Scottish Government - Incineration Review

Opportunities to Decarbonise the Waste Treatment Infrastructure

Final Report

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eunomia

Report For

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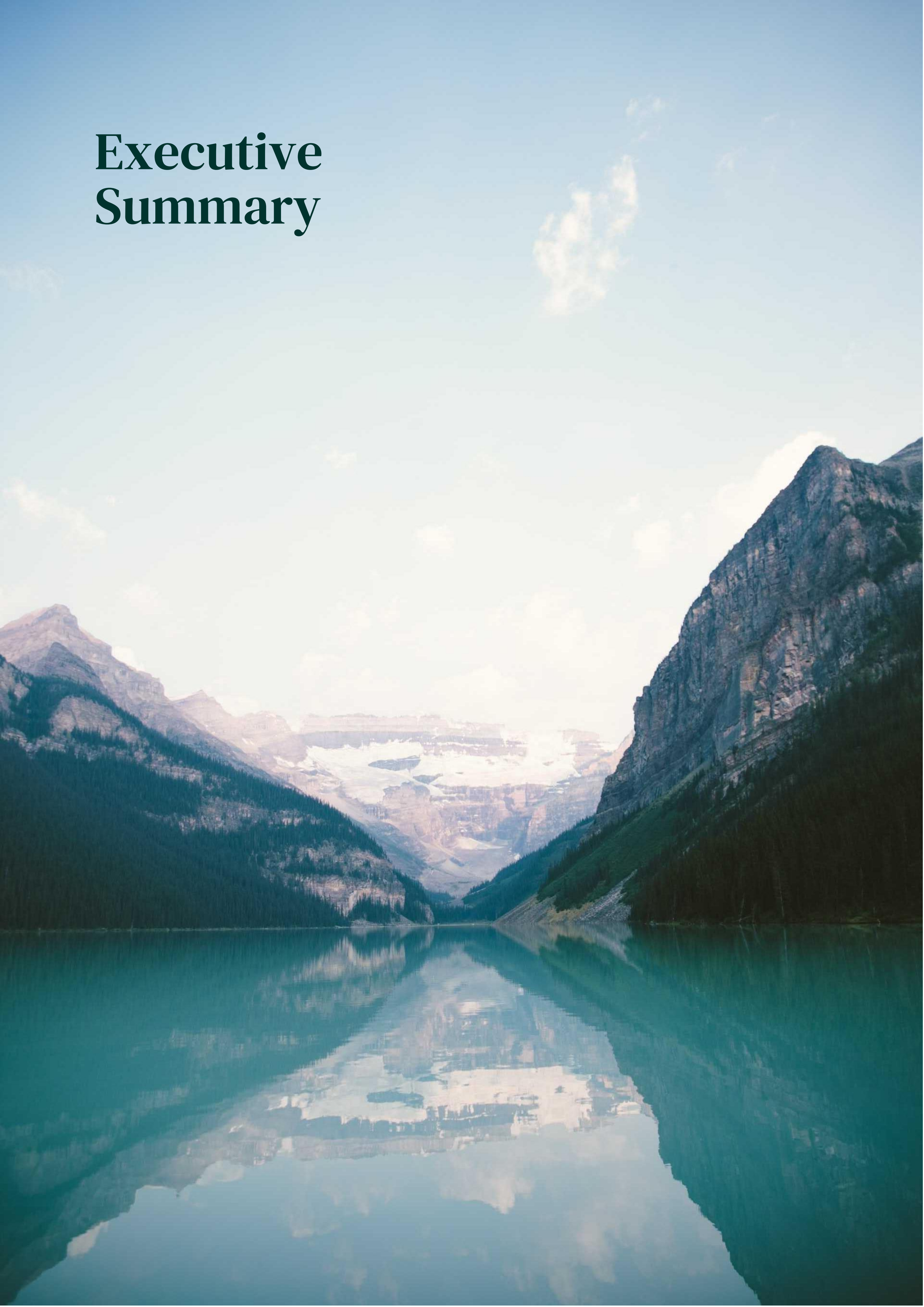
Executive Summary



Executive Summary

Context

Scottish Incineration Review

In May 2021, the Scottish Government made a commitment to assess the role of incineration in the waste hierarchy in Scotland, to ensure alignment between its management of residual waste and decarbonisation ambitions. The review, led by Dr Colin Church, seeks to address:

- Scotland's current progress towards waste management ambitions and what is required to achieve them;
- The options for managing residual waste;
- The economic, environmental and social trade-offs;
- Where capacity should be located and in what form; and
- How to improve existing treatment facilities in terms of carbon performance and societal impact.

A large amount of work has already been completed, including a review of treatment capacity and an options appraisal undertaken and published by Riccardo, a Rapid Evidence Assessment (REA) of the health impacts of incinerating waste since 2009 coordinated by Public Health Scotland, and a Call for Evidence which allowed stakeholders to submit written and verbal evidence and considerations.

Overarching Objectives

This report seeks to compliment the above research by assessing the Greenhouse Gas (GHG) emissions for existing facilities, including a categorisation based on type and volumes of waste feedstocks; a review of additional and alternative decarbonisation technology options; and a high-level commentary of each of these options and pathways to decarbonise, covering how these would change over time.

To meet these research objectives, data available in the literature was analysed alongside the results from the Call for Evidence, and primary evidence was gathered from relevant stakeholders. Modelling was also conducted which utilised in part, data and statistics from work undertaken by Riccardo.

Background Policy Context on Decarbonisation

There are a variety of policies and legislation that impact on the formation, management and treatment of residual waste in Scotland. These have been delivered by multiple jurisdictions, including the Scottish Government, the UK Government and formally the EU. The policies and legislation relate to wide range of objectives, including the achievement of carbon reduction targets, increased resource efficiency (including waste prevention and increased recycling), and improving air quality.

The Intergovernmental Panel on Climate Change (IPCC) warnings to limit warming to 1.5°C is a key driver that has shaped policy. Scotland has legislated for 75% emissions reduction compared to 1990 levels by 2030, and net-zero by 2045 (5 years ahead of the UK Government target).

In line with this, the Climate Change Committee (CCC) calls for waste sector emissions to fall 75% from today's levels by 2050. Around 80% of the abatement by 2035 is forecast to be delivered by waste prevention. By 2050 30% is attributed to carbon emission reductions such as Carbon Capture, Utilisation and Storage (CCUS), while the additional 10% covers capturing landfill methane, reducing wastewater treatment emissions, and improving composting. [1]

Scotland has outlined two major national targets for waste prevention to 2025, to reduce total waste arisings by 15% against 2011 levels and reduce food waste by 33% against 2013 levels. [2] Subsequent policies to achieve these targets include a ban on landfilling Biodegradable Municipal Waste (BMW), and legislation to improve recycling, such as the Environmental Protection Act (EPA) 1990, Extended Producer Responsibility (EPR), the UK Plastics Pact (a voluntary industry initiative), Waste (Scotland) Regulations 2012, Route Map and Circular Economy Bill, Deposit Return Scheme (DRS), and New Plastics Economy.

Emission-related policies generally have wide scopes and refer to numerous sources besides waste. Covered in this report are UK Emissions Trading Scheme (ETS), CCUS, and Heat Networks (Scotland) Act 2021.

Carbon Appraisal of Residual Waste Treatment – Baseline

There are a wide variety of treatment options currently used to manage residual waste including landfill, incineration, gasification, Mechanical Biological Treatment (MBT), and Refuse Derived Fuel (RDF) export.

Carbon Baseline Appraisal – Introduction to Approach

Based on the listed treatment options, a baseline of the associated carbon impacts was developed. The scope covers direct emissions including from the combustion of waste streams, energy use at facilities, and avoided emissions. The treatment of biogenic carbon was an important consideration, given that generally only fossil CO_2 emissions are accounted for in life cycle assessments (LCA). Eunomia's models include a credit for carbon sequestration where biogenic carbon is stored in landfill. This approach is applied to all residual waste flows, with specific emission factors for the type of waste treated (paper, plastics etc.). Scenarios to examine the GHG impacts associated with treatment facilities are outlined in Table ES- 1

Table ES- 1: Baseline Scenarios Modelled for 2020 and 2035

Current	This baseline scenario considers 2020 information, with household recycling at 42%, and C&I recycling at 58%.
Business As Usual (BAU)	This baseline scenario is a forecast at 2035, with household recycling at 51% and C&I recycling at 61%. The improvement in recycling rates compared to the baseline is on the basis of the rate of progress in recycling seen over recent years. This functions as a "worst case scenario" in relation to achieving recycling ambitions.

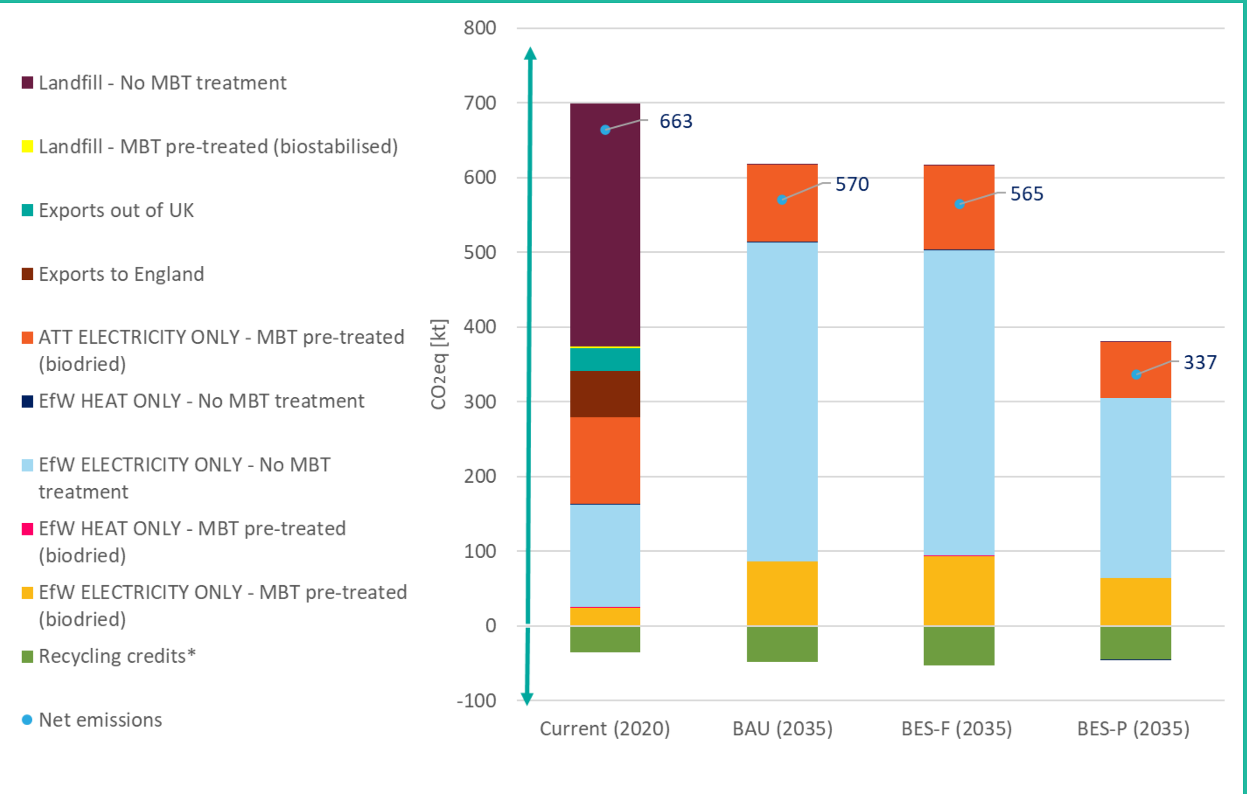
[1] Climate Change Committee (2022) The Sixth Carbon Budget: Waste. https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Waste.pdf
[2] Scottish Government (2022) Managing waste.

Best Effort Scenario - Food (BES-F)	This 2035 baseline scenario forecast has household recycling at 55% and C&I recycling at 65%. Notably increased food waste collection is assumed. Thus, this baseline assumes that progression in organics collection rates is due to increased collection service provision of food for households and businesses, strong communications, and higher uptake and engagement. The advancement in plastics capture is less successful (compared to BES-P, described below).
Best Effort Scenario - Plastic (BES-P)	This 2035 forecast has the same overall recycling rates as in the BES-F baseline scenario. It is assumed that plastic capture increases, as well as food capture, to achieve the overall recycling rate. Compared to BES-F, this scenario leaves residual waste with a composition containing more food and less plastic.

Carbon Emissions Baseline – Current and Future

Figure ES- 1 shows the emissions associated with the residual waste infrastructure for the scenarios.

Figure ES- 1: Current and Future Baseline Annual Residual Waste Emissions, Split by Treatment Route



*Note: the credits associated with recycling of metals from bottom ash are directly subtracted from the emission of EfW, and are not included in "Recycling". For a clear split of credits and direct emissions, please refer to the chart in Section 4.3

The baseline modelling shows that progress towards Net Zero ambitions are expected through reductions in residual waste, but highlights that more action is needed. In the 2035 baseline scenarios, with a predicted surplus of incineration capacity available, no waste is expected to be landfilled or exported apart from a fixed 1% of C&I waste which is assumed to be still directed to landfill. In the 2035 baseline scenarios with less plastic in the residual waste stream (resulting from greater recycling), the impact per tonne of waste for EfW with electricity generation is higher than landfill. Although performance improves under the Best Effort scenarios, residual waste remains a net contributor to climate change impacts.

Carbon Appraisal of Residual Waste Treatment – Decarbonisation Pathways

Potential technology options chosen to deliver the decarbonisation pathways include **Advanced Sorting (AS), CCUS, heat networks and biostabilisation**. These technologies are introduced below.

