short-run marginal source of electricity is the source of electricity that would be brought online to meet a small increase in demand.

The marginal source of generation is important because it is the first source to 'drop off' when there is a reduction in demand or an increase in generation from elsewhere. It is the source of electricity that would be displaced by incineration plant, and therefore its carbon intensity of electricity production is what incineration must be compared against.

The short-run marginal source of electricity is often assumed to be CCGT plant fuelled by natural gas. However, it is extremely likely that the contribution of gas generation will fall over the next decade; BEIS data indicates that the contribution of CCGT to total electricity demand will halve by 2035 from current day levels. As this occurs, other sources of generation will fill the gap, including (mostly) renewables, imported electricity and power storage. The carbon intensity of these sources is lower than that of gas.

The UK government provides data on the *long-run* marginal carbon intensity out beyond 2050. The literature elsewhere defines the long-run marginal factors as considering: [15]

> *the change in CO_2 emissions relating to a unit change in electricity demand, where structural change in the electricity system is explicitly taken into account (i.e. demand-side interventions dynamically interact with power stations commissioning and decommissioning, and with system operation).*

Individual incineration facilities are relatively small generators of electricity (in comparison to conventional power stations), and as such, the addition of one new facility would not be expected to result in a structural change to the electricity system. This suggests that the short-run marginal is a more appropriate factor to use. However, there is no data anticipating how the short-run marginal will be affected by the changes in decarbonisation set out above. As such, the long-run marginal figures provide a useful indicator of the trajectory of grid decarbonisation that is expected to occur over the coming decades.

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[15] Hawkes, A.D. (2014) Long-run marginal CO2 emissions factors in national electricity systems, *Applied Energy*, Vol.125, pp.197–205

The long-run marginal electricity emissions intensity as forecast by BEIS for the years 2020 and 2035 was used: 0.270 kgCO_2e/kWh and 0.066 kgCO_2e/kWh respectively.[16] This approach is analogous to that taken in Defra's 2014 report comparing landfill to incineration.[17]

2.2.3.2 Heat

Today, heat is almost entirely provided by burning natural gas in boilers, leading to a net carbon intensity of 0.23 kgCO_2e/kWh (this is used in both the Today and Low heat decarbonisation scenarios.

In the absence of published forecasts for the marginal source of heat, our approach for estimating the carbon intensity of the marginal source of heat in the Expected-2035 scenario is based on the following:

- GHG emissions from heating all the UK's buildings must be extremely close to zero by 2050 to meet net-zero targets. By 2035 significant progress will need to have been made towards achieving this. Furthermore, half of all councils in the UK have declared their intention to be net-zero by 2040 or earlier – this is just one signal of a step change in ambition that has become evident in recent years. Government has already signalled its intention to provide some financial support to households for the transition to low carbon heat.[18]
- However, it is anticipated that progress in the decarbonisation of heat will be slower in the coming decade and accelerate thereafter. Therefore, we propose that a reasonable – and somewhat conservative – assumption for the marginal emissions of heat provision is 67% of the current value.
- This leads to the carbon intensity of the marginal source of heat of 0.15 kgCO_2e/kWh in the Expected-2035 scenario.

2.3 Climate Change Impacts

This section describes the modelling approach, key assumptions and results of the analysis of the climate change impacts of the residual waste treatment options.

2.3.1 Approach to the Modelling

The modelling performed in this work compares the emissions of the waste treatment systems described in Section 2.1. The Functional Unit (FU) of this assessment was one

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[16] BEIS (2018) *Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal*, accessed 14 August 2018, https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[17] Department for Environment Food and Rural Affairs (2014) *Energy recovery for residual waste: A carbon based modelling approach*, accessed 31 March 2020, http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19019

[18] See https://www.gov.uk/government/consultations/future-support-for-low-carbon-heat

tonne of residual waste, meaning the analysis compares the emissions from each system's treatment of one tonne of residual waste.

Methane, carbon dioxide and nitrogen dioxide are the GHGs considered in this report. As they have different GWPs, their impacts are converted into carbon dioxide equivalents (CO_2e) using the GWP values. [19]

The GHG emissions analysis uses a 'consumption' approach, meaning all emissions are included regardless of their location. For example, the emissions benefits of recycling are included even though they are unlikely to occur in the UK.

2.3.2 Key assumptions

The assumptions that apply to all treatment systems and scenarios are explained below.

2.3.2.1 Residual waste composition

The composition of municipal residual waste in the Today scenario (the current composition) and in the Expected-2035 scenario are shown in Table 2-2.

2.3.2.2 Treatment of biogenic carbon dioxide emissions

Biogenic carbon emissions are those that originate from organic material like food and garden waste, as opposed to the emissions coming from fossil carbon in oil-derived materials. It is often considered that biogenic carbon emissions need not be incorporated into total emissions, because they are 'short cycle', i.e. "only relatively recently absorbed by growing matter". [20] Note that methane emissions from organic material *are* included because they are considered to be anthropogenic in nature, whereas biogenic CO_2 emissions are in effect viewed as similar to or part of the natural carbon cycle.

This perspective follows the approach taken in developing the national inventories for climate change emissions, which countries submit on an annual basis to the United Nations Framework Convention on Climate Change (UNFCCC). Biogenic CO_2 emissions occurring from, for example, the combustion of wood and other organic items, as well as that arising the organic decay in ecosystems, are excluded from these annual inventories. The carbon incorporated within these items is assumed to have been sequestered from the atmosphere into the plant within the previous years' growth. Inclusion of both impacts is therefore considered to result in a double-counting of impacts. A similar approach has been taken in life-cycle assessments, which consider the global warming potential of systems over a 100-year period.

However, application of the above approach is problematic when accounting for landfill impacts, as a significant proportion of the biogenic carbon is not released as biogenic

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[19] Converting to carbon dioxide equivalent gives the mass of carbon dioxide that would need to be emitted to have the same effect on the atmosphere as a particular mass of that gas.

[20] DEFRA (2014) *Energy from Waste: A Guide to the Debate, Revised Edition*, February 2014

CO_2 (or as methane) but instead remains sequestered in the landfill; in this way, landfills act as an imperfect ‘carbon capture and storage’ facility. In contrast, all of the biogenic CO_2 emissions are released from incineration at the point of combustion. As such, the two systems are not being compared on a like-for-like basis where this approach is applied to considering emissions from residual waste treatment systems.

Therefore, this omission of short cycle biogenic carbon emissions is acceptable *as long as a carbon credit is applied for the biogenic carbon which is stored in a landfill*. If no adjustment is made, the exclusion of the biogenic CO_2 emissions will overestimate landfill impacts relative to other forms of treatment in which all the biogenic carbon is released as CO_2 into the atmosphere.

The use of such an approach is recommended by authors from the Technical University of Denmark (who developed the EASEWASTE model), and in Defra’s modelling guidance.[21, 22] Despite often being omitted from similar analyses in the literature, a carbon sequestration credit is included in this analysis. A similar approach was used in the peer-reviewed EU Reference Model on Municipal Waste as well as Eunomia’s work for the Greater London Authority in developing an Environmental Performance Standard for municipal waste treatment.[23,24]

2.3.2.3 Emissions timescales

The GWPs of methane at 20- and 100-year timescales used in this study are 86 and 34.[25]

2.3.2.4 Treatment specific assumptions

Full details of the assumptions used are provided in Appendix A.1.2. Key points to note on treatment specific assumptions are:

- Landfill modelling is largely in line with the national methane emissions model used in the UK’s submission to the UNFCCC, apart from the application of the ‘sequestration’ credit for the storage of biogenic carbon.

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[21] Christensen, T., Gentil, E., Boldrin, A., Larsen, A., Weidema, B. and Hauschild, M. (2009) C balance, Carbon Dioxide Emissions and Global Warming Potentials in LCA-modelling of Waste Management Systems, Waste Management & Research, 27, pp707-717

[22] Department for Environment Food and Rural Affairs (2014) *Energy recovery for residual waste: A carbon based modelling approach*, accessed 31 March 2020, http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19019

[23] Eunomia Research & Consulting Ltd., Copenhagen Resource Institute, and Satsuma (2019) *The European reference model on municipal waste*, 2019, https://www.eionet.europa.eu/etcs/etc-wmge/products/final-version-of-waste-model-handbook_april-2019.pdf

[24] Eunomia Research & Consulting (2017) *Greenhouse Gas Emissions Performance Standard for London’s Local Authority Collected Waste – 2015/16 Update*, Report for Greater London Authority, January 2017, https://www.london.gov.uk/sites/default/files/gla_eps_report_2015-16_final.pdf

[25] Myhre, G., Shindell, D., Bréon, F.-M., et al. (2018) *Anthropogenic and Natural Radiative Forcing (IPCC)*, 2018, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

- Data relating to the energy generation performance on the UK's incineration fleet is not available in or near real-time, limiting the possibility of performing analyses based on the UK fleet's average efficiencies (year-round electricity and heat generation data are collated by the Environment Agency but do not contain energy generation efficiencies). [26]
  Therefore, in keeping with the forward-looking nature of this analysis, the energy generation efficiency performance for electricity-only incineration plant is based on a relatively high performing facility, which may not be typical of older facilities operating in the UK. Similarly, assumptions for the performance of incineration facilities operating in CHP-mode are based on that seen for the Sheffield facility, which is the best performing facility of this type operating in the UK at the time of writing. It is noted, however, that better performance is seen in facilities operating elsewhere in Europe.
- Assumptions for the performance of pre-treatment facilities are based on data provided by plant operators, based on facilities operating in Europe and elsewhere.