AS - Residual waste sorting, particularly of plastics, will reduce the direct fossil-derived CO_2 emissions from incineration, while also providing emission reduction benefits due to recycling. The 2035 modelling considers high ambition AS technologies, achieving high rates of recovery (18% of residual waste) predicated on design for recycling and recycling market improvements. It is difficult to provide certainty on future costs for AS since much depends on material revenues and avoided disposal savings, but costs are expected to be markedly lower than for CCUS, and an indicative range estimate of £0-50/tonne is given.

CCUS - This technology has not yet been integrated with EfW at a commercial scale in Scotland, however Scotland's relatively young fleet is well placed for this. Eunomia estimated the combined capture, transport and storage costs ranging from £60-110/tonne.

Heat Networks - The ability to recover heat from incinerators is well established across Europe, though almost all operational facilities in Scotland are electricity-only. While most EfW facilities are built CHP ready, and heat recovery and distribution technology is mature and well understood, viability is dependent on finding sufficient local customers and implementing self-sustaining heat networks. A cost range of £30-120/tonne is provided, covering the capital costs, while operational costs are expected in addition.

Biostabilisation – This technology is a form of mechanical and biological treatment (MBT) which seeks to stabilise waste prior to landfill to reduce methane emissions, while also recovering certain materials for recycling. While not prevalent in the UK, there are examples of its successful deployment across Europe. It is considered in this study only as an option for a small amount of remote rural location waste, and is addressed separately from the main results.

Overview of Pathways

Each of the technology options listed above has been combined to generate four future pathways, shown in Table ES- 2**Error! Reference source not found.**.

Table ES- 2: Overview of the modelled pathways

Pathway 1: Advanced Sorting	This pathway includes the addition of AS to 100% of the waste that was going directly to EfW plants in the baseline. It also involves improved recycling efficiencies for all the operating MBTs.
Pathway 2: Advanced Sorting and Heat Recovery	This pathway includes AS as detailed in pathway 1 plus the benefit associated with the implementation of heat recovery in 5 facilities (Millerhill, GRREC, Aberdeen, Dundee and Earls Gate).
Pathway 3: Advanced Sorting and CCUS	This pathway includes AS as detailed in pathway 1 plus the benefit associated with the implementation of CCUS in all mainland EfW facilities (excluding two gasification facilities).
Pathway 4: Advanced Sorting, Heat Recovery and CCUS	This scenario combines the technologies detailed for pathways 1, 2 and 3.

Biostabilisation	This scenario assesses the benefit of biostabilisation. Due to the increase in EfW capacity, and the anticipated decrease in amount of residual waste sent to landfill by 2035, the impact of this technology is discussed separately to the first four pathways.

The main assumptions behind the modelling are reported in Table ES- 3.

Table ES- 3: Main assumptions behind the modelling of the technology options

Technology	Approach to modelling	Potential constraints – not considered in the model
Advanced sorting	• We assume that the technology can be applied to all waste that is going to incineration • We assume that the same capture efficiencies of AS can be applied to all MBT facilities	• Barriers to technical implementation are relatively few assuming the material can be in practice recycled – the main issue may be cost, especially when considering smaller facilities. But the technology is likely to be cheaper than CCUS • We have not considered local constraints that might exist and prevent some flow of waste from being sorted, especially in the case of rural areas/islands • With respect to existing MBT facilities, in practice it might not be possible to retrofit the required technology to meet the same capture rates as AS
CCUS	• This is assumed to be fitted on all plant meeting the following criteria: minimum annual capacity of 100,000 tonnes and located close to a potential Scottish CCUS project, as these will be priority facilities for receiving CCUS. Others may follow but they are less likely to have advanced by 2035. For those further away from the pipelines, the costs of implementing CCUS will likely be higher	• In practice, there may be technical restrictions at a given site that prevent the retrofit of CCUS (such as insufficient space for the equipment)
Heat Recovery	• We modelled heat recovery for those facilities where the Scottish Government heat networks team indicated have the more realistic heat offtake potential in the near term – Millerhill, Aberdeen Recycling & Energy Recovery (NESS), GRREC, Dundee and Earls Gate	• We have been somewhat conservative with heat recovery deployment – more research on each incineration facility's potential for heat recovery is needed, as the available literature has not specifically evaluated this

Summary of Results

Figure ES- 2 shows the emissions associated with the baseline and the pathways, described in Table ES- 1 for each scenario considered (BAU, BES-F and BES-P). It indicates that, under the baseline scenarios, residual waste infrastructure is a net contributor to carbon emissions, i.e. the residual waste treatment technologies contribute to the total lifecycle emissions of the materials considered. By contrast, under each scenario of each Pathway option, the emissions benefits from recycling, benefits from avoided energy generation and from biogenic carbon capture are such that these outweigh the direct emissions from the treatment processes – leading to net negative emissions results. However, it should be noted that the net negative emissions results stand only from the perspective of residual waste in isolation, and do not constitute a global system benefit when production emissions are taken into account. In particular, focussing on end-of-life treatment means that the scope of these results consider only part of the lifecycle of the materials/products that become waste.

Figure ES- 2: Carbon emissions associated with the baseline and the pathways for each scenario

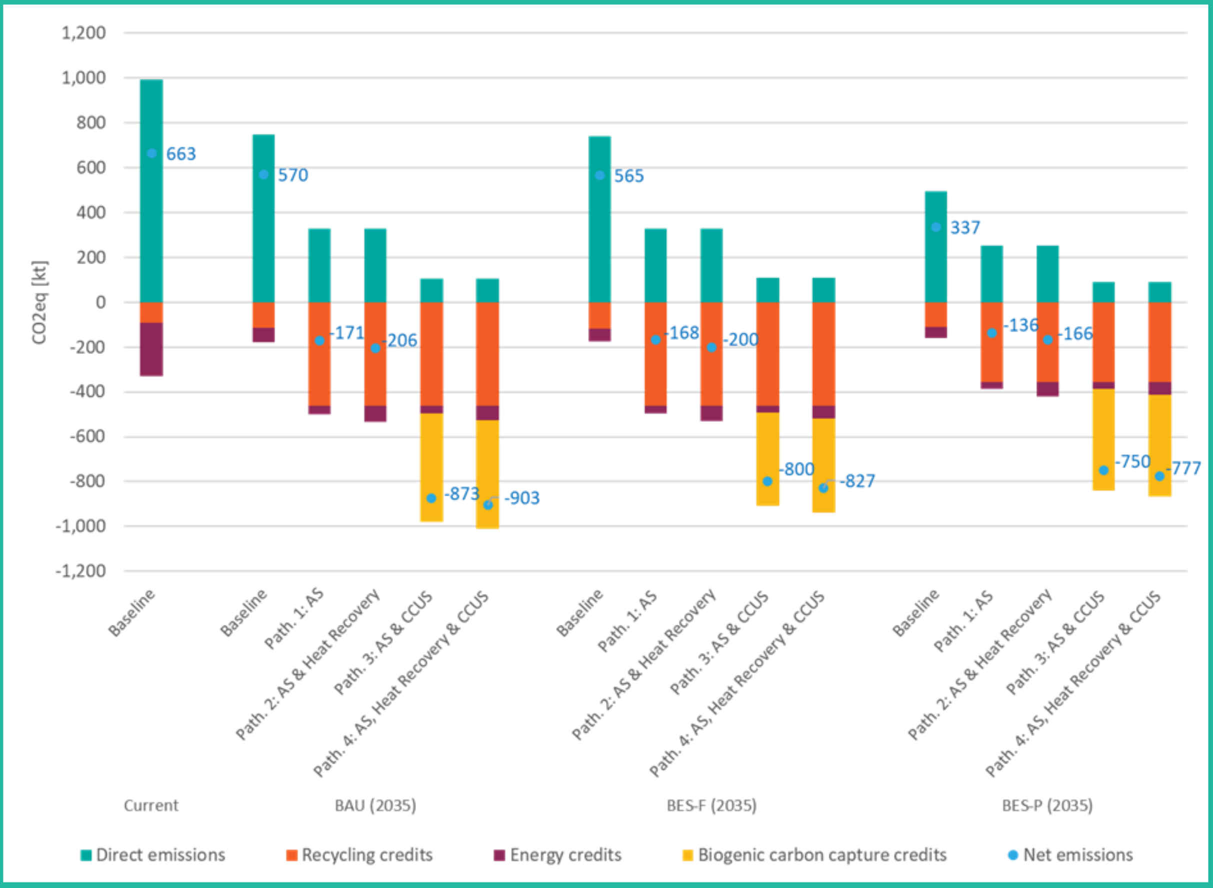
Note: The negative emissions in the Pathway results are primarily driven by the carbon benefits associated with the extraction of recyclables through advanced sorting (as is included in all Pathways), and CCUS in Pathways 3 and 4. Biogenic CO2 emitted to atmosphere is not accounted, while a credit is applied for capture of biogenic carbon in the CCUS pathways.

The single most cost-efficient and effective method to reduce direct emissions, from the residual sector across all scenarios (BAU, BES-F, and BES-P) was the implementation of **AS,** as demonstrated in Pathway 1 and shown in Figure ES- 3. Alongside reduction of EfW's direct emissions, AS has the further benefit of emissions savings from additional recycling recovered from residual waste.

Deployment of **CCUS** is the next largest contributor to the reduction of forecast direct carbon emissions from residual waste, as is shown in Pathway 3. It is also the single largest net contributor to the decarbonisation of residual waste, when considering biogenic capture credits alongside the reductions in direct emissions. However, CCUS only decarbonises EfWs; it does not directly support keeping materials in circulation for longer nor promote a more circular economy (unlike AS). This assessment also takes an optimistic approach of the forecast level of deployment of CCUS across the Scottish EfW fleet (broadly aligned with the CCC's modelled Tailwinds scenario).

Heat recovery, compared to CCUS and AS, resulted in a relatively lower impact on emissions (Pathway 2). This is in part due to assuming that only five facilities – Millerhill, GRREC, Aberdeen, Dundee and Earls Gate – out of 10 implement heat recovery and connect to heat networks. There is policy support for the development of heat networks generally, including funding such as the £300 million Heat Network Fund (some of which is supporting networks using heat from EfWs). However, unlike CCUS and AS, there is a less targeted focus on residual waste treatment facilities being the source of this heat.

Figure ES- 3: Carbon emissions associated with the baseline and the pathways for each scenario, split by direct emissions and carbon credits



A further pathway demonstrates the potential impact of **biostabilisation** by sending 10kt of HH waste either directly to landfill or via an MBT where biostabilisation occurs. This was assessed to help demonstrate the potential benefit of this solution were it to be applied to rural and sparsely populated areas of Scotland that may not be well served by EfW or ATT facilities. The pathway showed a decrease in emissions (and possibility for net negative emissions, depending on accounting principles) for all three scenarios when stabilisation at MBTs occurs as pre-treatment.

Conclusions

In summary, to reduce direct emissions from the residual waste sector and promote a more circular economy, AS is identified as the most significant and readily deployable decarbonisation pathway modelled. It comes at a lower cost and risk compared to other technologies, is less dependent on public funding, and can be deployed imminently (albeit with greater effect as recyclability design and market development improves). However, the largest net carbon reduction overall – including the benefits of capturing biogenic carbon – stems from AS alongside the introduction of CCUS across the majority of the Scottish EfW fleet. This level of impact modelled within this study is considered to be optimistic and will require the successful deployment of the Scottish Cluster in order to be fully achieved. Heat networks do have the benefit of additional energy benefits gained for EfW, although the impact of this will reduce as low carbon heat sources become more prominent. Nevertheless, the use and purpose of heat networks spans beyond the scope of the residual waste sector and this report. Finally, as the use of landfills for residual waste decreases into the future, the effect of decarbonisation technologies that impact landfill - such as biostabilisation – also reduces. However, where landfill use is unavoidable (e.g., due to geographical constraints), such technologies should still be considered.