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[26] Environment Agency (2020) *2019 waste incineration monitoring reports*, October 2020, https://environment.data.gov.uk/portalstg/home/item.html?id=5f25d4693fe8499282070ea40e08d0a0

2.3.3 Results: Climate Change Comparison of Waste Treatment Facilities

The carbon impacts of the different waste treatment systems are shown in Figure 2-1 and given in Table 2-3. A more detailed breakdown of these results is provided in Technical Appendix Section A.1.3.

Figure 2-1 The GHG impacts of the treatment options under each scenario

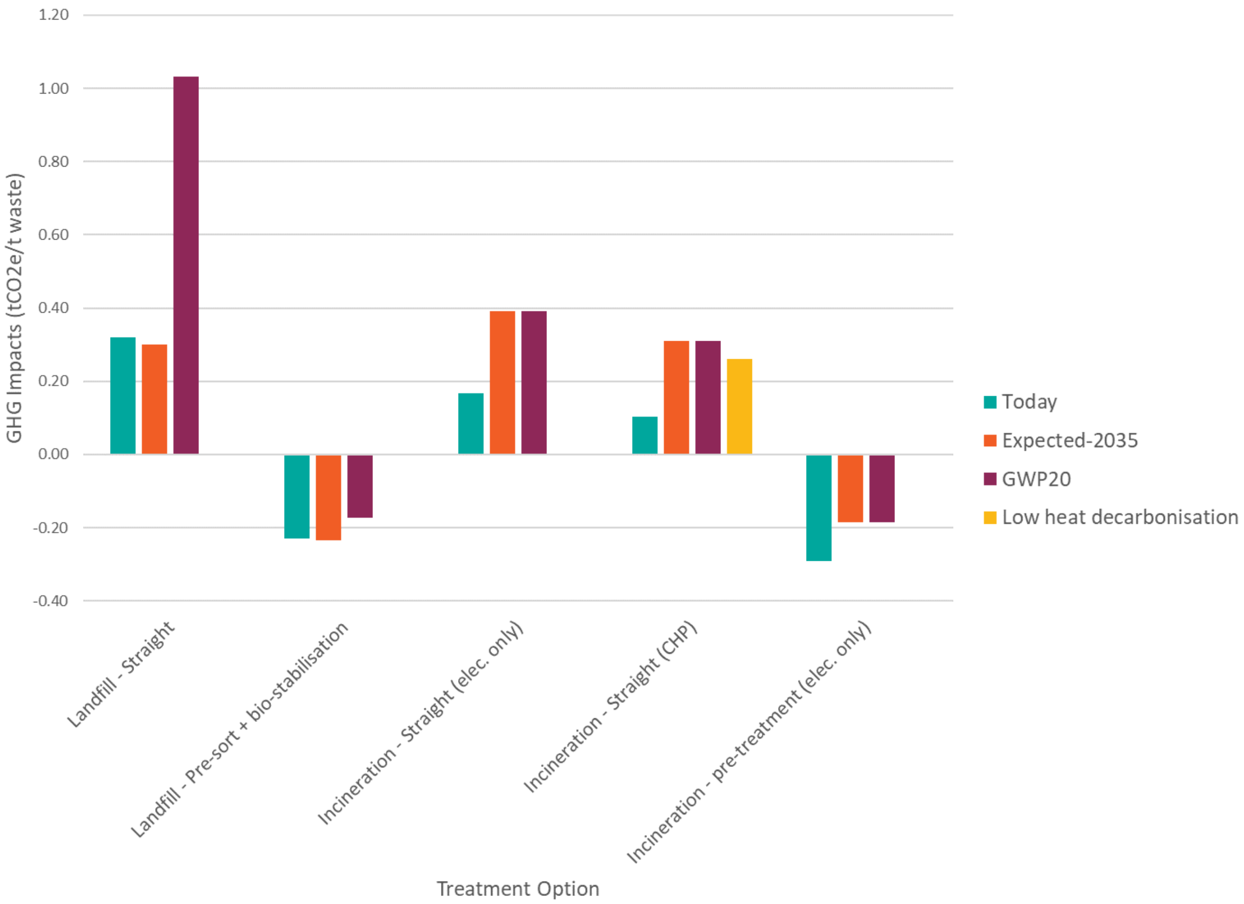

Table 2-3 Tonnes of carbon dioxide equivalent emitted (net) per tonne of waste treated

Scenario	Landfill		Incineration		
	Straight	Bio-stabilisation[1]	Straight		Pre-treatment
			Electricity only	CHP	Electricity only
Today	0.32	-0.23	0.17	0.10	-0.29
Expected-2035[2]	0.30	-0.23	0.39	0.31	-0.18

Scenario	Landfill		Incineration		
	Straight	Bio-stabilisation[1]	Straight		Pre-treatment
			Electricity only	CHP	Electricity only
Low heat decarbonisation	0.30	-0.23	0.39	0.26	-0.18
GWP20[2]	1.03	-0.17	0.39	0.31	-0.18

1. **Includes a pre-treatment step to remove recyclables**
2. **Assumes the 65% recycling target is met and there is progress towards decarbonising energy systems**

Today, incineration performs better than landfill, largely because of its electricity credit, i.e. the emissions reduction brought about by avoided electricity production elsewhere. Incineration plants operating as CHP perform better than plants generating only electricity. However, in both cases it should be noted that the energy generation performance assumed here is consistent with the best available technology operating in the UK. Many older facilities generating only electricity will perform worse than those modelled here, and the analysis considers one of the best-performing CHP facilities in the UK at the time of writing.

Pre-treatment of waste prior to either landfill or incineration would result in a net emissions benefit today due to the additional credit arising from recycled materials, provided that, in the case of landfill, the remaining organic waste in the residual stream was also bio-stabilised prior to sending it to landfill. Under this scenario, the pre-treatment option with incineration performs somewhat better than that of the bio-stabilisation with landfill option. This is because pre-treatment also effectively removes a significant proportion of the remaining fossil carbon contained within the residual waste stream sent to the incineration facility.

In the **Expected-2035** scenario, which represents the expected residual waste composition and energy context in 2035, electricity-only incineration performs worse than landfill, while incineration operating in CHP mode and landfill are essentially equivalent in climate terms. Note that these results depend to a certain extent on the carbon intensity of the marginal sources of energy: if electricity and heat provision decarbonise less quickly than needed and anticipated, incineration may continue to perform better than landfill at this point. This is, again, subject to the previously mentioned caveat that many existing facilities generate energy at lower efficiencies than those considered here.

Nonetheless, if no progress was made in decarbonising heat provision (**Low heat decarbonisation** scenario), incineration facilities operating in CHP mode would continue to be a net contributor to climate change without any form of pre-treatment. More generally, the results confirm that improvements in energy generation efficiency at incineration plant will be of diminishing value as the energy systems decarbonise. This trend is anticipated to continue beyond 2035, and the relative performance of incineration in comparison to landfill is expected to worsen up to 2050.

The capture rates of waste containing high amounts of biogenic carbon, like garden and food wastes, are much higher in the future Expected-2035 scenario than today (see Table 4-3).[27] Similarly, the capture rates of waste containing fossil carbon (e.g. plastics) also increase over today in the Expected-2035 scenario. These two changes ‘cancel each other out’ to a certain extent, meaning that while there is some change, the biogenic and fossil carbon per tonne of residual waste are not markedly different from today (Table 2-4). The relatively small drop in the amount of biogenic carbon in the residual waste stream means that (remembering that analysis is performed on a per-tonne of waste basis) landfill would perform only slightly better in the Expected-2035 scenario than today.

Table 2-4 The carbon content of residual waste in the 'Today' and 'Expected-2035' scenarios

Scenario	**‘Today’ scenario**	**‘Expected-2035’ scenario**
Composition	**Today's composition**	**Circular Economy Package Implemented**
Biogenic carbon (t/t waste)	0.134	0.119
Fossil carbon (t/t waste)	0.122	0.135

In the Expected-2035 scenario, landfill and incineration (whether electricity-only or in CHP mode) will both contribute heavily to climate change, with landfill outperforming electricity-only incineration because of the diminishing energy generation credit associated with the latter.

Without pre-treatment, both landfill and incineration would result in continued contributions to climate change emissions, which is likely to be inconsistent with meeting a net-zero climate change target at the local and UK levels. Improved performance in either case requires the use of pre-treatment, which further reduces the climate change impacts (note that these reductions may occur outside the local authority’s geographical boundaries).

The timeframe considered in the analysis has an impact on the conclusions drawn. When only the emissions in the first 20 years are considered and a GWP value of 86 is used for methane (**GWP20 scenario**), landfill appears significantly more damaging than incineration. This suggests that, when taking a short-term perspective with the view that climate action is extremely urgent, incineration might be preferable to landfill.

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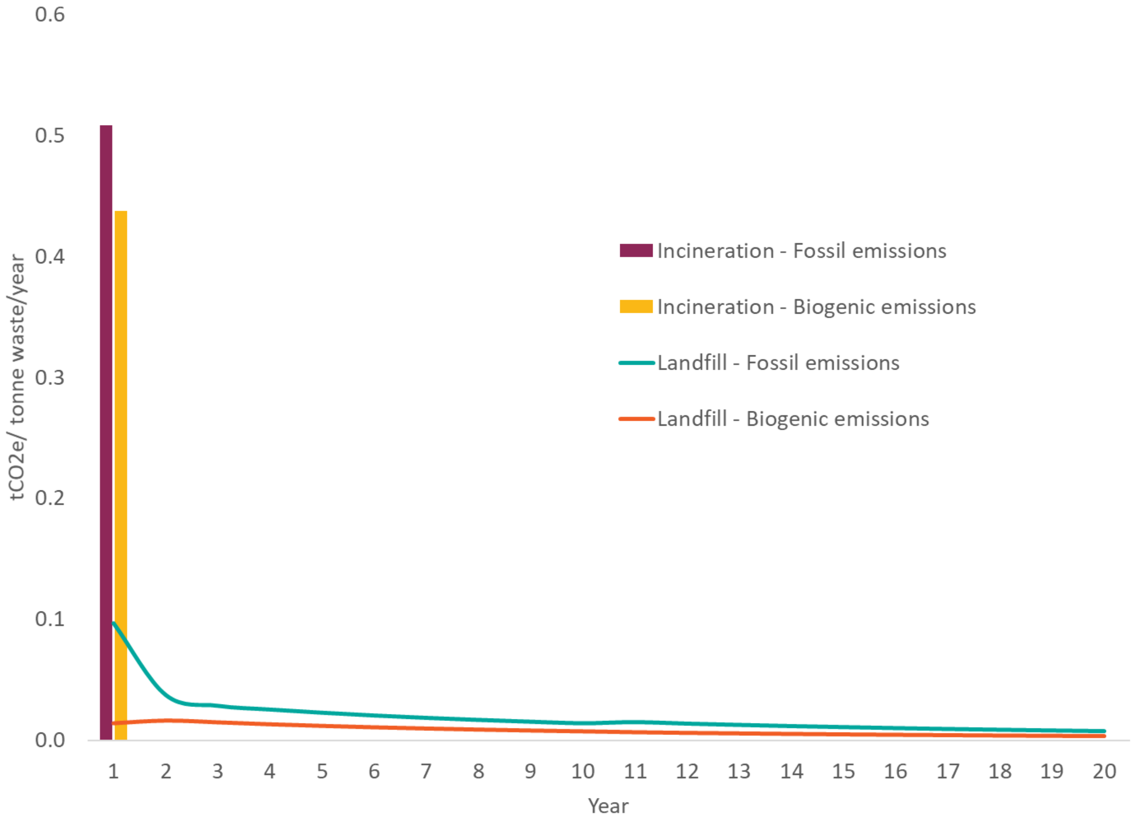
[27] Capture rates represent the proportion of waste that is removed from the residual stream and sent for recycling, and thus excluded from this analysis.

However, taking these results at face value risks masking carbon dioxide's long-term warming effect; the Paris Agreement targets 1.5°C of warming *by 2100*, so limiting warming in the second half of the century is also critical to meeting this. As such, the GWP20 scenario results should not be considered the only framework for assessing climate change impacts.

In considering the results of the GWP20 scenario, it is also necessary to consider the timeframe over which emissions from the two types of treatment process are released. In this respect, it is important to note that results generated by the lifecycle analysis methodology (which is followed in all scenarios modelled here) effectively do not properly consider the timeframe over which emissions from landfill are released. Figure 2-2 shows the year-on-year emissions profile from both treatment processes over the first 20 years. The figure shows both biogenic and fossil emissions, as this is relevant where the profiling is concerned given landfill's propensity to store biogenic carbon.

This confirms that, where incineration is concerned, all emissions occur immediately after treatment in the first year. Year 1 emissions from landfill, on the other hand, are a relatively small proportion of the total amount released over that 20-year period.

Figure 2-2 Profile of GHG Emissions in the first 20 years in the Expected-2035 scenario



It is noted, however, that even under the GWP20 scenario, the best performance is seen where pre-treatment is used in conjunction with either landfill or incineration, provided the residual waste sent to landfill is sent for bio-stabilisation first. As with the other scenarios, the performance of either pre-treatment option leads to similar results under the GWP20 scenario.

2.3.3.1 Composition and the Expected-2035 scenario

The residual waste compositions shown in Table 2-2 were calculated assuming that the EU's Circular Economy Package was adopted into UK law, which appears likely.[28] This section discusses how the results of Section 2.3.3 could be impacted if the Circular Economy Package target is not implemented or met.

Residual waste is managed largely by Local Authorities. It can be assumed that Local Authorities that have not declared a Climate Emergency or set a net-zero target date will not, without any forthcoming mandate from central Government to achieve a 65% recycling rate, improve recycling drastically. This would be a continuation of the slow progress seen in the last few years.[29]

Those Local Authorities which have set ambitious climate change targets would be under more pressure to quickly align their waste treatment to these goals. Currently, 300 Local Authorities (74% of the total number) have declared a Climate Emergency, with 200 of those setting net-zero target dates of 2040 or earlier.[30] This is driving further, earlier cuts to territorial emissions from waste management, which may be in line with, or exceed, a 65% recycling rate.

Therefore, current trends suggest that even in the absence of a nationwide 65% recycling rate, a substantial proportion of the country will be aiming to improve on today's performance. This suggests that a concentration of fossil carbon will be seen in the residual stream (as shown in Table 2-4), tending to lower incineration's performance against landfill. This reinforces the conclusion that pre-treatment of residual waste will be essential regardless of the path taken by Government.

2.3.4 Comparisons with the literature

This section compares the key conclusions of notable reports by Defra, Zero Waste Scotland and Policy Connect to the analysis presented here. A more complete comparison of methods and conclusions is given in the Technical Appendix A.1.4.

2.3.4.1 Defra Carbon-based modelling study

- Defra indicated that by "using conventional analysis (disregarding biogenic carbon) the model indicates a good carbon case for continuing to include EfW as a key part of the hierarchy." However, while the Defra study used a similar

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[28] Cole, R. UK Circular Economy Package to set 65 per cent recycling target for 2035, *Resource Magazine*

[29] Defra (2020) *UK Statistics on Waste*, March 2020, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/918270/UK_Statistics_on_Waste_statistical_notice_March_2020_accessible_FINAL_updated_size_12.pdf

[30] https://www.climateemergency.uk/blog/list-of-councils/

landfill model to that used in the current analysis, it is noted that the sequestration of biogenic carbon is considered only as a sensitivity.

- The study differs in its approach to the current work in its attempt to compare simple incineration (in electricity-only mode) and landfill treatments, and to identify the electricity generation efficiency at which incineration and landfill are equivalent in GHG emissions terms. In doing so, they limit their analysis to simple incineration and landfill treatments; no consideration is made of the effects of likely future waste compositions or the effects of pre-treatment. They thus ignore whether *either* of these approaches is suitable given that rapid decarbonisation is necessary.

2.3.4.2 Zero Waste Scotland: The climate change impacts of burning municipal waste in Scotland

- Zero Waste Scotland's study reaches the same conclusions as those presented here, namely that electricity-only incinerators are a more carbon-intensive form of electricity generation than the current marginal grid average, and thus "EfW technologies can no longer be considered low carbon solutions".[31]
- The authors find that pre-treating residual waste sent to landfill (i.e. reducing the mass of biogenic carbon from 15% to 5%, vs. 13% to 9% in this study) would also dramatically reduce its climate impacts, and that this may be the most climate-friendly means of residual waste treatment (although they do not consider the impact of incineration in conjunction with pre-sorting).

2.3.4.3 Policy Connect: No Time to Waste

- Policy Connect's report is significantly more optimistic in its assessment of incineration's ability to have positive climate impacts.[32] It makes a favourable assumption about how much CO_2e is saved by diverting waste from landfill to incineration, without any discussion of the impact decarbonising the grid would have on this assumption.
- The modelling behind the report also considers it possible that 70% of UK incinerators will operate in CHP mode by 2030. This appears optimistic given that just 20% do so today, with – as the report notes – significant barriers for plants to find heat off-takers.
- The report recommends that Carbon Capture and Storage (CCS) is used in conjunction with incineration to reduce its emissions, without acknowledging

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[31] Zero Waste Scotland (2020) *The climate change impacts of burning municipal waste in Scotland*, October 2020, https://www.zerowastescotland.org.uk/sites/default/files/ZWS%20%282020%29%20CC%20impacts%20of%20incineration%20TECHNICAL%20REPORT.pdf

[32] Policy Connect (2020) *No Time to Waste: Resources, recovery & the road to net-zero*, July 2020, https://www.policyconnect.org.uk/research/no-time-waste-resources-recovery-road-net-zero

that this technology is in its infancy and is much more expensive than waste pre-treatment.

2.3.5 Transferability of Findings to Less Developed Countries

No scenarios applicable to less developed countries have been modelled as part of this report. It is, however, possible to consider how the conclusions drawn here may be affected by expected differences in key assumptions.