Overall, this report outlines potential sequencing priorities and impacts from deployment of residual waste infrastructure decarbonisation technologies. Even so, the magnitude of the decarbonisation challenge required across the Scottish economy is immense. It should therefore be considered that all of these options – plus further core policies geared towards zero waste and the circular economy – are all vitally important to help Scotland achieve Net Zero by 2045

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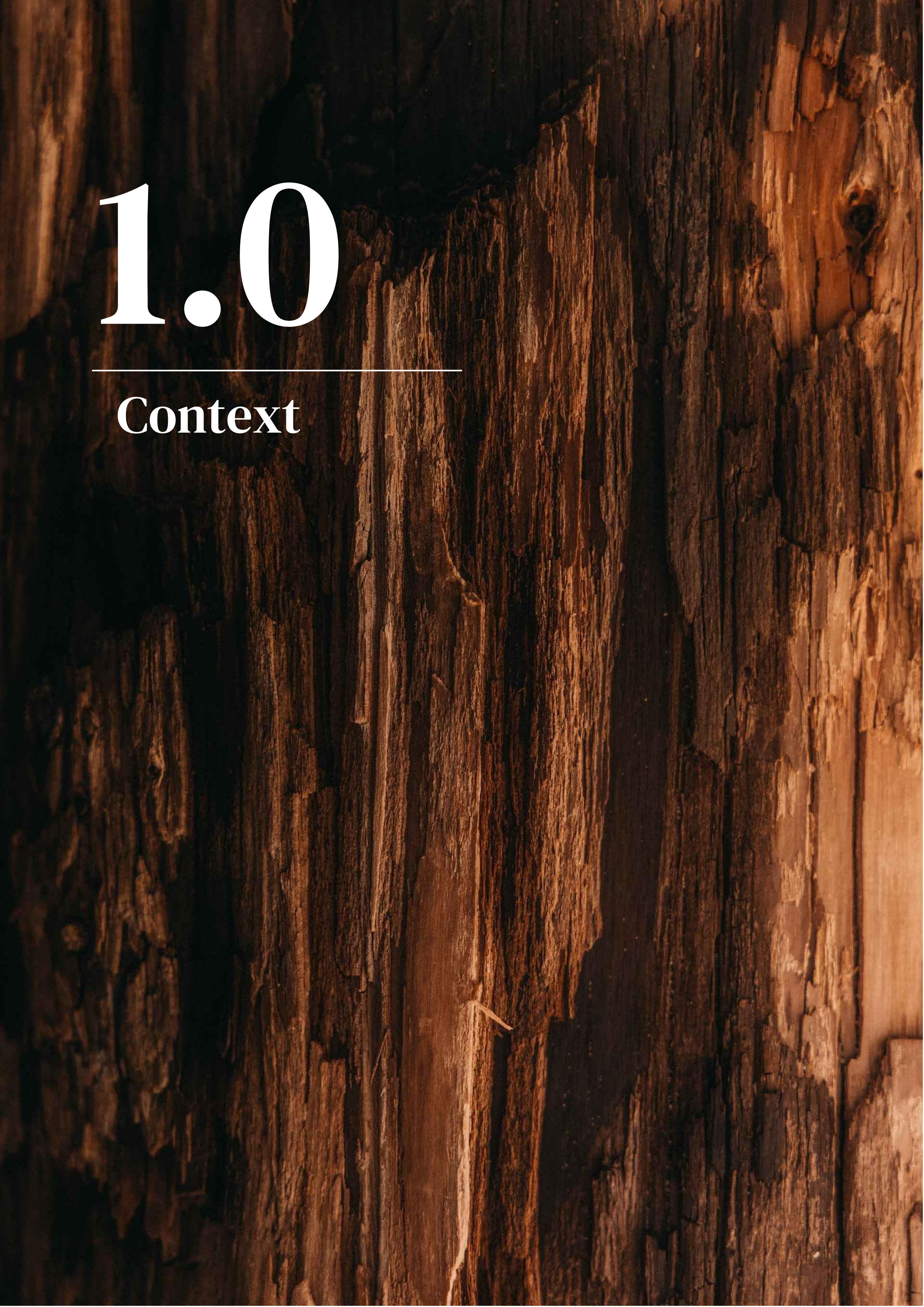
Acronyms

- AD – Anaerobic Digestion
- AS – Advanced Sorting
- ATT - Advanced Thermal Treatment
- BAU - Business as Usual
- BES-F - Best Effort Scenario - Food
- BES-P - Best Effort Scenario - Plastic
- BMW – Biodegradable Municipal Waste
- C&D – Construction and Demolition
- C&I – Commercial and Industrial
- CCC – Climate Change Committee
- CCGT - Combined Cycle Gas Turbine
- CDR – Carbon Dioxide Removal
- CCUS – Carbon Capture, Utilisation and Storage
- CHP - Combined Heat and Power
- CIF – Carbon Capture and Storage Infrastructure Fund CO_2 - Carbon Dioxide
- COP26 - Conference of the Parties 26
- CV – Calorific Value
- DAERA - Department for Agriculture, Environment and Rural Affairs
- DRS – Deposit Return Scheme
- EfW - Energy from Waste[3]
- EPA – Environmental Protection Act
- EPR – Extended Producer Responsibility
- ESA - Environmental Services Association
- ETS – Emissions Trading Scheme
- FNA - First National Assessment of Potential Heat Network Zones
- GHG – Greenhouse Gases
- GHNF - Green Heat Network Fund
- HH – Household
- HNDU - Heat Networks 5 Delivery Unit
- ICC – Industrial Carbon Capture
- IPCC - Intergovernmental Panel on Climate Change
- LCA – Life Cycle Analysis
- LPG – Liquefied Petroleum Gas
- MTL - Making Things Last: A Circular Economy Strategy for Scotland
- MBT – Mechanical Biological Treatment
- MRF – Material Recovery Facility

[3] 3 The term 'energy from waste' can include multiple processes, however this report focusses on incineration of waste, with heat and/or energy recovery

- NIR – Near Infra-Red
- NOx – Nitrogen Oxide
- POP's – Persistent Organic Pollutants
- PPC – Pollution Prevention and Control
- PPWD – Packaging and Packaging Waste Directive
- RDF – Refuse Derived Fuel
- REA – Rapid Evidence Assessment
- SEPA - Scottish Environmental Protection Agency
- SUP - Single-Use Plastics
- TWh - Terawatt hours
- The Authority - United Kingdom ETS Authority (including the Scottish, UK, and Welsh Governments, and the DAERA Northern Ireland)
- UNFCCC – United Nations Framework Convention on Climate Change
- T&S – Transport and Storage
- WRAP – Waste and Resources Action Programme
- ZWP – Zero Waste Plan
- ZWS – Zero Waste Scotland



1.0

Context

1.1 Scottish Incineration Review

The Scottish Government committed to reviewing the role of incineration in Scotland, to ensure that the management of residual waste aligns with Scotland's carbon reduction ambitions. The review (the 'Independent Incineration Review') follows a commitment – made in May 2021 by the Cabinet Secretary for Net Zero, Energy and Transport – to review the role of incineration in the waste hierarchy in Scotland. This included a shared policy programme between the Scottish Government and the Scottish Green Party, recognising the necessity of an assessment into the need for new incineration capacity.

The Independent Incineration Review, led by Dr Colin Church, covers the treatment of household (HH), commercial and industrial (C&I) and the biodegradable fraction of construction and demolition (C&D) waste streams. [4] The Review seeks to address the following broad topics:

- Given Scotland's waste management ambitions and current progress towards these, what capacity is required to manage residual waste in Scotland?
- What are the options for managing residual waste (including but not limited to, landfill, mechanical biological treatment (MBT), and biostabilisation)?
- What are the economic, environmental and social trade-offs of those residual waste management options?
- How does the Scottish Government decide where capacity should be located, and in what form?
- What can be done to improve existing residual waste treatment facilities in terms of carbon performance and societal impact?

To respond to the above topics, the Review considered existing evidence and commissioned additional capacity modelling, an appraisal of waste treatment options and a Rapid Evidence Assessment (REA) of the potential health impacts of incinerating waste. Additionally, the Review opened a Call for Evidence, allowing stakeholders to submit written and verbal evidence and considerations for the Review, which was launched in February 2022. Thus far as part of the Independent Incineration Review, capacity modelling and an options appraisal has been undertaken and published by Riccardo and a REA relating to the health impacts of incinerating waste since 2009 was conducted by Public Health Scotland. [5] [6] [7] This report builds on that work, as part of the Independent Incineration Review, by evaluating the opportunities to decarbonise the residual waste treatment infrastructure sector in Scotland.

[4] While biodegradable C&D waste was in scope of the Independent Incineration Review, it has been excluded from this current review on the basis that these wastes are generally not incinerated.
[5] Ricardo (2022) Incineration Review: Capacity Analysis. https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/incineration-review-capacity-analysis/incineration-review-capacity-analysis/govscot%3Adocument/incineration-review-capacity-analysis.pdf
[6] Ricardo (2022) Incineration Review: Options Appraisal. https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/incineration-review-options-appraisal/incineration-review-options-appraisal/govscot%3Adocument/incineration-review-options-appraisal.pdf
[7] Public Health Scotland (2022) Municipal Solid Waste Incineration and Reported Health Effects. https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/municipal-solid-waste-incineration-reported-health-effects-rapid-evidence-review/municipal-solid-waste-incineration-reported-health-effects-rapid-evidence-review/govscot%3Adocument/municipal-solid-waste-incineration-reported-health-effects-rapid-evidence-review.pdf

1.2 The Need to Decarbonise

As mentioned in Section 1.1, the Scottish Government is seeking to evaluate opportunities to decarbonise the residual waste treatment infrastructure sector, with the main focus being on waste incineration infrastructure (including that in construction and likely to be developed). These include consideration of technology changes as well as systematic changes.

Decarbonisation refers to the "declining average carbon intensity of primary energy over time". [8] Regarding waste, emissions mostly arise from decomposition of organic matter in landfills, wastewater treatment processes and combustion of residual waste in energy-from-waste (EfW) plants. [9] Although sectoral emissions have halved over the past 30 years, through a dramatic phase out of landfilling and increased recycling, there has been little improvement in the past few years due to a plateau in recycling and significant growth in fossil emissions from EfW plants.[10] While the whole lifecycle carbon impacts of Scotland's HH waste in 2020 was 5.8Mt CO_2e, an increase of 3.2%~ from 2019. Carbon impacts from incineration and landfilling HH waste were among the largest carbon contributors at 171,300t CO_2e and 244,300t CO_2e, respectively. However, currently almost all Scottish methane emissions in the wider waste sector come from landfill (1.2Mt CO_2e).[11] This carbon metric covers the entire carbon cycle in Scotland's waste, from resource extraction and manufacturing emissions to waste management emissions. Given this, the Climate Change Committee (CCC) has stated that waste sector emissions can be reduced by 75% by 2050, according to its 'Balanced Net Zero Pathway' predictions for waste.[12] In line with the highly ambitious emissions targets the Scottish Parliament is seeking to meet,, the exploratory 'Tailwinds' scenario, modelled by the CCC, assumes substantial success regarding both innovation and behavioural change, seeking to achieve net zero by 2042 and net negative by 2050.

Although a large amount of the responsibility and expectation for addressing decarbonisation lies with central government (both the Scottish Government and wider UK Government), 300 out of the 404 UK councils have declared a climate emergency with many pledging to achieve net-zero by 2030, 20 years before the UK's 2050 target. The list includes 20 out of the 32 Scottish Councils (Edinburgh, Falkirk, Fife, Glasgow, Highland, Moray, North Lanarkshire, Orkney, Renfrewshire, West Dunbartonshire, Angus, Dumfries and Galloway, Dundee, East Lothian, Midlothian, North Ayrshire, Scottish Borders, Shetland, Stirling, and West Lothian). [13]

Residual waste is a sector which requires urgent attention in order to reach net zero targets. [14] Managing these emissions is highly contingent on early legislative decisions to drive the potential change assessed in this report.

[8] IPCC (2022) Carbon-free energy and decarbonisation. https://archive.ipcc.ch/publications_and_data/ar4/wg3/en/ch3s3-4-1.html
[9] Climate Change Committee (2020) Waste. https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Waste.pdf
[10] Climate Change Committee (2020) The Sixth Carbon Budget: Waste. https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Waste.pdf
[11] Scottish Government (2020) The carbon footprint of Scotland's household waste. https://www.zerowastescotland.org.uk/sites/default/files/2020%20Carbon%20Metric%20HH%20Brief%20-%20Final%20Report%20-%20V01.00.pdf
[12] Climate Change Committee (2020) The Sixth Carbon Budget: The UK's Path To Net Zero. https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf
[13] Climate Emergency UK (2022) List of Councils who have declared a climate emergency. https://www.climateemergency.uk/blog/list-of-councils/ The list for Scotland includes: Edinburgh, Falkirk, Fife, Glasgow, Highland, Moray, North Lanarkshire, Orkney, Renfrewshire, West Dunbartonshire, Angus, Dumfries and Galloway, Dundee, East Lothain, Midlothain, North Ayrshire, Scottish Borders, Shetland, Stirling, and West Lothian
[14] Environmental Services Association (2021) A net-zero greenhouse gas emissions strategy for the UK recycling and waste sector Executive Summary. http://www.esauk.org/application/files/7316/2496/7294/ESA-Net-Zero-Exec-Summary.pdf

1.3 Overarching Objectives

The overarching objectives for this assessment are as follows:

- Evaluation of the Greenhouse Gas (GHG) emissions for existing residual waste management facilities within scope, including a categorisation based on type and volumes of waste feedstocks;
- A review of additional and alternative technologies to the current systems in use, with particular focus on the existing incineration facilities, by assessing the viability and potential impact of each option – including its technical, environmental, economic and social impacts, together with its limitations and risks;
- A high-level commentary of each of these options and combinations of options to decarbonise the existing residual waste facilities, and how these paths would change over time.

These objectives are assessed using data available in the literature, the results of the Call for Evidence and primary evidence gathered from relevant stakeholders. Modelling was also undertaken to determine how effected the assessed technologies will be at decarbonising the existing residual waste infrastructure sector in Scotland.

As such the report covers:

- the key policies seeking to achieve net zero and decarbonisation (Section 2.0.). This provides a broad view of the current drivers and barriers to decarbonisation, and how these are expected to change in future
- the carbon appraisal of residual waste treatment (Section 3.0). This details the treatment options for residual waste management, before delving into the baseline carbon appraisal resultant from our modelling.
- A carbon appraisal of residual waste treatment – decarbonisation pathways (Section 4.0). This assesses each of the technology options on a range of criteria covering, technical viability, potential costs and economic benefits, impact on emissions, wider societal impacts, and key drivers. The modelled pathways are then outlined following which the results of the modelling are summarised.

2.0

Background Policy Context on Decarbonisation

2.1 Wider Policy Landscape: Drivers and Barriers

This section details key policies that impact residual waste composition and infrastructure, and therefore Scotland's ability to decarbonise. Such policies and legislation have become increasingly relevant and prominent in recent years, creating both opportunities and barriers to the sector. Present and future policies in Scotland will be explored, alongside a high-level review of relevant UK, European and other Intergovernmental policies.