One would expect residual waste to contain more food waste in countries that have less infrastructure to treat it separately, which would have an effect on the climate impacts of both landfill and incineration. The direct methane emissions per tonne of treated waste in landfill would increase sharply. Meanwhile, more auxiliary fuel may be needed in an incinerator (food waste lowers the overall Net Calorific Value of residual waste), increasing process emissions.

In countries that are currently more reliant on fossil fuels than the UK, and where the speed of the UK grid's decarbonisation isn't matched, incineration may appear more favourable. This is because the credit gained by offsetting other sources of carbon-intense generation would be higher.

It is likely that the climate case for incineration over landfill is therefore stronger in developing countries than in the UK at the current time. However, the situation in these other countries is also likely to change in the future as progress is made in decarbonising energy supplies.

2.4 Air Quality Impacts

The results of incineration air quality impact modelling are presented here.

2.4.1 The literature on air quality impacts of incineration

The air quality impacts of incinerators have been a key focal point of campaign groups representing those who are opposed to the development of incinerators. Analysis published on behalf of UK government bodies, however, has generally indicated there are no significant health concerns associated with pollution released from well-managed incineration facilities.

In the UK context, studies on this topic include that undertaken by Enviros *et al.* on behalf of Defra in 2003. That study focussed primarily on an examination of epidemiological studies looking specifically at incinerators.[33] It found relatively few studies of this nature, with those that did exist relating to older facilities with higher emissions. Even today there is relatively little in the way of research specifically focused

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[33] Enviros Consulting / University of Birmingham / Risk Policy Analysts / Thurgood M (2003) Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes, Report for Defra

on incinerators and health impacts: a study in the academic literature published this year and focussing on similar literature concluded there was "*a dearth of health studies related to the impacts of exposure to WtE emissions*".[34]

Later, the Health Protection Agency, which subsequently became part of Public Health England, undertook its own research of the literature and concluded:[35]

> *While it is not possible to rule out adverse health effects from modern, well regulated municipal waste incinerators with complete certainty, any potential damage to the health of those living close-by is likely to be very small, if detectable.*

That study focused primarily on the potential carcinogenic effects of pollution from incinerators including emissions of dioxins, with some consideration of the impact of particulate pollution. The study did not consider the impact of NO_x emissions. The potential relative impact of the various pollutants is discussed in Section 2.4.3, where government data on the health impacts is used to evaluate the relative impacts. This type of assessment suggest that NO_x emissions make the most significant contribution to the total health impacts from incinerators.

The Health Protection Agency study was the basis of the Public Health England statement on the health impacts of incinerators, which was published in 2009 but withdrawn in 2019.[36] Around this time, PHE released another study. The research in this case was undertaken by Imperial College, and focussed only on foetal abnormalities. This informed a subsequent position statement produced by PHE, which indicated that emissions from incineration were not felt to result in significant harm to health.[37]

A recent study undertaken by Air Quality Consultants for the GLA was one of the first to attempt to quantify the impact on health of both particulate and NO_x pollution from incineration. The authors concluded that 15 deaths of London residents per year were associated with emissions of nitrogen oxides and particulate matter from the city's five EfW facilities.[38] That analysis also used government datasets to establish the anticipated health impacts of the pollution from these facilities.

It is important to note that existing evaluations of the impact of pollution on health are likely to be relatively conservative. The current data used by the UK government to assess the health effects of pollution does not include any consideration of the emerging evidence with regards to the health impacts, such as the links between NO_x pollution

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[34] Cole-Hunter T et al (2020) The health impacts of Waste-to-Energy emissions: A systematic review of the literature, *Environ. Res. Lett*, article in press

[35] Health Protection Agency (2010) The Impact on Health from Municipal Waste Incinerators

[36] Health Protection Agency (2010) The Impact on Health from Municipal Waste Incinerators

[37] https://www.gov.uk/government/publications/municipal-waste-incinerators-emissions-impact-on-health/phe-statement-on-modern-municipal-waste-incinerators-mwi-study

[38] Air Quality Consultants (2020) Health Effects due to Emissions from Energy from Waste Plant in London, Report for the GLA

and dementia and mental health issues.[39] Elsewhere, other papers confirm there is a lack of evidence regarding the threat to health posed by emissions of superfine particles emitted by facilities such as incinerators.[40]

2.4.2 Approach to the modelling

The UK government has developed a dataset which considers the impacts upon human health associated with the emission of key air pollutants. The data are based on the estimated costs to society of these emissions occurring, including the financial costs associated with ill health such as hospital admissions related to respiratory illness. The dataset has been developed for use when assessing relatively small impacts on air quality occurring as a result of government policy.[41]

Table 2-5 presents the current damage cost dataset, with the data presented in terms of the financial impact per tonne of pollutant emitted. Three data points are developed for each pollutant, reflecting the uncertainties surrounding the evaluation of these impacts.

Table 2-5 Damage cost data – health impacts of air pollution

Pollutant	Damage cost for air pollution health impacts, £ / tonne of pollutant		
	Low Sensitivity	Central	High Sensitivity
NH_3	£1,521	£7,923	£24,467
VOCs	£55	£102	£205
PM2.5	£15,799	£74,029	£216,443
SO_x	£2,893	£13,026	£37,611
NO_x	£663	£7,060	£26,837

Source: Defra Air Quality Appraisal Damage Costs Toolkit 2020

The upper and lower bounds of the range reflect different approaches to considering the following key impacts:[42]

- The assumed health impact for a given amount of particulate pollution;
- The amount of time before the chronic health impact of particulate pollution is felt;

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[39] Examples of the literature include: Cerza F, Renzi M, Gariazzo C, Davioli M, Michelozzi P, Forastiere F and Cesaroni G (2019) Long-term exposure to air pollution and hospitalization for dementia in the Rome longitudinal study, *Environmental Health*, 18, pp72; King J (2019) Air pollution, mental health, and implications for urban design: a review, *Journal of Urban Design and Mental Health*, 4, pp6

[40] The literature is summarised in: Drew (2019) Particulates Matter: Are Emissions from Incinerators Safe to Breathe?

[41] See Appraisal Toolkit Spreadsheet 2020, available at https://www.gov.uk/government/publications/assess-the-impact-of-air-quality

[42] Ricardo Energy and Environment (2019) Air Quality Damage Cost Update 2019, Report for Defra

- The valuation of a life lost as a result of the negative health impacts of air pollution.

This dataset has been applied to data on the pollution releases from waste treatment facilities which are, for the most part, derived from information submitted from some example facilities during the application for an environmental permit (these data are given in Appendix A.1.2.5).

Operators do publish annual performance reports for specific facilities which sometimes include pollutant emissions data. However, not all reports contain this information and there is no central repository of the pollution monitoring data, or the associated datasets regarding the amount of exhaust air produced by facilities (the latter being needed to ascertain the emission of pollutant in kg or tonnes, to which the damage cost data can then be applied). It is therefore difficult to ascertain either the typical performance of UK facilities in respect of emissions to air of the key pollutants, or what is best practice.

The assessment uses the "central" damage cost data point. The climate change impacts assessment considers the avoided carbon emissions associated with the energy generated at waste facilities. This is appropriate for the climate change impacts, which are global emissions. However, air pollution impacts are local, making the adjustment to account for avoided emissions less useful. The air quality impacts of different forms of electricity generation are discussed further in Section 3.0. Benefits occurring as a result of avoided emissions from energy generation and recycling are therefore excluded, as these would occur in different locations to that of the waste treatment facility. In the case of the recycling impacts, these might occur in multiple locations, and, in some cases outside of the UK.

It is also important to note that the above dataset does not include consideration of the health impacts associated with dioxins or furans. Such impacts are of considerable concern to some stakeholders due to their potential to cause hormone disruption and cancer. Eunomia has previously undertaken analysis of the health impacts from incineration relating to these pollutants, using a different dataset developed for the European Environment Agency. This indicates that the impact of emitting one tonne of dioxin is associated with a damage cost of €28m (value in 2010 prices).[43]

Although the impact per tonne of pollution is large, the results of the analysis of incinerator pollution using these data typically show that the impact of this pollution is negligible, as quantities of dioxin emitted are very small. However, such analyses use the data provided by incinerator operators showing the operation of facilities under optimal conditions. Emissions, and therefore health impacts, can be much higher under plant shut down and start up, and may also rise where operational issues occur. Unlike pollutants such as NO_x and particulates which are subject to continuous monitoring,

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[43] European Environment Agency (2011) Revealing the Costs of Air Pollution from Industrial Facilities in Europe

dioxin levels are only assessed at particular points in the year. There is thus greater uncertainty regarding on-going emissions levels and the associated health risks.