2.1.1 Net Zero Policies and Targets

This subsection provides an overview of the high-level policies and targets required to achieve decarbonisation and net zero. It covers Scottish policy alongside international targets. In combination, they aim to support the development and deployment of decarbonisation technologies, as well as promote the necessary behaviour change. However, achieving these targets is heavily dependent on appropriate solid budget allocations, some of which are not well outlined.

The latest Intergovernmental Panel on Climate Change (IPCC) report revealed that failing to limit warming to 1.5ºC above pre-industrial levels will have catastrophic impacts on the natural environment and humanity, with earth systems reaching unprecedented climatic tipping points. As such, decarbonisation was a key topic during the Conference of the Parties 26 (COP26) where Scotland, alongside countries across the globe, pledged to adopt decarbonisation measures. Key takeaways from the final conference statement thus included a commitment to reduce emissions by 45% from 2010 levels by 2030, to limit warming to 1.5ºC.[15] While the Paris Agreement sought to "make efforts" to restrict warming, COP26 produced new building blocks to advance this action through strategic, sustainable and low carbon pathways.

Ending Scotland's contribution to climate change requires a long-term reduction in GHG emissions. As such, the Scottish Government has committed to a 75% emissions reduction compared to 1990 levels by 2030 (i.e., emissions to fall from 85.1 to 21.3 $MtCO_2e$), followed by net-zero by 2045. As part of this, the Climate Change Emissions Reduction Targets (Scotland) Act 2019, introduced a world-leading net-zero goal for all GHG's, and a series of stretching targets on the path to achieving that goal.

The CCC's advice on the 6th (UK) Carbon budget mostly targets the UK as a whole; however, there are some bespoke recommendations for Scotland. For example, low-carbon capital investments of up to £5-6 billion per year by 2030 in Scotland is recommended (compared to around £50-60 billion for the UK).[16] The most ambitious scenario within the CCC's recommendations is 'Tailwinds' – a highly optimistic scenario which assumes success across developing infrastructure, innovation, societal and behavioural change. It combines the highest waste prevention and recycling rates for all HH and C&I waste (68% recycling by 2030 and 79% by 2050), landfill bans (2025 ban on biodegradable wastes, 2035 full ban), and the highest technical improvements at landfill and compost sites. CCUS also starts being installed on EfW plants from the late 2020s (and is fitted to 100% of EfW plants by 2050). The result is emissions fall further and much faster than in the other scenarios.

[15] United Nations Climate Change Conference UK 2021. COP26 Outcomes. https://ukcop26.org/the-conference/cop26-outcomes/
[16] Climate Change Committee (2020) Advice on the UK's Sixth Carbon Budget 2033-37 – implications for Scotland https://www.theccc.org.uk/wp-content/uploads/2020/12/What-the-Sixth-Carbon-Budget-means-for-Scotland.pdf

The CCC also published the tenth annual progress report to the Scottish Parliament in December 2021, which provides a general update on Scotland's progress towards the 2030 75% emissions reduction target.[17] This identified that by 2019, emissions had fallen to 44% below 1990 levels and that the Scottish Government has set laudable ambitions for emissions reductions in its Climate Change Plan update; supported to some extent by funding announcements in the most recent Programme for Government. However, the report did not establish whether and how, current policies and proposals add up to the required future emissions reductions. It recommends a comprehensive policy framework be rapidly established to implement real world actions in delivering the challenging further progress which is needed. Waste sector emissions are not well delineated within the data (since EfW emissions are accounted in the power sector). Nevertheless, a set of strong recommendations for waste are given in the annex. These include the following [abridged] recommendations envisaged to reduce Scotland's emissions:

- Publication of the review into the role of EfW and incineration in meeting Scotland's ambition to become a zero-waste nation, prioritising efforts to improve resource efficiency.
- Work with the UK Government to develop a policy and funding framework to retrofit existing EfW plants with CCS from the mid-2020s and ensure any new EfW plants are all built 'CCS-ready'.
- Bring forward the planned circular economy package within the forthcoming programme for government.
- Advance key policies such as extended producer responsibility (EPR) and confirm that the ban on biodegradable waste to landfill is extended to commercial and industrial waste.
- Detail the policy and support needed to deliver the 2025 prevention and recycling targets and set new targets for 2030.

As mentioned in Section 1.2, 20 Scottish councils have declared a climate emergency pledging to achieve net-zero by 2030, 20 years before the UK's 2050 target. Waste management will be an important factor in reaching these targets, however this is heavily dependent on appropriate budget allocations. In times of economic hardship, which is becoming increasingly prevalent in Scotland due to the recession, money will often be diverted from such areas, and thus acts as a barrier to this progression. In order to understand the economic solidity of these pledges, Climate Action has scored each council's Climate Action Plan on 'Governance, Development, and Funding', which examines who will lead the plan, the net-zero targets, the council's commitment to the plan, funding and costing, council limits and monitoring, and reviewing and updating the plan. Other criteria include mitigation and adaptation, commitment and integration, community engagement and communications, measuring and setting emissions targets, co-benefits, diversity and inclusion, education, skills, and training, and ecological emergency. Rounded percentage scores for 'Governance, Development, and Funding' for each of the Scottish Councils are detailed in Table 2-1Table 2-1. At the time of the assessment, several councils did not have a climate plan, and have thus not been allocated a score.

Table 2-1 Council Climate: Climate Action Plan Scores[18]

Scottish Council	Rounded percentage score for 'Governance, Development and Funding' (%)[19]
City of Edinburgh Council*	95
Glasgow City Council*	76

[17] Climate Change Committee (December 2021) *"Progress in reducing emissions in Scotland, 2021 Report to Parliament"*, https://www.theccc.org.uk/publication/progress-reducing-emissions-in-scotland-2021-report-to-parliament/

[18] Climate Council Plan Scorecards (2021) About the scoring https://councilclimatescorecards.uk/

[19] Examines who will lead the plan, the net-zero targets, the council's commitment to the plan, funding and costing, council limits and monitoring, reviewing and updating the plan.

Fife Council*	71
Dumfries and Galloway Council*	67
North Lanarkshire Council*	67
Midlothian Council*	62
Perth and Kinross Council	62
East Lothian Council*	56
Argyll and Bute Council	52
Dundee City Council*	52
West Dunbartonshire Council*	52
Aberdeen City Council	48
Scottish Borders Council*	48
South Ayrshire Council	48
Comhairle nan Eilean Siar	43
North Ayrshire Council*	43
Stirling Council	43
The Moray Council*	43
East Dunbartonshire Council	38
Orkney Islands Council*	33
South Lanarkshire Council	33
Falkirk Council*	28
Inverclyde Council	24
West Lothian Council*	24
East Ayrshire Council	19
Aberdeenshire Council	-
Angus Council*	-
Clackmannanshire Council	-
East Renfrewshire Council	-
Renfrewshire Council*	-
Shetland Islands Council*	-
The Highland Council*	-

** Councils who have declared a climate emergency.*

- Councils with no plan to assess when the research was undertaken.

2.1.2 Waste Prevention

Alongside having net zero targets, one way to decrease carbon emissions within the waste sector is to reduce the quantity of material becoming waste, i.e., waste prevention. Waste 'prevention' is defined in the

EU Waste Framework Directive (2008/98/EC) as measures taken before a substance, material or product has become waste. [20] This includes actions that reduce:

- The quantity of waste, including through the re-use of products or the extension of the lifespan of products;
- The adverse impacts of the generated waste on the environment and human health; and
- The content of harmful substances in materials and products.

The best form of residual waste management and progression towards net zero is by preventing waste from occurring in the first place. There are a number of policy drivers promoting prevention, published by the CCC and the Scottish Government.

The aforementioned recommendations by the CCC on the 6th (UK) carbon budget also allocates around 80% of the abatement by 2035 to waste prevention, increased recycling, and banning biodegradable waste from landfill. Advice in the report includes a reduction of edible food waste by just over 50% by 2030 (meeting UN Sustainable Development Goal 12.3) and just over 60% by 2050, compared to 2007 levels.

Scotland has outlined two major national targets for waste prevention to 2025, to reduce total waste arisings by 15% against 2011 levels and reduce food waste by 33% against 2013 levels (via the Food Waste Reduction Action Plan, 2019). [21] In 2011, Scotland disposed of almost 5Mt of waste, reducing to just under 4Mt by 2019.[22] In 2013, there was almost 1Mt of food and drink waste in Scotland: 61% from households, 25% from manufacturing, and the rest from other sectors.[23]

In line with these reduction targets, Scotland's 'Making Things Last: A Circular Economy Strategy for Scotland' (MTL), seeks to build on Scotland's progress to zero waste and resource efficient agendas by setting priorities to realise a circular economy (for further details see Section 2.1.2). These national policy drivers aim to prevent waste arisings and promote re-use, thus reducing demand on finite natural resources, minimising GHGs, reducing local authority waste management costs and encouraging social inclusion and economic development. In line with this, the public consultation on proposals for a Route Map to 2025 and beyond was launched by the Sottish Government, which sets out a strategic plan to achieve Scotland's zero waste and circular economy ambitions. [24]

Policies aimed at reducing plastic waste are important for driving decarbonisation as it is this fraction of the waste stream that holds the fossil carbon and is damaging to the environment. Conversely, reducing food waste will not help decarbonise incineration, as biogenic CO_2 emissions are not included within the carbon accounting framework. Overall, waste prevention policy influences residual waste through total reductions in tonnages, as well as potential changes to composition. There are limits to what can be achieved through waste decarbonisation in the absence of firm financial levers such as 'Pay as You Throw', aimed at HH waste (where there is a differential payment for households for recycling services compared to residual waste). Such policies are not allowed under UK law. Given the full devolution of waste among UK nations, "Pay as You Throw" policies require primary legislation before introduction into Scottish law.

[20] Legislation.gov.uk (2008) Directive 2008/98/EC of the European Parliament and of the Council. https://www.legislation.gov.uk/eudr/2008/98/article/3
[21] Scottish Government (2022) Managing waste. https://www.gov.scot/policies/managing-waste/
[22] SEPA (2022) 2020 Limited Waste Data
[23] Scottish Government (2022) Food waste. https://www.gov.scot/policies/managing-waste/food-waste/
[24] Zero Waste Scotland (2022) Delivering Scotland's Circular Economy: Route Map to 2025 and beyond. https://www.zerowastescotland.org.uk/content/route-map-to-2025-and-beyond

2.1.3 Landfill Ban

Scotland has recently adopted a ban on the disposal of Biodegradable Municipal Waste (BMW) to landfill. This policy is set to come into effect from 31st December 2025 and applies to biodegradable waste, bulky waste, mixed municipal waste, combustible waste (Refuse Derived Fuel (RDF)), and mixed packaging. This legislation seeks to address the aim of ending the practice of landfilling BMW in Scotland by 2025, with the allowance of a maximum of 5% to landfill for all Scottish waste (including all C&D waste).

This policy will ultimately impact the quantities of waste needing diversion from landfill and treatment in 2025. In the 'business as usual' scenario modelled by Ricardo for the incineration review, there is a gap in current and planned treatment capacity to deliver the BMW landfill ban (0.68 Mt) in 2025. Under a 'Best Efforts' scenario, an estimated capacity gap in 2025 remains at 0.59 Mt. Finally, in the scenario where all policy targets are achieved, overcapacity is estimated due to the high impact of waste reduction measures on total waste requiring management, resulting in a surplus treatment capacity in 2025 for the materials within the scope of the BMW landfill ban. [25]

Even with the ban of key BMW streams from entering landfill, there will still be legacy methane emissions given the generally long decay time for some materials. As food degrades quickly, this longer-term decay is more prevalent for other biodegradable waste streams, although landfill management practices aim at slowing down the commencement of decay for all landfilled wastes.

2.1.4 Recycling

Once again, alongside decarbonisation technologies and waste prevention (as aforementioned in Section 2.1.2), one further way to decrease carbon emissions within the waste sector is through recycling. Currently around 43% of all HH waste is recycled in Scotland, down from 45%, largely due to impacts from Covid-19. The Scottish Government aims to increase the recycling rate to 70% of all waste by 2025.[26]

As the shift from landfill to incineration is played out, recycling is increasingly important – notably plastic recycling. The ability to recycle plastic is quite variable depending on the characteristics of the plastic item in question. There are policies in place, discussed later in this section, that seek to promote the recycling of specific types of plastic items (e.g., plastic beverage bottles). However, despite the advancements in legislation, certain plastics – such as multi-layer films – are still very difficult to recycle. This is due to a range of factors, including:

- technical factors (e.g., being composed of different polymer types – a design-stage barrier),
- logistical factors (e.g., lack of collection infrastructure and consistency), and
- commercial factors (e.g., lack of end markets or sufficiently valuable end products to allow for commercial viability).

The current and planned legislation aims to address these barriers to varying extents. As EU policy has the potential to significantly influence recycling policy in Scotland, a description of the most prominent EU policies in this area are below. This is followed by various prominent Scottish plans and policies of relevance, alongside those present in the UK which influence Scotland.

[25] Climate Change (2022) Implementing Scotland's Landfill Ban. https://www.climatexchange.org.uk/media/5141/cxc-implementing-scotlands-landfill-ban-final-report-jan-2022.pdf
26 SEPA (2018) Waste from all sources – summary data 2018. https://www.sepa.org.uk/media/500273/waste-from-all-sources-summary-document-and-commentary-text-2018.pdf

2.1.4.1 EU Legislation

In 2018, new targets for packaging waste were adopted to achieve a minimum recycling rate by weight of all packaging waste of 65 % by the end of 2025, and a minimum of 70 % by the end of 2030. These targets have been transposed into UK and subsequently Scottish law. The **EU Packaging and Packaging Waste Directive (PPWD)** has dual objectives to continuously improve the environmental performance of packaging and to facilitate the correct functioning of the EU Internal Market, thereby protecting the free circulation of packaging and packaged goods in all Member States. The Directive also contains the **Essential Requirements** for packaging that aim to reduce packaging waste and to put forth design requirements that cater to a wide range of packaging materials and packaged goods. Packaging that meets these requirements is guaranteed free circulation in the EU. A key focus of the Directive is on the design for recycling – which is aimed at ensuring recycling of waste streams that are currently not being recycled due to their technical complexity. A key focus of that activity is on plastics, and in particular plastic film, currently poorly recycled in many European countries.

The **EU Single Use Plastics (SUP) Directive** seeks to prevent and reduce the impact on the environment of certain plastic products and to promote a transition to a circular economy. In particular, the Directive aims to tackle plastic waste through a harmonised legislative framework across the EU. It introduces a number of different measures on SUP, including market restrictions, consumption reductions, marking requirements, mandatory recycled content and separate collections and clean-up litter costs. Scotland has made significant progress towards circular economy targets, notably through the Route Map to 2025 discussed in detail in Section 2.1.4.3.

2.1.4.2 UK-wide Legislation and Commitments

Environmental Protection Act 1990

The Environmental Protection Act 1990 (EPA) defines the system of integrated pollution prevention and control (PPC) for waste avoidance, minimisation, and disposal. Scotland builds on this further with the PPC (Scotland) Regulations 2012 and the Waste Management Licensing (Scotland) Regulations 2011. In combination, they aim to regulate the management of waste, including permitting and enforcement. Ensuring waste is managed legally and robustly is key to ensuring recycling can occur.

In Scotland, businesses have a legal responsibility to dispose of their waste in a way that takes all the reasonable steps to separate a list of key materials for recycling. Such duties to the management of waste are outlined in the **EPA 1990** for the UK and have been amended by the Scottish Government to implement several actions under the **MTL** (more on this in next section). [27] This has the likelihood to impact composition, however the full extent to how this will take shape is currently uncertain.

Extended Producer Responsibility (EPR) and Sorting

The implementation and operation of well-designed extended producer responsibility (EPR) schemes for a range of products is a fundamental element in the effective transition towards a circular economy. The

[27] Legislation.gov.uk (2022) Environmental Protection Act 1990. https://www.legislation.gov.uk/ukpga/1990/43/contents

OECD defines EPR as 'an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle'. [28] [29] EPR policy is characterised by:

- The shifting of responsibility (physically and/or economically; fully or partially) upstream toward the producer and away from municipalities; and
- The provision of incentives to producers to take into account environmental considerations when designing their products.

The existing UK EPR was introduced in 1997, prior to devolution, and covers packaging (plastic, wood, metal, paper and card, fibre based composite packaging). Under the current EPR, producers do not bear the full financial responsibility of end-of-life management and are not responsible for the environmental externalities created by it. However, Zero Waste Scotland (ZWS) is currently supporting the Scottish Government in its work with the UK Government to review the EPR schemes. At present, under the EPR for packaging and packaging waste, producers must take action to minimise product packaging, reduce how much packaging waste goes to landfill, and increase the amount that is recycled and recovered. However, the current system has several shortcomings. For example, local authorities receive limited direct financial support for collecting and recycling HH packaging waste. More action is required to reduce unnecessary packaging and increase the use of reusable packaging and is expected as part of the EPR updates. A key highlight of this is the expansion of EPR to include textiles which is currently in its consultation period and is expected by 2023.

EPR is an important policy tool for managing waste produced by society. New regulations should incentivise recyclability and reusability by rewarding/penalising producers according to specified criteria. Through the application of EPR and the improved recyclability of plastics occurring through the implementation of European policy, the Scottish Government is seeking to meet or exceed the amendment to the EU Waste Framework Directive, which sets out a 70% packaging recycling target. [30] At the core of this policy is a drive to prevent materials from entering the residual stream, this is especially important for plastic packaging and synthetic fabric, due to the high fossil carbon content in these materials. It is therefore reasonable to argue that in order to meet such targets, producers via EPR could be required to cover the costs of mixed waste sorting. This will lessen the financial burned on local authorities, which as mentioned above, receive limited direct financial support in this area. Despite this, given EPR is just a principle, its success is heavily reliant on the targets set and therefore does not always achieve the aims it sets out to.

UK Plastics Pact

The **UK Plastics Pact** brings together businesses from across the entire plastics value chain within the UK Government and NGOs, to tackle the source of plastic waste. It seeks to create a circular economy for plastics, capturing their value by keeping them in the economy and out of the natural environment. Pact members will eliminate problematic plastics reducing the total amount of packaging, stimulate innovation and new business models and help build a stronger recycling system in the UK. Its aim is to ensure that plastic packaging is designed so it can be easily recycled and made into new products and packaging and with the support of governments, ensure consistent UK recycling is met. The four overarching targets of the Pact include the elimination of problematic or unnecessary single-use packaging through redesign, innovation or alternative (reuse) delivery model, 100% of plastic packaging to be reusable, recyclable or compostable, 70% of plastics packaging effectively recycled or composted, and 30% average recycled

[28] OECD (2016) Extended Producer Responsibility, Updated Guidance for Efficient Waste Management, OECD Publishing, Paris
[29] OECD, Extended Producer Responsibility, Accessed 10th October 2021, https://www.oecd.org/env/waste/extended-producer-responsibility.htm
[30] European Union (2018) Directive (EU) 2018/852 of The European Parliament and of the Council. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L0852

content across all plastic packaging. The pact is the first of a global network of Pacts, enabled by the Ellen MacArthur Foundation's New Plastics Economy.

2.1.4.3 Scottish Legislation and Commitments

The Waste (Scotland) Regulations 2012

The Waste (Scotland) Regulations 2012 require every business operating in Scotland to separate their waste for recycling. The Waste (Scotland) Regulations require that any and all organisations in Scotland present the following materials for recycling;

- Glass (including drinks bottles & rinsed empty food jars);
- Metal (including cans, tins);
- Plastic (including, drinks bottles & rinsed empty food containers);
- Paper;
- Cardboard;

In addition to the above, urban food businesses (rural businesses are exempt) producing over 5kg of food waste weekly are required to present food waste for separate collection. In line with this, disposal of food waste into public drains or sewers is illegal. Systems which dewater food waste at source and store the solid material for collection and treatment are an acceptable form of management, but only if the loss of solid matter to sewers is minimal. Systems like enzymatic digesters which do not recover any organic waste prior to it going to sewer are banned under the Regulations, as the food waste is all going into the sewer.

Additional regulations include:

- Local authorities to provide a minimum recycling service to householders.
- Waste contractors to provide collection and treatment services which deliver high quality recycling.
- A ban on any metal, plastic, glass, paper, card and food collected separately for recycling from going to incineration or landfill.
- All new incinerators must ensure that metals and dense plastics have been removed from residual municipal waste prior to incineration.

Route Map and Circular Ecconomy Bill

The Scottish Government recently launched a twin consultation on the Circular Economy Bill and a Waste Route Map . The Circular Economy Bill will establish the powers and legislative framework to support Scotland's transition to a zero waste and circular economy, and looks to increase reuse and recycling rates, and modernise and improve waste and recycling services. [31] The Waste Route Map sets out a strategic plan to deliver Scotland's zero waste and circular economy. The Route Map consultation sought views on the strategic approach to meeting waste and resources goals by 2025 and looking beyond to 2030. The priorities set out are to:

- Promote responsible consumption and production (including reducing consumption of single-use items, promoting product design and stewardship and mainstreaming reuse)
- Reduce food waste from households and businesses

[31] Scottish Government (2022) Delivering Scotland's circular economy – proposed Circular Economy Bill: Consultation. https://www.gov.scot/publications/delivering-scotlands-circular-economy-consultation-proposals-circular-economy-bill/documents/

- Improve recycling from households and businesses
- Embed circular construction practices
- Minimise the impact of disposal of waste that cannot be reused or recycled
- Strengthen our data and evidence, sustainable procurement practices, and skills and training

The Circular Economy Bill and Waste Route Map build on Scotland's MTL (2016) strategy, which sets out priorities to achieve a fully circular economy. This strategy combines the targets and ambitions from the 2013 waste prevention plan, "Safeguarding Scotland's Resources" and the 2010 Zero Waste Plan (ZWP), placing both in the context of a more circular economy. Priorities included [32]:

- Continuation of progression towards waste reduction targets
- Influence of UK wide voluntary agreements with key business sectors, to ensure delivery for Scotland, in particular in relation to food waste.
- A new Scottish food waste reduction target
- As an early step, Resource Efficient Scotland will support SMEs to both prevent food waste and adapt to the new 5kg threshold for separate food waste which came into force in January 2016.
- Investigate the potential to develop supporting indicators to assess progress on the food reduction target
- Work with the construction sector to ensure building designs consider waste reduction in both new build and refurbishment, while also enabling more reuse and recycling at end of life.
- Build capacity to deliver change in the construction sector in collaboration with the Construction Scotland Innovation Centre and other partners.
- Work to avoid depletion of primary aggregates and timber resources through enhanced recycling of demolition materials.

Scotland's Food Waste Reduction Action Plan 2019 seeks to reduce food waste by one third by 2025 (compared to 2013 levels). [33] Reducing per capita food waste by 33% was first announced in 2016 as part of Scotland's MTL strategy. This is the first of its kind in Europe and recognises the critical role of food waste reduction in the fight against climate change and the transition to a more circular, resource efficient economy. The Food Waste Reduction Action Plan additionally outlines plans to consult on a mandatory national food waste reduction target and mandatory reporting of Scotland's food surplus and waste by food businesses by the end of 2019. These targets will thusly help implement the landfill ban in Scotland, by reducing the food waste in the municipal stream.

Deposit Return Scheme (DRS)

DRS charge consumers an additional deposit fee when they purchase a drink in a single-use container. This deposit acts as an incentive to support recycling and is redeemed when the consumer returns the empty container to a return point. In addition to increasing recycling rates, a well-designed DRS should improve the quality and increase the quantity, of material collected for recycling and reuse as new packaging.

Scotland's DRS is set to come into effect from 16th August 2023, postponed from the original date of July 2022, due to prolonged impacts from the COVID-19. The scheme will be applicable to single-use drinks containers, to help improve quality and quantity of recycling, reduce litter and achieve climate change targets. According to the Scottish Government, their DRS will be among the most environmentally

[32] Scottish Government (2016) Making Things Last: A circular economy strategy for Scotland. https://www.gov.scot/publications/making-things-last-circular-economy-strategy-scotland/documents/
[33] Zero Waste Scotland (2022) Scotland's Food Waste Reduction Action Plan. https://www.zerowastescotland.org.uk/food-waste/reduction-action-plan

ambitious and accessible in Europe, including tens of thousands of return points for plastic, metal and glass containers, as well as pick-ups for online deliveries. [34] In line with this, ZWS stated DRS are the only way to meet the 90% separate collection target for plastic beverage bottles by 2029 set in the EU SUP Directive. [35]

The DRS for Scotland Regulations 2020, passed by the Scottish Parliament in May 2020, created the legal framework for the scheme. The Environmental Regulation (Enforcement Measures) (Scotland) Amendment Order 2020 has also been passed, giving additional powers to the SEPA to enforce the scheme.

New Plastics Economy

The Scottish Government is a signatory to **the New Plastics Economy** global commitment which seeks to end plastic pollution. In lieu, the government is aiming to match the EU ambition for all plastic packaging to be economically recyclable or reusable by 2030. It is not however, clear how national policy can wholly shape international packaging markets, which is a potential barrier to mitigation. Notwithstanding this, the packaging markets are expected to change in any case as a result of the policy framework set out above, and particularly as a result of the European policy activity.

2.1.5 Emissions Reduction Policy and Targets

Beyond waste management and prevention, policies to control emissions are also in place and detailed below. However, many of these policies have wide scopes and thus target emissions from numerous sources, rather than specifically focussing on waste related emissions.

2.1.5.1 UK Emissions Trading Scheme

The UK Emissions Trading Scheme (UK ETS) was jointly established on 1st January 2021, by the Scottish, UK, and Welsh Governments, and the Department for Agriculture, Environment and Rural Affairs (DAERA) Northern Ireland, which are known together as the UK ETS Authority ("The Authority"). The UK ETS was initially functionally identical to the EU ETS (however both schemes are currently undergoing consultations) and established an increase in the climate ambition of the UK's carbon pricing policy, while protecting the competitiveness of UK business. Participants in the scheme are required to obtain and surrender allowances to cover their annual GHG emissions and can purchase allowances auctioned by The Authority or trade them amongst themselves. The scheme is applied to energy intensive industries, namely the non-renewable power generation sector and includes application to regulated activities which result in GHG emissions).

Municipal waste incineration is currently excluded from the ETS. However, if incineration is included in future, as is suggested by the CCC in its letter of development of the UK ETS, then waste companies will have to obtain allowances for each tonne of CO_2 they emit when treating HH, and C&I waste. [36] This additional cost of incineration can act as an incentive for waste prevention and recycling (or other decarbonisation measures), which will then become increasingly competitive compared to incineration. Shifting waste which has not been biologically treated to landfill should be avoided and will be restricted under the BWM Landfill Ban in Scotland (though the challenges involved in enforcing a landfill ban on specific waste streams should not be underestimated). The Authority initiated a consultation period to

[34] Scottish Government (2022) Managing Waste. https://www.gov.scot/policies/managing-waste/deposit-return-scheme/
[35] Zero Waste Scotland (2019) Deposit Return Systems: an effective Instrument towards a Zero Waste Future. https://zerowasteeurope.eu/2019/07/deposit-return-systems-an-effective-instrument-towards-a-zero-waste-future/
[36] Climate Change Committee (2022) Letter: Development of the UK Emissions Trading Scheme (UK ETS). https://www.theccc.org.uk/publication/letter-development-of-the-uk-emissions-trading-scheme-uk-ets/

further develop the UK ETS, which included a package of proposals to align the ETS to net zero targets and to expand the scope of the scheme, among various calls for evidence and operational amendments. Chapter 7 of the consultation focused on waste, and specifically included proposals to include EfW and waste incineration within the scope of the UK ETS. Though responses to the consultation, which has now closed, were expected early autumn, policy updates have been pushed back. It is expected that these outcomes will be published in due course.