2.4.3 Results: Air quality comparison of waste treatment facilities

and

Figure 2-3 Air quality impacts of waste treatment systems (assuming typical performance of incineration facilities)

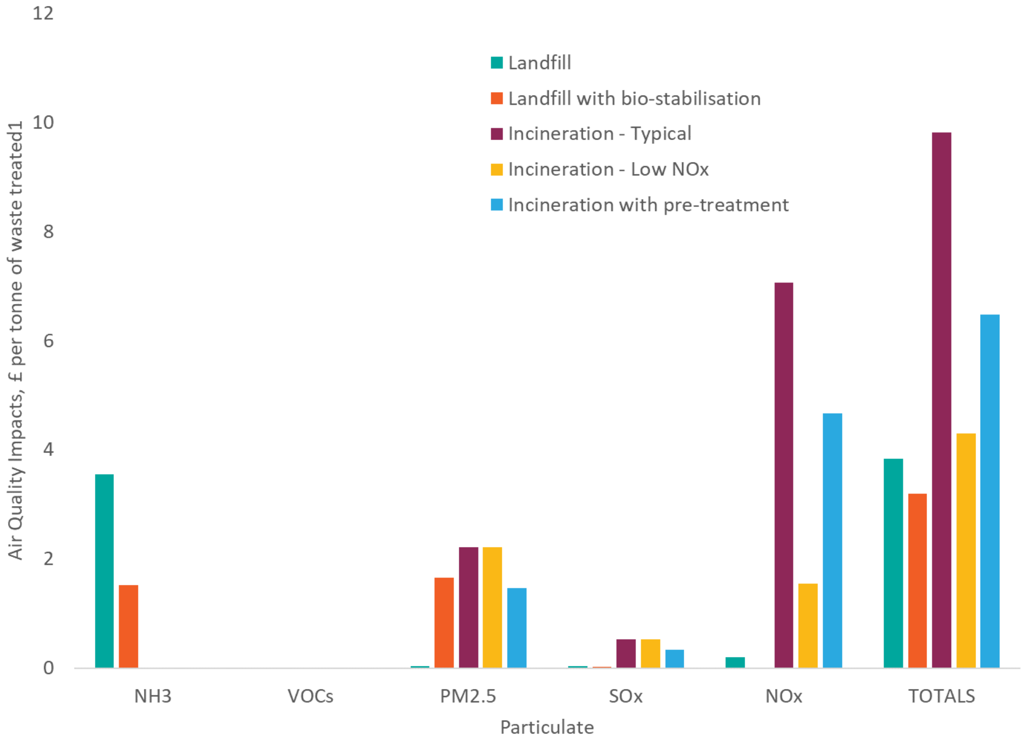


Table 2-6 present the air quality impacts of waste treatment systems (assuming typical performance of incineration facilities), with the impacts measured using the governments dataset to monetise the pollution impacts, as discussed in Section 2.4.2. The results show that ammonia emissions have the most significant impact on human health for landfill facilities. The use of pre-treatment/ bio-stabilisation reduces the impact slightly; although in this case, particulate emissions are increased. The analysis suggests that, for a landfill facility treating 400,000 tonnes of waste per annum, the cost to society of the human health impacts would be in the order of £1.5m for landfill facilities.

Emissions of NO_x account for the most significant contribution to health impacts from incineration according to our analysis. For facilities in the UK using typical abatement systems treating 400,000 tonnes per annum, this equates to annual impacts of £3.9m. However, these impacts can be reduced with improved abatement systems; where these are used the emissions and thus impacts are halved. Emissions reductions also occur where pre-treatment systems are used in combination with incineration. Where this approach is used, emissions are reduced by a third, compared to typical NO_x emissions levels. Clearly further emissions reductions are possible where improved abatement systems are combined with pre-treatment systems.

Figure 2-3 Air quality impacts of waste treatment systems (assuming typical performance of incineration facilities)

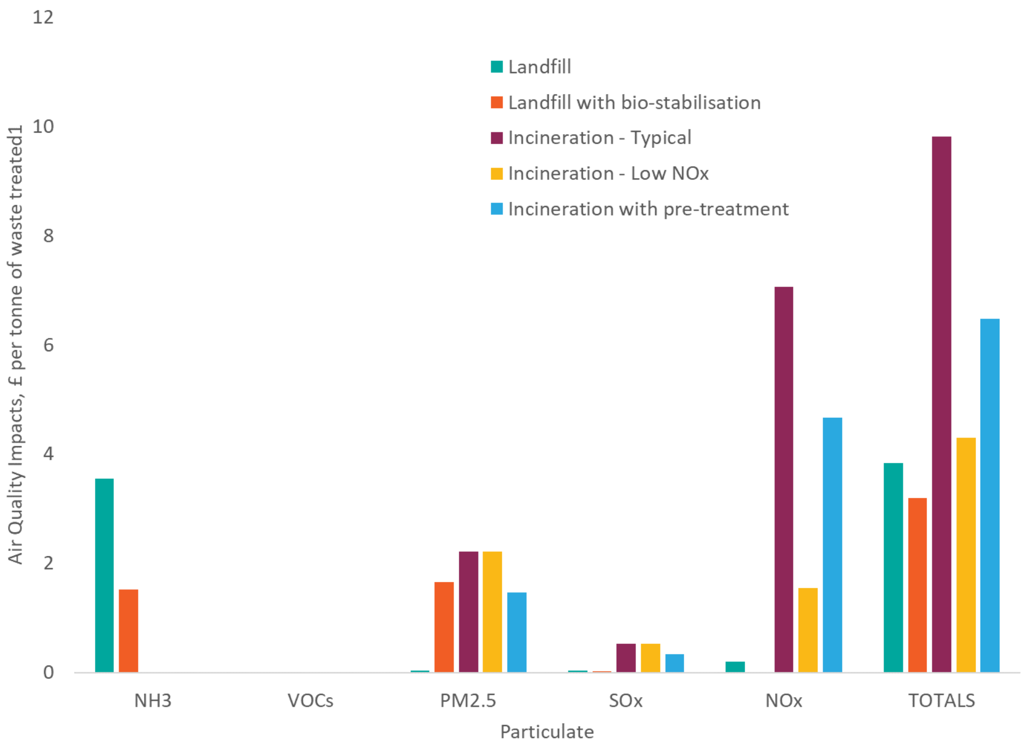


Table 2-6 Air quality impacts of waste treatment systems

	Air Quality Impacts, £ per tonne of waste treated[1]				
	Landfill	Landfill with bio-stabilisation	Incineration		Incineration with pre-treatment[2]
			Typical	Low NO_x	
NH_3	£3.55	£1.52			
VOCs		£0.01	£0.01	£0.01	£0.00
PM2.5	£0.04	£1.65	£2.22	£2.22	£1.47
SO_x	£0.04	£0.02	£0.52	£0.52	£0.34
NO_x	£0.20		£7.06	£1.55	£4.67
TOTALS	**£3.83**	**£3.19**	**£9.81**	**£4.30**	**£6.48**

	Air Quality Impacts, £ per tonne of waste treated[1]				
	Landfill	Landfill with bio-stabilisation	Incineration		Incineration with pre-treatment[2]
			Typical	Low NO_x	

Notes

1. Impacts consider the direct emissions from facilities, excluding the potential impact of avoided emissions occurring elsewhere (e.g. energy generation and recycling).
2. Assuming typical performance of incineration facilities

3.0 Comparing Electricity Generation Methods

The section compares the climate impacts of incineration (in both electricity-only and CHP modes) to other electricity generation technologies.

3.1 Approach to the Modelling

The basis of comparison is the amount of carbon dioxide equivalent produced per unit of electricity produced (kgCO_2e/kWh). This section also compares the impact of composition in ‘Today’ and ‘Expected-2035’ scenarios (see Table 2-2) on the results. Incineration as a form of energy generation is compared with both fossil fuel generation:

- CCGT;
- coal power plants, which are increasingly irrelevant in the UK but continue to be important in the international context;

and low carbon generation:

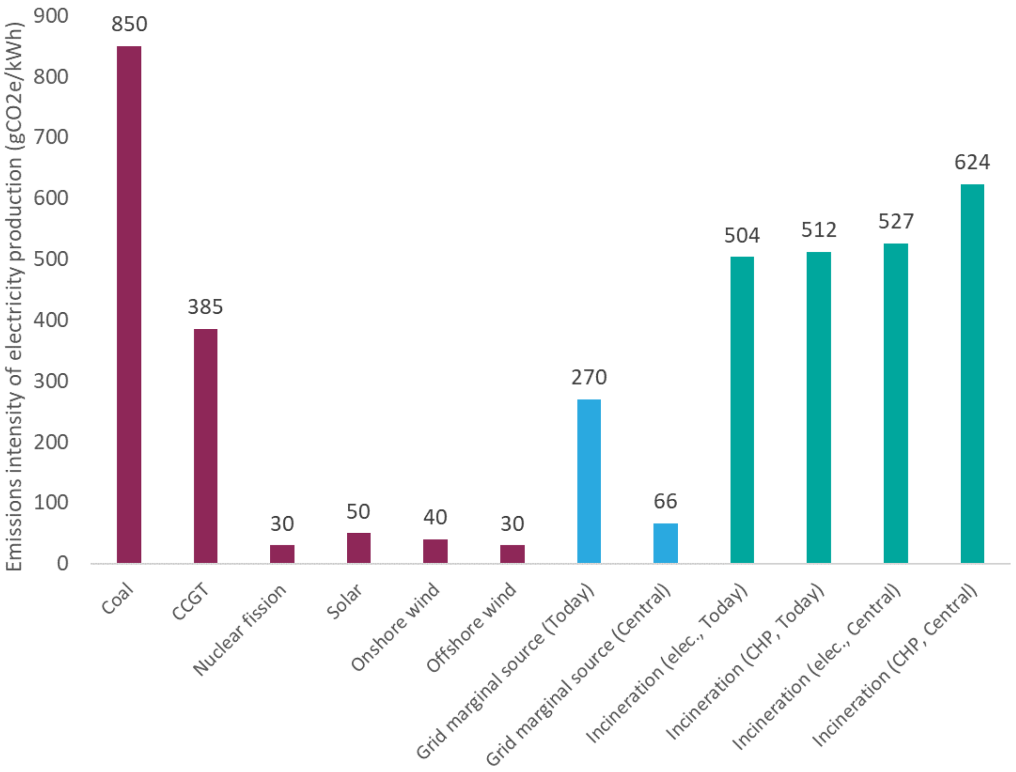
- wind;
- solar; and
- nuclear fission.

The analysis presented here uses the same assumptions as the treatment-based comparisons for incinerator/ engine efficiencies, residual waste compositions etc. presented in Section A.1.2.2. For incinerators operating in CHP mode, it is assumed that all of the GHG emissions are due to electricity generation. The emissions credit of displaced heat generation is then applied to this value to account for this.

3.2 Results: Comparing Electricity Generation Methods

Figure 3-1 shows the carbon dioxide equivalent emissions per unit of electricity generated for incineration (electricity-only and CHP modes), fossil fuel, and low carbon generation. The current (2020) and anticipated grid marginal carbon intensities are also shown.

Figure 3-1 The GHG emissions of electricity generation methods (excl. biogenic carbon emissions)



These results confirm that incineration is not a low carbon form of electricity production in either electricity-only or CHP mode. Incineration plants produce electricity that is more carbon intensive than CCGT, renewables and, most importantly, the marginal source of electricity in both scenarios. It should be noted that results here have been produced assuming the incinerator is relatively efficient in terms of energy generation: the performance of many older electricity-only plant will be considerably worse than that seen here, whilst actual CHP performance is also typically poorer in the UK than that considered in this analysis.

The anticipated changes in residual waste composition are also expected to increase the carbon intensity of electricity produced at incinerators, while the grid is expected to continue decarbonising. These two trends will exacerbate the carbon intensity deficit of residual waste incinerators.

According to this analysis, electricity produced in incinerators operating as a CHP plant is more carbon intensive than electricity-only plant. This is because, although an emissions credit has been applied accounting for the benefit of displaced heat generation, total electricity produced per tonne of waste treated (or indeed per tonne of CO_2e emitted) falls.

4.0 Conclusions and Recommendations

- When modelled using assumptions based on the most efficient plants running in the UK, **incineration (without pre-treatment) produces less GHG per tonne of waste treated today than landfill (without pre-treatment and bio-stabilisation).** However, these assumptions are not representative of the average incineration plant in the UK, meaning that it cannot be conclusively stated that all incineration is less carbon intensive than landfill.
- Methane emissions have a far greater impact when considered over a 20-year timeframe than over a 100-year timeframe, meaning that **incineration is preferable to landfill from a short-term perspective. However, this conclusion ignores the long-term impact of carbon dioxide released from both facilities** (including biogenic carbon emissions, which are typically ignored when applying the life cycle assessment approach to emissions accounting from waste facilities).
- In addition, the profile of emissions from incinerators, when compared to landfills, confirms that the impact of incineration is much more significant in the first year than is the case with the landfill. **Landfills offer the potential to sequester significant amounts of biogenic carbon beyond either the 20- or 100-year time horizon.**
- **If anticipated changes to residual waste composition and electricity and heat provision occur, incineration (without pre-treatment) will be more carbon intensive in 2035 than landfill (without pre-treatment and bio-stabilisation)**. Similar conclusions have been reached by a number of other studies published by policymakers in recent years, although different conclusions have been reached by industry.[44, 45]
- CHP offers relatively minor energy generation benefits. **Even if no progress is made in decarbonising heat provision, incineration facilities operating in CHP mode will continue to be a net contributor to climate change without any form of pre-treatment.**
- More generally, the results confirm that **marginal improvements in energy generation efficiency at incineration plant will be of diminishing value as energy systems decarbonise.** This trend is anticipated to continue beyond 2035. As such, **the relative performance of incineration in comparison to landfill is expected to continue to decrease beyond 2035**.

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[44] Department for Environment Food and Rural Affairs (2014) *Energy recovery for residual waste: A carbon based modelling approach*, accessed 31 March 2020, http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19019

[45] Zero Waste Scotland (2020) *The climate change impacts of burning municipal waste in Scotland*, October 2020, https://www.zerowastescotland.org.uk/sites/default/files/ZWS%20%282020%29%20CC%20impacts%20of%20incineration%20TECHNICAL%20REPORT.pdf

- **Without pre-treatment, both landfill and incineration will result in continued contributions to climate change and will be incompatible with meeting net zero climate change targets at the local and national levels**. Improved performance in either case requires the use of pre-treatment, which reduces the global climate change impacts, although the associated recycling benefits may occur outside a local authority’s geographical boundaries. Waste prevention activities may also be needed to further reduce territorial emissions down to close to zero within the local authority’s geographical boundaries, to achieve such targets.
- **Incineration cannot be considered a ‘green’ or low carbon source of electricity**, as the emissions per kWh of energy produced are higher than CCGT, renewables, and the aggregated marginal source of electricity in the UK. The carbon intensity deficit of residual waste incinerators will increase as the UK grid decarbonises. The use of incineration is therefore also incompatible with the achievement of local net zero climate change targets in respect of emissions from energy generation, unless coupled with carbon capture and storage. This technology is not yet commercially viable and its use will considerably increase the cost of waste treatment.
- **Incineration also makes a more significant negative contribution to local air quality than landfill**. These impacts can, however, be mitigated to a significant extent by appropriate abatement equipment.

Appendices

A.1.0 Technical Appendix

A.1.1 Key assumptions used in the modelling

A.1.1.1 Material assumptions

Table 4-1 shows avoided carbon emissions from material recycling. These values take into account the impurity of the recycling streams.

Table 4-1 Avoided impacts of material recycling

	tCO_2e/t
Plastics (PET)	1.4
Plastics (HDPE)	1.62
Plastic film	1.33
Glass	0.15
Ferrous (steel)	1.133
Nonferrous (aluminium)	9.1

Table 4-2 Properties of residual waste material streams.

	Moisture	Carbon	Proportion of C which is biogenic	Embodied energy (MJ/tonne)
Paper	15%	32%	100%	11.050
Card	20%	31%	100%	12.800
Plastic Film	15%	67%	0%	38.793
Dense Plastic	5%	66%	0%	31.907
Textiles	20%	30%	50%	12.800
Wood	17%	32%	100%	14.940
Nappies & sanitary	65%	7%	50%	6.300
Other misc. combustible	20%	17%	50%	14.400
Other misc. non-combustible	12%	0%	0%	2.526
Glass	5%	0%	0%	1.406
Ferrous	5%	0%	0%	0.000
Aluminium	6%	0%	0%	0.000
WEEE	5%	0%	0%	0.000
Potentially hazardous	5%	0%	0%	0.000

	Moisture	Carbon	Proportion of C which is biogenic	Embodied energy (MJ/tonne)
Garden waste	55%	18%	100%	7.650
Kitchen waste	70%	13%	100%	4.500
Other putrescibles	70%	0%	100%	4.500
Fines	70%	13%	100%	4.200

A.1.1.2 Composition Assumptions

The residual waste composition is affected by the amount of material captured from it through recycling schemes operated by local authorities. Table 4-3 shows capture rates of each material in the residual stream, now (observed) and under a Circular Economy Package scenario (calculated). The current capture rates of household and commercial residual waste streams are taken from WRAP's 2017 National Household Waste Composition[46] National Commercial Waste Composition reports[47].

The capture rates in the Circular Economy Package scenario are derived assuming that:

- Household and commercial *overall* waste compositions do not change, and
- A 65% municipal recycling rate is achieved by 2035.

These assumptions were made by Eunomia's subject-matter experts based on knowledge of waste technologies and markets.