The EU is currently also undergoing a review of its ETS scheme and is considering bringing EfW facilities within scope of its ETS. A lack of synchronisation between these two schemes could potentially have large ramifications for how waste is treated. For example, if EfW fell within scope of the EU ETS first and this caused EfW prices to rise in the EU, Scottish (and more widely UK) waste could be diverted to landfills.

2.1.5.2 Carbon Capture, Utilisation, and Storage (CCUS)

As part of efforts to meet Scotland's net zero targets, both the Scottish Government and the independent CCC support CCUS. CCUS will serve multiple industries, of which EfW is one, aiding the shift to a lower-carbon, more sustainable economy. In doing so, it can also help create new, potentially lower carbon manufacturing processes and opportunities. CCUS is discussed in more detail in relation to its technical viability and feasibility in Section 4.1.1, while a summary of the current policy situation and notable sector commitments are provided here.

Although the Scottish Cluster was not one of the two clusters earmarked in October 2021 for initial UK government funding and support, and was instead placed on a reserve list, the Scottish Parliament's Net Zero, Energy and Transport Committee continued to take evidence and wrote in March 2022 to the Scottish and UK Governments.[37] This raised questions around what reserve list status means for Scotland's 2030 and 2045 net zero targets, in what ways did the Scottish bid not have an advantage, and what could be improved to ensure that the Scottish Cluster goes ahead in Phase Two. This is anticipated to be key to unlocking the potential for investment in CCUS in Scotland.

In support of net zero ambitions more widely, the Environmental Services Association (ESA) strategy set a collective UK waste sector ambition to achieve net zero by 2040, five years ahead of the Scottish target. One of the methods outlined to achieve this includes working to enable CCUS technology to mitigate emissions, an approach which is said to have potential for negative emissions (a claim we review in brief within Section 4.3). Negative emissions or "Carbon Dioxide Removal—CDR" refers to the removal of CO_2 from the atmosphere and permanent or at least long-term storage underground, in trees or other biomass, or in soil, minerals or the deep ocean. Due to this potential for negative emissions, all new incineration plants built are advised within the ESA Net Zero Report to be built with CCUS or to be CCUS-ready from 2025 onwards, and for all plants to be fitted with CCUS where feasible by 2040. Plants will also need to extend F-gas regulations to all sources. In discussion with UK government representatives, the UK's ESA indicated that 50% of UK incineration plants are expected to retrofit CCUS technology – this proportion being required to assisting the sector in achieving carbon neutrality in the absence of any other substantive activity.[38]

[37] Net Zero, Energy and Transport Committee (March 2022) *"Convener's letter to the Cabinet Secretary for Net Zero, Energy and Transport, Scottish Government"*, https://www.parliament.scot/-/media/files/committees/net-zero-energy-and-transport-committee/correspondence/2022/20220330_ccus_con_to_cabsec_nzet.pdf

[38] This is further implied in the ESA's net zero strategy, see: ESA (2021) A net zero greenhouse gas emissions strategy for the UK recycling and waste sector

In its Energy Strategy (2017), the Scottish Government sets new targets for 2030: [39]

- The equivalent of 50% of the energy for Scotland's heat, transport and electricity consumption to be supplied from renewable sources; and
- An increase by 30% in the productivity of energy use across the Scottish economy.

Within this strategy, CCUS goals have been outlined: [40]

- Work with industry to assess opportunities for small-scale CCUS demonstration and CO_2 utilisation projects in Scotland across a range of sources including the application of CCUS within industrial processes;
- Explore the opportunity to combine bioenergy production and CCUS, with a view to maximising the benefits for the energy system as a whole;
- Maintain pressure on the UK Government to align its CCUS strategy with Scottish energy priorities;
- Support the commercialisation of CCUS through securing a demonstrator project, building on the conclusions of the Scottish and UK Government funded research into CCUS; and
- Work with industry and the Oil and Gas Authority to ensure the retention of existing critical infrastructure, including key oil and gas pipelines suitable for use with CCUS.

In line with this, there are several pieces of environmental legislation and regulation under which the Scottish Government seeks to regulate CCUS, including but not limited to the following:

- Regulate the operators of large thermal energy generation installations under the PPC (Scotland) Regulations 2012 (known as PPC 2012). Carbon capture for the purposes of geological storage is also a listed activity under the PPC Regulations.
- Review local air quality management plans and consider how emissions from regulated installations affect UK Air Quality Standards.
- Provide advice to Scottish Government as to whether a proposed new power station has met the requirements of the carbon capture readiness guidance provided by the Scottish Government in demonstrating that there is adequate space for carbon capture and that there are no barriers to retrofitting carbon capture equipment in the future.
- As the competent authority for the UK ETS in Scotland, SEPA issue permits to eligible installations and ensure that operators comply with the system's operational rules. CO_2 captured and stored will be considered as 'not emitted' under the UK ETS.

In December 2020, BEIS set out its minded-to position on the design of an Industrial Carbon Capture (ICC) business model, which was recently (2022) under consultation and incorporates: [41]

- An up to 15-year contract (the ICC Contract) that provides the emitter with a payment per tonne of captured CO_2, which is intended to cover operational expenses, Transport and Storage (T&S) fees and repayment of, and a rate of return on, capital investment in CCUS equipment; and
- A capital grant co-funding for a portion of the capital cost of capture projects, which will be available for initial projects only and is intended to mitigate against certain risks associated with these projects.

The capital grant co-funding will be funded via the Carbon Capture and Storage Infrastructure Fund (CIF). Despite this, BEIS have remarked they will set out details later this year on the provision of a revenue

[39] Scottish Government (2017) Scottish Energy Strategy: The future of energy in Scotland. https://www.gov.scot/binaries/content/documents/govscot/publications/strategy-plan/2017/12/scottish-energy-strategy-future-energy-scotland-9781788515276/documents/00529523-pdf/00529523-pdf/govscot%3Adocument/00529523.pdf
[40] Scottish Government (2022) Oil and Gas. https://www.gov.scot/policies/oil-and-gas/carbon-capture-utilisation-and-storage/
[41] BEIS (2022) Carbon capture, usage and storage (CCUS): Industrial Carbon Capture business model. https://www.gov.uk/government/consultations/carbon-capture-usage-and-storage-ccus-industrial-carbon-capture-business-model

mechanism to fund its business model to stimulate private sector investment into industrial CCUS projects. The Scottish Cluster is one such project seeking investment via this route, and is in reserve to receive funding as part of the first round of funding (Track-1). Due to being in reserve, projects linked to the Scottish Cluster have not been shortlisted for the second phase of Track-1 funding. For the Scottish Cluster and its associated projects to receive funding via this route, the Cluster would need to be elevated from reserve within Track-1 or be successful in the next (Track-2) round of funding. Nevertheless, the cost of such retrofit and implementation is still a huge potential barrier to incinerators. Costs related to this are discussed in further detail in Section 4.1.2.2.

2.1.5.3 The Heat Networks (Scotland) Act 2021

Existing heat policy is applied on a general high level, and not to the waste sector specifically. In the general case, the considerable costs associated with heat networks and the disruption of retrofit are major barriers to implementation. However, as all buildings moving towards decarbonised heat systems (such as heat pumps) will require some type of retrofit, this barrier is not unique to the deployment of heat networks. Although, costs and complexities do vary across different heat decarbonisation technology options. Historically, little progress has been made in developing heat networks in Scotland (and across the UK), although it is currently the subject of much discussion and has recently been supported by some Scottish policy.

The Heat Networks (Scotland) Act 2021 aims to accelerate the deployment of heat networks in Scotland through the introduction of a regulatory system aimed at boosting consumer confidence in the sector and provide greater certainty for investors. The Act sets statutory targets for heat network deployment in 2027 and 2030, which are broadly equivalent to an estimated 120,000 and 400,000 additional homes being connected to heat networks respectively. Multi-building heat networks are generally anchored around large non-domestic buildings, which account for a significant portion of the heat supplied. As such it is anticipated that the number of homes which will need connecting to heat networks to meet these targets will be lower, with a significant proportion of connections being to non-domestic buildings, which are more suitable as anchors and early customers of heat networks. Though the number of domestic connections would be expected to rise once heat networks are established and being further developed. How big a role heat networks will have beyond the 2030 target of the 2021 Act, for example in meeting wider emissions reduction targets, will depend on a number of factors including location and viability relative to other zero emission solutions. This should be caveated by noting this does not specifically relate to the residual waste sector and its infrastructure. Further detail on heat networks is provided in Section 4.1.3.

The Scottish Government is currently working with the heat networks sector and local government to develop detailed regulations and statutory guidance to put a functioning regulatory system (subject to public consultation) in place by 2024.

2.2 Policy Context Concluding Remarks

Policy drivers and legislation are a pivotal tool for driving progress towards net zero and enabling the decarbonisation of residual waste treatment infrastructure in Scotland. As covered within this section, there are a range of current and future policy targets covering Scotland, the UK and international policymakers. These broadly cover high level net zero policy, waste prevention, waste diversion, and emission reduction.

Though there is significant policy in place to drive the decarbonisation of the waste sector, it is not yet clear whether they are sufficient to achieve net zero across the sector as a whole in Scotland.

3.0

Carbon Appraisal of Residual Waste Treatment - Baseline

3.1 Introduction

Addressing climate change, decarbonisation and the sustainable management of waste are pivotal societal challenges, as recognised by the Paris Agreement and other benchmark policy outlined in Section 2.0. One of the guiding principles, now enshrined in law, for Scottish waste management has been the concept of a hierarchy of waste management options, where the most desirable option is waste prevention and the least desirable is to dispose of the waste to landfill with no recovery of either materials and/or energy. Between these two extremes there are a wide variety of waste treatment options that may be used as part of a strategic approach to waste management to recover, process or reprocess materials, or generate energy.

This section of the report focuses on the main treatment options used for residual waste[42] (Section 3.2), and describes their 'baseline' carbon impact associated in Scotland – i.e., the current and expected future GHG emissions associated with Scotland's residual waste management if additional decarbonisation options are not deployed beyond the current level (Section 3.3.3).

3.2 Treatment Options

This section provides a brief overview of the main treatment options for residual waste management in Scotland.

3.2.1 Landfill

Landfill is the deposit of waste into or onto land. Since the technique is well established there are less potential unknown risks from implementation and management. However, this is not to say that there are no risks associated with landfill. Environmental risks, including emissions (particularly methane), leaching and pollution are exceedingly high with this option. Leachates have the capacity to widely disperse through aquatic and terrestrial systems, impacting wetlands and natural ecosystems in the vicinity. Furthermore, some sites are potentially at risk of flooding and erosion, both of which could endanger wildlife. Also, whilst higher temperatures (which can be expected as common place in the future) accelerate the waste degradation of landfills, they also result in higher leachate chemical oxygen demand and ammonium nitrogen concentrations. This will prolong the landfills' aftercare period in order to meet the effluent discharge limits. This has also been corroborated by the IPCC, who in their latest report, warned that landfill emissions will increase with warming due to enhanced decomposition with higher temperatures. [43]

The technology is widely used in part because the cost is relatively low in comparison to other residual treatment technologies – in part because of its relatively low technical complexity. However, landfill is associated with relatively high GHG emissions in comparison to other forms of residual waste treatment and are a relatively significant source of anthropogenic methane emissions, which are 28-34 times that of CO_2 over a 100-year GWP (this increases to 84-86 times measured over 20 years).[44]

Emissions arise from the landfill gas that escapes the landfill's gas capture systems. There is relatively little scope for avoided emissions although some energy generation occurs at landfill sites, with the captured gas

[42] Residual waste is waste that is from households, or is alike to waste from households, and which is collected as a mixed stream (i.e., not separately collected for recycling). It comprises household waste collected by local authorities and similar ('bin type') waste from commercial and industrial sources.
[43] IPCC (2021) Climate change widespread, rapid, and intensifying – IPCC. https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/
[44] UNEC (2022) The Challenge. https://unece.org/challenge

being used for electricity generation. Decarbonisation activity for this type of technology relates to improvements in landfill gas capture technologies. The performance of landfills in climate change terms improves as more biowaste is captured for recycling, as such performance would also be expected to improve as the landfill ban is implemented.

The storage of carbon in landfills can offer potential for GHG emission reduction. Some materials – such as plastic – do not decompose, and if not recycled, the alternative form of treatment would likely be incineration – which would result in emissions into the environment. As such, until all forms of plastic are more readily recyclable and the material is more successfully reprocessed for recycling markets, storing plastic in landfill could be considered as a lower impact option. Similarly, carbon in slow degrading organic materials like wood can also be effectively stored in landfills. This is particularly the case for treated wood, where decay is prevented by the chemical treatment.

While landfilling plastic can be a form of carbon storage, it should be noted that this this is not appropriate for Persistent Organic Pollutant (POP) containing waste (often small WEEE and furniture items), for which the regulation requires incineration. Landfill carries ongoing risks of environmental pollution, which must be balanced against the benefits and risks of alternate management approaches.

3.2.2 Incineration

Incineration refers to conventional incineration of waste, which tends to involve energy recovery. Energy generation occurs using a steam turbine with a maximum electricity generation efficiency in the order of around 30% (this is lower for smaller facilities). It is difficult for the facilities to go much higher than this because of the toxicity of the flue gases; this sets a ceiling on the temperature at which combustion processes treating municipal solid waste can operate.[45]

Although combustion itself is a relatively simple technology, technical complexity is added to incinerators through the need to manage the air pollution that arises from combusting a relatively heterogenous stream of material. These systems are well established and as such the technology is widely used in the UK and Europe. The risks associated with technical implementation are therefore relatively low. Incineration typically results in both energy generation and the recovery of some metals for recycling and these activities both result in avoided emissions where such activities are considered in carbon assessments.

As was indicated in Section 3.2.1, in recent years quantities of waste incinerated have increased in Scotland, and landfill reduced. European and Scottish waste policy, such as the landfill tax and BMW landfill ban, has helped to ensure this transition occurred, much of which has been aimed at reducing waste sent to landfill. A key factor in this is the higher carbon emissions associated with landfill in comparison to incineration. This is in large part because of the energy generation benefit associated with incineration. Benefits associated with this are reasonably substantial where grid electricity is generated with fossil fuels such as coal and gas – which was historically the case in Scotland. However, such benefits are anticipated to decline as electricity grids decarbonise, eroding much or all of the climate change benefit seen for incineration relative to landfill. This benefit is highlighted by Client Earth to prevail until around 2035. [46]

Given this balance, the Review found that currently, incineration is less damaging to the environment than landfill. However, increased incineration, predicted changes to waste composition and wider

[45] Wang W and Liu Z (2020) Principle and Protective Measures of High temperature Corrosion of Garbage Incineration Boiler, Journal of Physics doi:10.1088/1742-6596/1635/1/012087
[46] Client Earth (2021) Greenhouse Gas and Air Quality Impacts of Incineration and Landfill. https://www.clientearth.org/latest/documents/greenhouse-gas-and-air-quality-impacts-of-incineration-and-landfill/

decarbonisation will make this less favourable in the future when compared to alternative methods for decarbonising the waste sector, as is described in Section 4.1. In addition, it has been revealed that air pollution impacts are somewhat higher for incineration plants relative to landfill – with such facilities being a source of Nitrogen Oxides (NOx) and particulates in particular, when considered on the basis of the external costs of such pollution using the UK government's approach to appraising air pollution.[47] There is scope for further mitigation of the NOx pollution but high performing technologies in this respect are not uniformly applied to the incineration fleet in Scotland .

3.2.3 Gasification

Gasification is considered an advanced thermal technology (ATT) and involves the partial oxidation of a substance at elevated temperature in a low oxygen environment. [48] Unlike incineration, untreated mixed residual waste is generally inappropriate for gasification because facilities are sensitive to inputs outside of a strict material specification; feedstock preparation generally requires sizing, possible drying, removal of non-desirables, and possible blending to stick within the desired specification.

In addition to feedstock challenges, problems related to tarring, blockages and reduced operational efficiencies can occur. The greater technical challenges and increased risks compared to incineration have led to some high-profile plant failures and inefficiencies at several pilot and commercial scale facilities. Costs are usually higher for gasification processes than is the case for incineration due to the greater technical complexity of the systems. Although the UK market is generally moving away from gasification, Scotland has two operational ATT facilities (see Table in A 1.1.2).

Gasification technologies theoretically have the scope to produce more energy than incinerators where the syngas is burnt in a gas engine. This adds complexity, however, and has not been achieved at commercial scale in Europe. Most facilities burn the syngas in a steam turbine. This results in energy losses associated with the syngas conversion stage and, in turn, usually less energy generation than incinerators. Gasification facilities also tend to be smaller than incinerators. As such, gasification facilities do not usually perform better than incinerators with respect to climate change emissions.

Since there is typically lower air flow in gasification facilities, there is theoretically less air pollution (for pollutants such as NOx and particulates) than is the case for incineration plant. In practice, the increase in technical complexity has tended to result in higher emissions than is the case for incinerators.

3.2.4 Mechanical Biological Treatment (MBT)

MBT is a generic term for the integration of several mechanical and biological processes. MBT typically utilise residual waste from HH, C&I sources. MBT plants may be configured in a variety of ways to sort and partially treat waste. The process involves size reduction and sorting of the residual waste into different components, which are typically separated into recyclable fractions, RDF, contaminants and organic rich fractions. MBT plants can dry and reduce the biodegradability of BMW. It is not considered a final treatment destination, as outputs from the process, such as RDF, still require further treatment.

A key element of the MBT processes is the recovery of materials for recycling. This has scope to reduce emissions of waste sent to incineration in particular where the plastics are recovered for recycling. In

[47] Data are presented for example in Eunomia (2020) Greenhouse Gas and Air Quality Impacts of Incineration and Landfill, Report to Client Earth
[48] Defra (2013) Advanced Thermal Treatment of Municipal Solid Waste

practice, however, due to current market conditions most MBT facilities in the UK do not recover much plastic for recycling.

MBT systems are widely used in Europe, but some facilities operating in the UK have historically experienced operational and commercial difficulties (particularly in the case of high disposal prices for RDF). Emissions from MBT's with biodrying systems operating in the UK are typically fairly similar to that of incineration. Conversely, MBT's with stabilisation systems can be associated with lower costs than is the case for incineration as the technology is relatively low in complexity.

3.2.5 RDF Export

RDF is typically pre-treated, baled residual waste, which is suitable for export to be utilised for recovery of energy in an EfW facility or other suitable facilities. From Scotland, RDF tends to be exported to other destinations within the UK, as well as to Europe. While exports outside the EU do take place, these are set to be limited and, to certain destinations, even banned under the EU Waste Shipment Regulation revisions. Despite this, given the UK has left the common market, these changes will not apply to the UK and as yet, there is nothing in the pipeline to replicate this in UK law. Where waste is sent overseas, some treatment – typically metals recovery and shredding – is necessary to meet the shipment regulations.

Environmental impacts depend on where the waste that is exported is being sent for incineration. Such appraisals need to consider not only the energy generation efficiency of the recipient EfW or ATT plant, but also the extent to which electricity and heat systems in that country have been decarbonised. Although energy generation performance of large European facilities can be much higher than incinerators currently in operation in Scotland, Scotland has committed to fully decarbonise their electricity supply by 2035. In fact, in 2020, the equivalent of 98.6% of gross electricity consumption came from renewable sources (up 89.8% from 2019).[49] Some countries, such as Sweden, have also significantly decarbonised their energy systems, which somewhat negates the benefit of higher energy generation performance in climate change terms. There are also impacts associated with transporting the waste, although those associated with shipping tend to be relatively modest.

Air pollution impacts from the pre-treatment process are negligible, so much of the impact relates to what happens when the waste is incinerated. Impacts may be lower in some countries which have stricter permit limits than is the case in the UK – this is the case with Dutch incineration facilities, for example.

Pre-treatment of the waste is relatively simple and as such technical risks associated with treatment are relatively low, as are costs. There can be risks associated with fuel offtakers no longer accepting the material – this has been the case in the past with shipment to cement kilns during economic downturns.

3.3 Baseline Carbon Appraisal

Based on these treatment options, a baseline of the carbon impacts was appraised. Below, the scope, overview of approach, and the resulting baselines are described.

[49] Scottish Government (2021) Annual energy statement and quarterly statistics bulletin: December 2021. https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2018/10/quarterly-energy-statistics-bulletins/documents/energy-statistics-summary---december-2021/energy-statistics-summary---december-2021/govscot%3Adocument/Scotland%2BEnergy%2BStats%2BQ3%2B2021.pdf?forceDownload=true

3.3.1 Introduction to Approach

In modelling the potential carbon impacts associated with residual waste treatment, the scope of the emissions accounting covers the following activities and impacts:

- Direct emissions such as those arising from the combustion of waste streams;
- Impacts arising from energy use at facilities;
- Avoided emissions. These arise as a consequence of energy being generated via the waste management process (combustion of landfill gas in a gas engine or energy generation at incinerators) which therefore negates the requirement for energy to be generated elsewhere. They also include emissions avoided by dry recycling (for incinerators, this relates to the recovery of metals from bottom ash[50]).

When modelling organic waste streams in particular, the treatment of biogenic carbon becomes an important consideration. Emissions of biogenic CO_2 are typically ignored in life cycle assessments. Carbon in natural materials such as paper is sequestered during plant growth. When materials degrade in natural systems, the carbon sequestered during growth is then released back into the atmosphere as CO_2. By convention, the release is ignored in inventories because within the course of a year this would effectively double count the carbon that was taken up. The same convention has been typically applied in life cycle assessments: as such, only fossil CO_2 emissions are accounted for when waste combustion occurs.[51] The approach causes problems when take up was some time before the release – since, in effect, carbon is being sequestered over this time period. For this reason a credit for carbon sequestration is applied in this case; Eunomia's models include this where biogenic carbon is stored in landfill. A similar approach is also taken for carbon sequestration occurring as a result of carbon capture and storage.

The above approach is applied to all residual waste flows. Emissions factors are developed on the basis of one tonne of waste being treated – with such factors being specific to the type of waste being treated. Thus, specific emissions factors are developed for paper, plastics, ferrous metals, etc.

Full details of the methodology are set out in the Appendix.

3.3.2 Scenarios, Waste Volumes and Infrastructure

The modelling was carried out to examine the GHG impacts associated with the residual waste treatment facilities required to manage the HH and C&I residual waste in Scotland. Both current and future scenarios have been considered. The 'current scenario' refers to the year 2020, the latest for which the HH recycling rate is available for Scotland at the time this work is completed. The future baseline scenarios (i.e., possible future situations without additional residual waste policy implementation) consider the situation for 2035, accounting for the following:

- Changes in source separated recycling by this time - which impact on the modelling by changing the residual waste composition and the amount of waste that is sent to residual treatment. In particular, future recycling rates of glass, aluminium and plastic reflect possible achievable capture rates typically associated with DRS schemes and with improved design for recyclability for plastics;
- New residual treatment facilities coming online (and some closing);

[50] The credits associated with using IBAA as a replacement for quarried stone have not been included as it is associated with negligible carbon benefits

[51] Biogenic methane emissions are included since this activity is considered to be anthropogenic.

- Changes in the GHG impacts of electricity and heat generation/use, compared to the current scenario.

The year 2035 was selected because it represents a point in time in which all the planned and consented facilities would be operational. Additionally, selecting a year that is further away in the future would have increased uncertainty of the scenarios, particularly around waste quantities, composition, and the energy grid impacts. However, it allows time for some policy implementation and deployment of decarbonisation technologies.

This work focuses on the residual waste treatment only, and does not consider other aspects beyond this scope, such as the recycling credits associated with separately collected materials.

The four scenarios that have been explored in this work are detailed in Table 3-1.

Table 3-1: Baseline Scenarios Modelled

Current	This scenario considers 2020 information, with recycling rates and waste tonnages as described in Table 3-2.
Business As Usual (BAU)	This scenario **is forecast to** 2035, with recycling rates and waste tonnages as described in Table 3-2. An improvement in recycling rates compared to the baseline is predicted on the basis of a slow but steady increase in recycling equivalent to the rate of progress seen over recent years. This functions as a "worst case scenario" in relation to achieving recycling ambitions.
Best Effort Scenario - Food (BES-F)	This scenario **is forecast to** 2035, with recycling rates and waste tonnages as described in Table 3-2. A notably increased food waste collection is assumed. Thus, this baseline assumes that progression in organics collection rates is due to increased collection service provision of food for households and businesses, strong communications, and higher uptake and engagement. The advancement in plastics capture is less successful (compared to BES-P, described below). The recycling rates of the other waste streams are equal to the BAU scenario.
Best Effort Scenario - Plastic (BES-P)	This scenario **is forecast to** 2035, with recycling rates and waste tonnages as described in Table 3-2. It is assumed that plastic capture increases, as well as food capture, to achieve the overall recycling rate. Compared to BES-F, this scenario has a residual composition of slightly more food and slightly less plastic. The recycling rates of the other waste streams are equal to the BAU scenario.

The tonnages of residual waste, both current and predicted, together with the relative recycling rates, are presented in Table 3-2. [52] These have been extracted from the analysis completed by Ricardo on the future residual waste infrastructure capacity in Scotland[53]. The BAU scenario considers an overall increase of recycling rate of ca. 0.4% per year between 2018 and 2050, while the BE Scenarios take into account an overall average increase in recycling of 0.5% per year between 2018 and 2050. The analysis from Ricardo was completed using 2018 as a baseline year. Since this was completed, the real recycling rate for HH in

[52] The total recycling rates obtained in this work may slightly differ from those predicted by Ricardo, to reflect policy introduction while creating consistency between the various scenarios. The actual recycling rates per material stream are presented in the appendix

[53] Ricardo for Scottish Government on behalf of the Independent Review of the role of Incineration in the Waste Hierarchy of Scotland, Incineration Review Capacity Analysis, April 2022, https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/incineration-review-capacity-analysis/incineration-review-capacity-analysis/govscot%3Adocument/incineration-review-capacity-analysis.pdf

2020 was published by SEPA, and this has been used in this work. [54] The relative tonnage for HH residual waste in 2020 has been calculated accordingly.