Table 4-3 Recycling capture rate assumptions[48]

	Current System		Circular Economy Package	
	Household	Commercial	Household	Commercial
Paper	55%	59%	80%	80%
Card	68%	0%	70%	75%
Plastic Film	2%	0%	40%	30%

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[46] WRAP (2020) *National household waste composition 2017*, accessed 19 October 2020, https://wrap.org.uk/sites/files/wrap/National%20household%20waste%20composition%202017.pdf

[47] WRAP (2020) *National municipal commercial waste composition, England 2017*, January 2020, https://wrap.org.uk/sites/files/wrap/National%20municipal%20commercial%20waste%20composition_%20England%202017.pdf

[48] Recycling capture rate refers to the proportion of materials captured for recycling

	Current System		Circular Economy Package	
	Household	Commercial	Household	Commercial
Dense Plastic	31%	31%	60%	60%
Textiles	11%	0%	20%	10%
Wood	79%	54%	80%	60%
Nappies & sanitary	1%	0%	5%	5%
Other misc. combustible	3%	34%	10%	40%
Misc. Non-combustible	51%	0%	60%	10%
Glass	74%	77%	85%	80%
Ferrous	58%	20%	60%	30%
Aluminium	48%	0%	85%	50%
WEEE	62%	10%	70%	50%
Potentially hazardous	23%	0%	23%	0%
Garden waste	86%	69%	90%	87%
Kitchen waste	14%	11%	70%	70%
Other putrescibles	0%	0%	10%	10%
Fines	0%	0%	40%	40%

Table 4-4 Household and commercial residual waste compositions in 2017

	Household		Commercial	
Material	Residual	Recycling	Residual	Recycling
Paper	9%	14%	9%	14%
Card	4%	10%	4%	10%
Plastic Film	6%	0%	6%	0%
Dense Plastic	7%	4%	7%	4%
Textiles	8%	1%	8%	1%
Wood	1%	7%	1%	7%
Nappies & sanitary	7%	0%	7%	0%
Other misc. combustible	7%	0%	7%	0%
Other misc. non-combustible	5%	7%	5%	7%
Glass	3%	11%	3%	11%
Ferrous	2%	3%	2%	3%
Aluminium	1%	1%	1%	1%
WEEE	1%	2%	1%	2%
Potentially hazardous	1%	0%	1%	0%
Garden waste	4%	33%	4%	33%
Kitchen waste	28%	6%	28%	6%
Other putrescibles	4%	0%	4%	0%
Fines	2%	0%	2%	0%

A.1.2 Treatment-specific key assumptions

A.1.2.1 Landfill

Table 4-5 General assumptions used in landfill modelling.

	Assumption
Proportion of biogenic carbon stored (100 years)	52%
Composition of landfill gas	50% methane / 50% carbon dioxide
Landfill gas use	92% used to generate electricity / 8% flared
Landfill gas capture rate	62%

	Assumption
Gas engine efficiency	35%
GWP20 of methane	86
GWP100 of methane	34
GWP N_2O	265
Time horizon of methane emissions	100 years

A.1.2.2 Incineration

The CHP generation efficiencies shown in Table 4-6 are taken from best practice in the UK achieved by the Sheffield EfW plant.[49]

Table 4-6 Energy generation efficiencies of EfW.

Operating mode	Energy type	Efficiency
Electricity-only	Electricity	29%
CHP	Electricity	19%
	Heat	20%

Table 4-7 Materials extraction from bottom ash residues. Material is recycled at a rate of 90%.

Metal	Extraction rate
Ferrous	70%
Non-ferrous	30%

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[49] Environment Agency (2020) *2019 waste incineration monitoring reports*, October 2020, https://environment.data.gov.uk/portalstg/home/item.html?id=5f25d4693fe8499282070ea40e08d0a0

A.1.2.3 Pre-treatment

Table 4-8 Recycling Capture rates - Pre-sorting Treatment[50]

Material	Capture rate
Paper	65%
Card	85%
Plastic film	78%
Dense plastic	90%
Glass	73%
Ferrous metals	97%
Non-ferrous metals	83%
Notes **These capture rates represent the proportion of material removed for recycling from the residual waste accepted at the pre-treatment plant**	

Table 4-9 Organic carbon loss of biogenic carbon compounds in bio-stabilisation of residual waste for landfill.

Compound	Cellulose	Lignin	Protein	Sugar / starch	Fat
Organic carbon loss during maturation	83%	12%	66%	97%	78%

A.1.2.4 CHP

Table 4-10 shows the generation efficiency assumptions for incineration plant operating in CHP mode.

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[50] Recycling capture rate refers to the proportion of materials captured for recycling

Table 4-10 Generation efficiencies of electricity and heat generation

Energy type	Efficiency
Electricity	19%
Heat	20%

A.1.2.5 Air Quality Impacts

Data on the air pollution emissions from waste treatment facilities is presented in Table 4-11.

Table 4-11: Emissions to Air from Waste Treatment Facilities

	Emissions, g pollutant/tonne of waste treated[51] [52]				
	Landfill	Landfill / biostabilisation	Incineration		Incineration with pre-treatment
			Typical	Low NO_x	
NH_3	495	191	15	15	15
VOCs	1	55	55	55	55
PM2.5	1	22	30	30	30
SO_x	4	2.5	40	40	40
NO_x	40	3	1000	200	1000

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[51] Enviros Consulting Ltd, University of Birmingham, Risk and Policy Analysts Ltd, Open University, Maggie Thurgood, and Defra (2004) *Review of Environmental and Health Effects of Waste Management*, 2004, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69391/pb9052a-health-report-040325.pdf

[52] Marner, D.B., Richardson, T., and Laxen, D. (2020) *Health Effects due to Emissions from Energy from Waste Plant in London*, 2020, https://www.london.gov.uk/sites/default/files/gla_efw_study_final_may2020.pdf

A.1.3 Results

A detailed breakdown of the GHG impacts of each technology across each scenario is given in tables here.

Table 4-12 Breakdown of GHG impacts of landfill (without pre-treatment) across all scenarios

	GHG impact (tCO2e/t)		
Scenario	Today	Expected-2035	GWP20
Composition	Current composition	Circular Economy	Circular Economy
Timeframe	100-year GWP	100-year GWP	20-year GWP
Electricity marginal intensity	0.270 kgCO2e/kWh	0.066 kgCO2e/kWh	0.066 kgCO2e/kWh
Heat marginal intensity	0.22 kgCO2e/kWh	0.15 kgCO2e/kWh	0.15 kgCO2e/kWh
Total excluding biogenic carbon	0.32	0.30	1.03
Direct process emissions			
Including biogenic carbon	0.58	0.51	1.24
Excluding biogenic carbon (fossil CO_2 emissions only)	0.36	0.31	1.04
Inputs & offsets			
Process energy use (all fossil CO_2)	0.00	0.00	0.00
Total offset through energy generation (all fossil CO_2)	-0.04	-0.01	-0.01
Total offset through materials recovery (all fossil CO_2)	0.00	0.00	0.00
Carbon sequestration credit (all biogenic CO2)	-0.23	-0.21	-0.26

Table 4-13 Breakdown of GHG impacts of landfill with pre-treatment across all scenarios

	GHG impact (tCO2e/t)		
Scenario	Today	Expected-2035	GWP20
Composition	Current composition	Circular Economy	Circular Economy
Timeframe	100-year GWP	100-year GWP	20-year GWP
Electricity marginal intensity	0.270 kgCO2e/kWh	0.066 kgCO2e/kWh	0.066 kgCO2e/kWh
Heat marginal intensity	0.22 kgCO2e/kWh	0.15 kgCO2e/kWh	0.15 kgCO2e/kWh
Total excluding biogenic carbon	-0.228	-0.233	-0.173
Direct process emissions			
Including biogenic carbon	0.341	0.326	0.381
Excluding biogenic carbon (fossil CO_2 emissions only)	0.096	0.095	0.158
Inputs & offsets			

	GHG impact (tCO2e/t)		
Scenario	**Today**	**Expected-2035**	**GWP20**
Composition	**Current composition**	**Circular Economy**	**Circular Economy**
Timeframe	**100-year GWP**	**100-year GWP**	**20-year GWP**
Electricity marginal intensity	**0.270 kgCO2e/kWh**	**0.066 kgCO2e/kWh**	**0.066 kgCO2e/kWh**
Heat marginal intensity	**0.22 kgCO2e/kWh**	**0.15 kgCO2e/kWh**	**0.15 kgCO2e/kWh**
Process energy use (all fossil CO_2)	0.015	0.004	0.001
Total offset through energy generation (all fossil CO_2)	-0.003	-0.001	-0.001
Total offset through materials recovery (all fossil CO_2)	-0.337	-0.331	-0.331
Carbon sequestration credit (all biogenic CO2)	0.002	0.002	0.010

Table 4-14 Breakdown of GHG impacts of incineration (without pre-treatment) across all scenarios

	GHG impact (tCO2e/t)				
	Incineration (straight - electricity only)		**Incineration (straight - CHP)**		
Scenario	**Today**	**Expected-2035**	**Today**	**Expected-2035**	**Sensitivity (heat)**
Composition	**Current composition**	**Circular Economy**	**Current composition**	**Circular Economy**	**Circular Economy**
Timeframe	**100-year GWP**	**100-year GWP**	**100-year GWP**	**100-year GWP**	**100-year GWP**
Electricity marginal intensity	**0.270 kgCO2e/kWh**	**0.066 kgCO2e/kWh**	**0.270 kgCO2e/kWh**	**0.066 kgCO2e/kWh**	**0.066 kgCO2e/kWh**
Heat marginal intensity	**0.22 kgCO2e/kWh**	**0.15 kgCO2e/kWh**	**0.22 kgCO2e/kWh**	**0.15 kgCO2e/kWh**	**0.22 kgCO2e/kWh**
Total excluding biogenic carbon	0.167	0.392	0.104	0.310	0.261
Direct process emissions					
Including biogenic carbon	0.951	0.946	0.951	0.946	0.946
Excluding biogenic carbon (fossil CO_2 emissions only)	0.458	0.508	0.458	0.508	0.508
Inputs & offsets					

	GHG impact (tCO2e/t)				
	Incineration (straight - electricity only)		Incineration (straight - CHP)		
Scenario	Today	Expected-2035	Today	Expected-2035	Sensitivity (heat)
Composition	Current composition	Circular Economy	Current composition	Circular Economy	Circular Economy
Timeframe	100-year GWP	100-year GWP	100-year GWP	100-year GWP	100-year GWP
Electricity marginal intensity	0.270 kgCO2e/kWh	0.066 kgCO2e/kWh	0.270 kgCO2e/kWh	0.066 kgCO2e/kWh	0.066 kgCO2e/kWh
Heat marginal intensity	0.22 kgCO2e/kWh	0.15 kgCO2e/kWh	0.22 kgCO2e/kWh	0.15 kgCO2e/kWh	0.22 kgCO2e/kWh
Process energy use (all fossil CO_2)	0.028	0.012	0.028	0.012	0.012
Total offset through energy generation (all fossil CO_2)	-0.261	-0.067	-0.324	-0.149	-0.198
Total offset through materials recovery (all fossil CO_2)	-0.059	-0.062	-0.059	-0.062	-0.062
Carbon sequestration credit (all biogenic CO2)	0	0	0	0	0

Table 4-15 Breakdown of GHG impacts of incineration with pre-treatment across all scenarios

	GHG impact (tCO2e/t)	
Scenario	Today	Expected-2035
Composition	Current composition	Circular Economy
Timeframe	100-year GWP	100-year GWP
Electricity marginal intensity	0.270 kgCO2e/kWh	0.066 kgCO2e/kWh
Heat marginal intensity	Regular	Forward
Total excluding biogenic carbon	-0.291	-0.185
Direct process emissions		
Including biogenic carbon	0.437	0.451
Excluding biogenic carbon (fossil CO_2 emissions only)	0.118	0.151
Inputs & offsets		

Process energy use (all fossil CO_2)	0.031	0.011
Total offset through energy generation (all fossil CO_2)	-0.116	-0.032
Total offset through materials recovery (all fossil CO_2)	-0.325	-0.315
Carbon sequestration credit (all biogenic CO2)	0.000	0.000

A.1.4 Comparisons to the literature

This section compares the results described above to notable reports by Defra, Zero Waste Scotland and Policy Connect, noting key differences in methodology and conclusions.

4.1.1.1 Defra Carbon-based modelling Study

This study, published by Defra in 2014 sought to "*identify the key factors necessary to maximise the benefits of EfW over landfill in carbon terms in line with the [waste] hierarchy*".[53] Implicit within the analysis was that there would come a point where EfW would perform worse than landfill, as the electricity grid decarbonised, should the quantity of biogenic carbon in the waste stream decline over time. The study did not identify when this situation would occur but sought to explore the different factors that would lead to this situation, as well as look at what incineration facilities would need to do to continue to perform better than landfill.

Defra indicated that by "using conventional analysis (disregarding biogenic carbon) the model indicates a good carbon case for continuing to include EfW as a key part of the hierarchy." A key area of focus was on the beneficial use of CHP.

The study differs in its approach to the current work in its attempt to compare simple incineration (in electricity-only mode) and landfill treatments, and to identify the electricity generation efficiency at which incineration and landfill are equivalent in GHG emissions terms. In doing so, they limit their analysis to simple incineration and landfill treatments, thereby ignoring whether *either* of these approaches is suitable given that rapid decarbonisation is necessary.

The effect of compositional changes on the outcome was considered, although these changes were not linked to changes in recycling rates. However, the study indicated that, when EfW plants are operating in electricity-only mode, high levels of biogenic content

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[53] Department for Environment Food and Rural Affairs (2014) *Energy recovery for residual waste: A carbon based modelling approach*, accessed 31 March 2020, http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19019

are needed for incinerators to emerge favourably, which would need to be brought about through pre-treatment methods.

The Defra study used a similar landfill model to that used in the current analysis, although it is noted that the sequestration of biogenic carbon is considered in the current study only as a sensitivity.

4.1.1.2 Zero Waste Scotland: The climate change impacts of burning municipal waste in Scotland

Despite some differences in method and assumptions (noted below), Zero Waste Scotland's study reaches the same conclusions as those presented here, namely that electricity-only incinerators are a more carbon-intensive form of electricity generation than the current marginal grid average, and thus "EfW technologies can no longer be considered low carbon solutions".[54] The report also concludes that landfill is currently a more carbon-intensive form of waste treatment than incineration.

The climate impacts of treating one tonne of residual waste in an electricity-only incinerator were found by Zero Waste Scotland to be largely in line with this report (0.23 tCO_2e/t vs 0.17 tCO_2e/t), with the discrepancy being borne out of a more favourable generation efficiency assumed in this study.

The ZWS study also tests the impact of varying the composition of waste on the climate impact of incineration and landfill. Specifically, it finds – in agreement with the current study – that an increase in the proportion of plastic waste will improve the relative performance of landfill and reduce that of incineration, and that the emissions intensity of incineration is particularly sensitive to this composition.

The authors find that pre-treating residual waste sent to landfill (i.e. reducing the mass of biogenic carbon from 15% to 5%, vs. 13% to 9% in this study) would also dramatically reduce its climate impacts, and that this may be the most climate-friendly means of residual waste treatment (although they do not consider the impact of incineration in conjunction with pre-sorting).

Key methodological differences are that:

- no sequestration credit is applied to landfill by ZWS (no other method of compensation is applied);
- the fossil carbon content of residual waste is lower than assumed in the current study;
- residual waste sent to landfill is sorted by default, with about 10% of material being removed: and

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[54] Zero Waste Scotland (2020) *The climate change impacts of burning municipal waste in Scotland*, October 2020, https://www.zerowastescotland.org.uk/sites/default/files/ZWS%20%282020%29%20CC%20impacts%20of%20incineration%20TECHNICAL%20REPORT.pdf

- plant efficiencies are lower in the ZWS study (25% for electricity-only and 34% for CHP, against 29% and 39% respectively in the current study).

4.1.1.3 Policy Connect: No Time to Waste

Policy Connect's report is significantly more optimistic in its assessment of incineration's ability to have positive climate impacts.[55] Its finding that 4 MtCO2e could be avoided by 2030 by diverting waste from landfill is based on an assumption (cited from the Green Investment Bank) that incineration today saves 200kgCO2e/tonne waste treated today, which is considerably more than found in the modelling presented here and in the Zero Waste Scotland report (150 kgCO2e/tonne and 50 kg/tonne respectively). [56,57] No acknowledgement is made of the expected fall in this benefit as the grid decarbonises.

It is not clear what assumptions were used in the study in respect of energy generation performance, marginal energy sources, and waste composition. The analysis undertaken in the current report suggests, however, that these are unlikely to be consistent with a future-facing trajectory as far as the decarbonisation of energy supplies and the changing composition of waste is concerned.

The modelling behind the report also considers it possible that 70% of UK incinerators will operate in CHP mode by 2030. This appears optimistic given that just 20% do so today, with – as the report notes – significant barriers for plants to find heat off-takers.

Separately, the report makes the recommendation that "Government should support the development and integration of Carbon Capture and Storage (CCS) technology into EfW facilities," claiming that "a number of EfW plants across Europe have incorporated CCS both during the design and retrospectively." While there has been some research into the viability of CCS in the UK, to the best of the authors' knowledge, there are no EfW facilities in existence that are actively capturing and using or storing CO_2. Pre-treatment technologies, conversely, are market-ready in the UK and in Europe.

A parliamentary inquiry by the UK Government confirmed that costs have to date been a barrier to further take-up (although these are expected to reduce over time as the technology matures).[58] The cost of storing the CO_2 from the Klemetsrud incinerator over

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[55] Policy Connect (2020) *No Time to Waste: Resources, recovery & the road to net-zero*, July 2020, https://www.policyconnect.org.uk/research/no-time-waste-resources-recovery-road-net-zero

[56] Green Investment Bank (2014) *The UK residual waste market*, July 2014, https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjRy9WCw_jsAhXLVsAKHbahCToQFjAAegQIAxAC&url=https%3A%2F%2Fwww.infrapppworld.com%2Fdownload-file%2F2682&usg=AOvVaw21zNRQ9Q8m4pXAMUDjmHRi

[57] Zero Waste Scotland (2020) *The climate change impacts of burning municipal waste in Scotland*, October 2020, https://www.zerowastescotland.org.uk/sites/default/files/ZWS%20%282020%29%20CC%20impacts%20of%20incineration%20TECHNICAL%20REPORT.pdf

[58] House of Commons, and Department for Business, Energy and Industrial Strategy (2019) *Carbon Capture Usage and Storage: Third Time Lucky?*, April 2019, https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/1094/1094.pdf

a five-year period has recently been estimated at close to £1 billion for the 400,000 tonne per annum facility (suggesting the five year costs alone to be c. £2.5k per tonne).[59] Capture from power plants also requires significant additional energy expenditure, although this is not necessarily the case where CCS is used with other industrial processes.

While this technology may become be viable in the future, it appears premature and risky to base a residual waste strategy on as-yet unproven technologies.

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[59] Moe, O.M. (2019) *Carbon capture may solve the climate crisis but how do we get there?*, June 2019, https://www.cowi.com/insights/carbon-capture-may-solve-the-climate-crisis-but-how-do-we-get-there