Table 3-2: Recycling Rates & Residual Waste Tonnages[55]

Waste Stream	2020 Recycling Rate	2020 Residual Waste (t)	BAU - 2035 Recycling Rate	BAU - 2035 Residual Waste (t)	BES[56] - 2035 Recycling Rate	BES[56]- 2035 Residual Waste (t)
Household	42.0%	1,372,844	50.6%	1,190,000	55.0%	1,080,000
C&I	58.3%	930,000	61.6%	550,000	65.1%	500,000

The list of facilities that have been considered in the model is presented in A 1.1.2. The modelled available capacities split by technology are shown in Table 3-3. In line with Scottish, UK, and European waste policy, we assume residual waste treatment will always be about the "least worst" option, after all other prevention, reuse, and recycling options have been eliminated. However, we note the nature of those "upstream" policies as outlined in Section 2.0, may impact the composition of residual waste arising and this may affect the impacts of different management routes. Therefore, this study only comments on the implications of specific compositions, or the technical requirements for specific compositions, in relation to waste treatment technologies

Table 3-3: Modelled available capacities split by technology

Technology	2020 capacity (tpa)	2035 capacity (tpa)
MBT/Biostabilisation	40,000	0
MBT/RDF	332,759	502,759
EfW	580,000	1,456,000
ATT	198,800	198,800

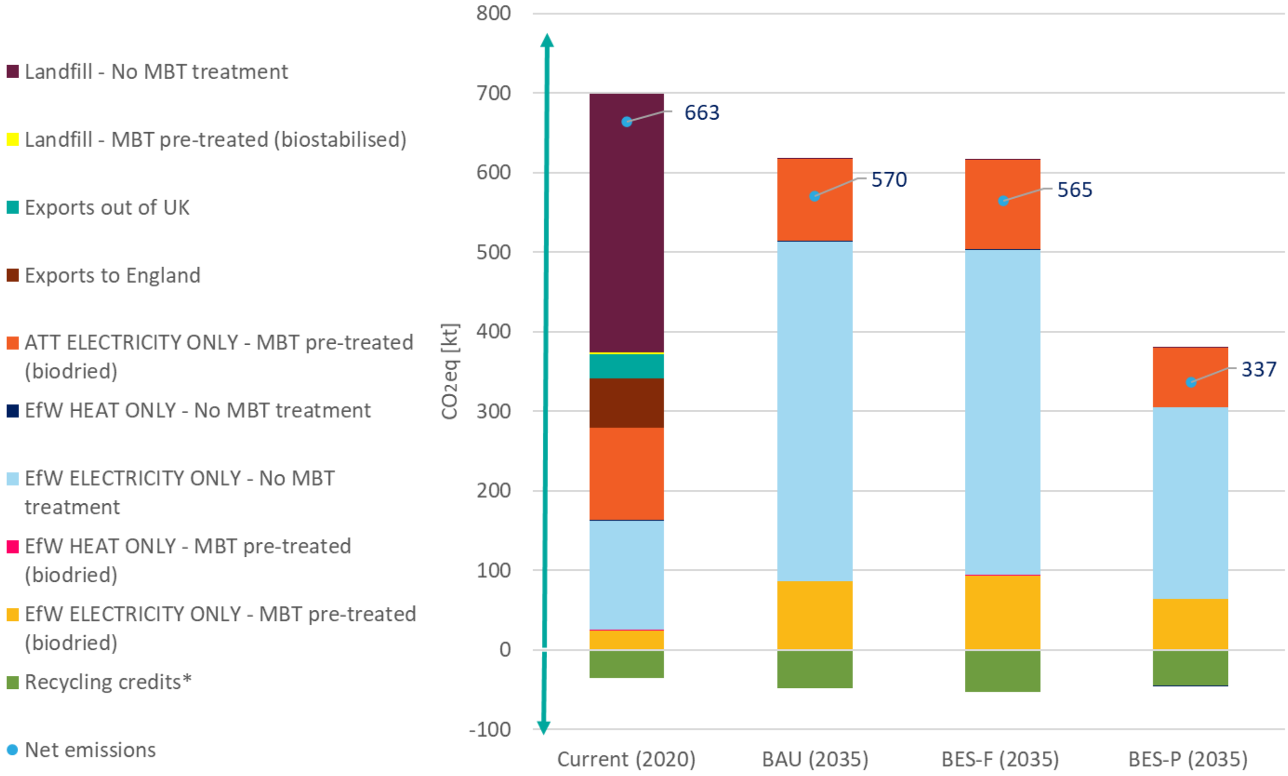
The assumptions used in the model of the baseline scenarios, including composition, capture rates, emission factors and plants efficiencies, are detailed in Section A 1.1.

3.3.3 Carbon Emissions Baseline: Current and Future

Figure 3-1 shows the emissions associated with the residual waste infrastructure for the scenarios described in Table 3-1. A more detailed breakdown of these results is provided in Appendix A 3.1.

[54] https://media.sepa.org.uk/media-releases/2021/official-statistics-publication-for-scotland-household-waste-summary-jan-dec-2020-waste-landfilled-in-scotland-2020-and-waste-incinerated-in-scotland-2020-statistics.aspx#:~:text=Household%20waste%20recycled%20and%20landfilled,main%20driver%20behind%20this%20reduction
[55] Ricardo for Scottish Government on behalf of the Independent Review of the role of Incineration in the Waste Hierarchy of Scotland, Incineration Review Capacity Analysis, April 2022, https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/incineration-review-capacity-analysis/incineration-review-capacity-analysis/govscot%3Adocument/incineration-review-capacity-analysis.pdf
[56] BES-F and BES-P scenarios have the same amount of waste and the same overarching recycling rates

Figure 3-1: Current and Future Baseline Annual Residual Waste Emissions, Split by Treatment Route



*Note: the credits associated with recycling of metals from bottom ash are directly subtracted from the emission of EfW, and are not included in "Recycling". For a clear split of credits and direct emissions, please refer to the chart in Section 4.3

The following considerations on the baseline results can be made:

- In the current baseline case, using the accounting methodologies described in Section 3.3.1, residual HH and similar C&I waste is responsible for about 660kt CO_2e emissions per year. This represents just less than 1% of Scotland's GHG inventory totals where the impacts are considered on a consumption basis (emissions were 70.4Mt in 2018 on this accounting method)[57]. Impacts are around 2% where the territorial emissions inventory approach is used. Assuming Scotland is to achieve its 2045 net zero target, the waste sector needs to reduce these impacts in the future. The BAU and BES baselines show that progress is expected to be made towards reducing residual waste emissions through reductions in residual waste[58] – but that more action is needed to achieve the net zero target. In this respect, waste prevention activities can also potentially play a part but are out of scope for this analysis;
- In the current baseline, landfill accounts for almost 50% (48.8%) of the total emissions. In all future scenarios sufficient capacity of incinerators is present, no waste is sent to landfill and the impact associated with landfilling disappear (apart from that associated with a fixed 1% of C&I waste which is unsuitable for thermal treatment and assumed to be still directed to landfill, as described in Appendix A 1.1.1);
- In the future scenarios, the total recycling rates have progressed towards circular economy targets, adding ~5% in the BAU or ~10% in the BE scenario to the total recycling rate compared to the current scenario, leading to an overall reduction in residual waste tonnages. The differing source

[57] https://www.gov.scot/news/scotlands-carbon-footprint-1998-2018/
[58] The focus on the residual waste sector within this report means that benefits from source separated recycling activities are in scope here.

separated recycling outcomes in the different future baseline scenarios leads to different residual waste compositions, which in turn impacts on emissions from residual waste treatment;

- Given the study only considers residual waste, the carbon benefits of recycling associated with kerbside collection are not accounted in the results. The recycling benefits shown are associated with the capture of recyclables from MBT facilities. It is important to observe that if the recycling credits associated with waste captured at kerbside (or through alternative source separation collection methods) were considered, these would have a higher beneficial impact on emissions on the scenarios with highest recycling rates (BES);
- In all future scenarios, given the forecast surplus capacity of incinerators, no tonnages of waste are predicted to be export from Scotland, hence no impacts associated with exports are reported;
- The BAU scenario shows the shift away from landfill towards incineration. In this scenario there is some progress towards recycling and as such, the amount of plastic (among others) in the waste stream decreases. However in spite of the increased recycling, the impact per tonne of waste of EfW with electricity generation only is higher in the BAU scenario (0.351 t CO_2e/tonne) than in the current scenario (0.274 t CO_2e/tonne), as reported in Table 3-4 and Figure 3-2. This is due to the fact that the energy credits associated with the electricity generated through incineration of waste decrease as the electricity grid decarbonises in the future, as detailed in Appendix A 1.1.6.1;

Table 3-4: Impact per tonne of waste of EfW with electricity generation for the Current and BAU scenarios

Technology	Current (t CO_2e/tonne)	BAU (t CO_2e/tonne)
EfW Electricity only - No MBT treatment	0.274	0.351

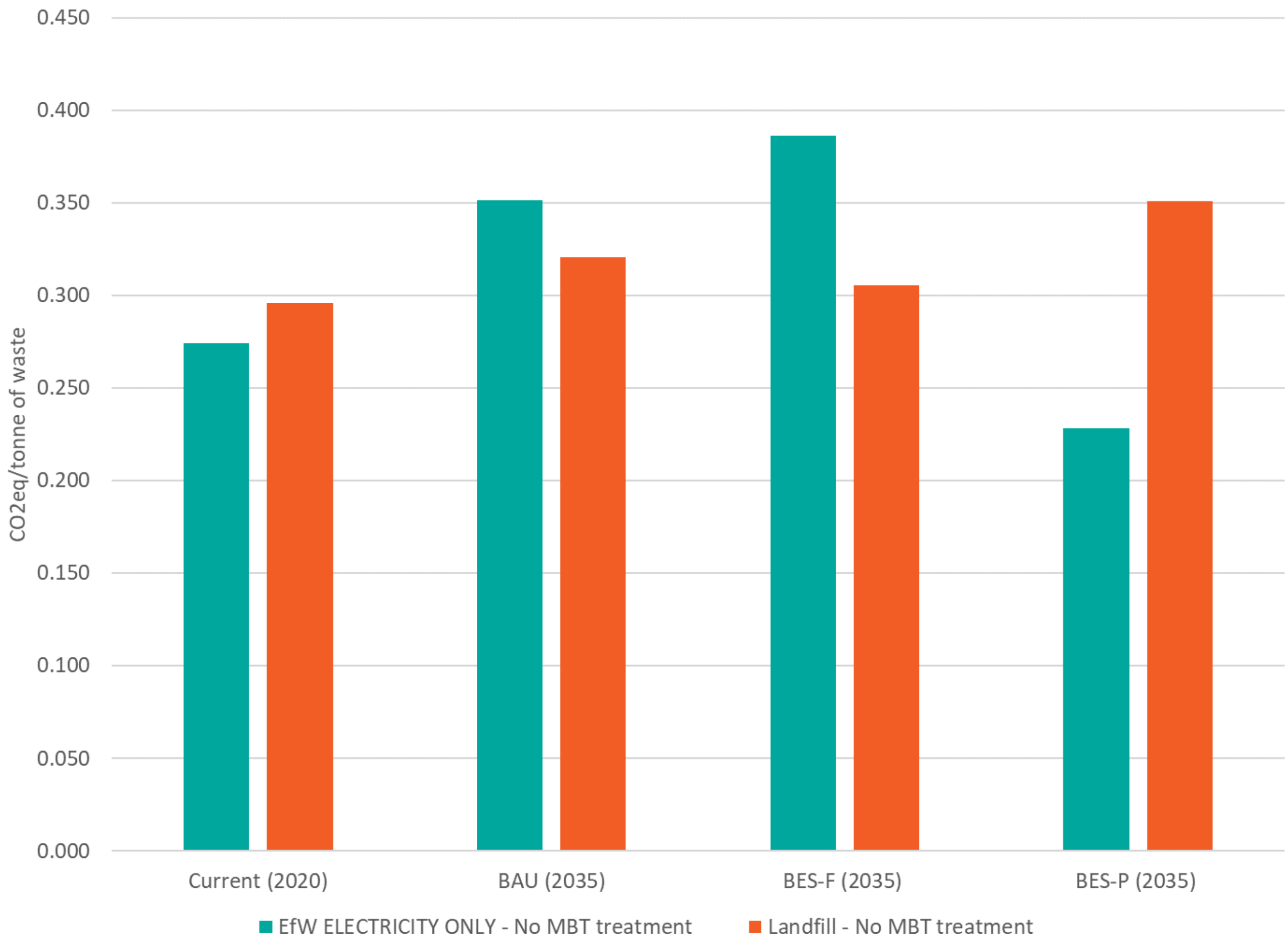
- In the BES-F scenario, levels of plastic waste compared to food waste are relatively high as the quantity of food waste recycled is assumed to increase significantly. As such, the impact per tonne of waste of EfW with electricity generation (0.386 t CO_2e/tonne) is higher than the impact per tonne of waste of landfill (0.305 t CO_2e/tonne). For the BES-P scenario however, EfW has a lower impact (0.228 t CO_2e/tonne) than landfill (0.351 t CO_2e/tonne), as reported in Table 3-5 and Figure 3-2; this is due to the low percentage of plastic present in the residual waste in this scenario as a consequence of the higher recycling of that material.
- Removing plastics from residual waste is vital to lower the impact of incineration per tonne of incinerated waste;

Table 3-5: Impact per tonne of waste of EfW with electricity generation and landfill for the BES-F and BES-P scenarios

Technology	BES-F (t CO_2e/tonne)	BES-P (t CO_2e/tonne)
EfW Electricity only - No MBT treatment	0.386	0.228
Landfill - No MBT treatment	0.305	0.351

- Although performance improves under the BE scenarios compared to the current and BAU ones, residual waste is still a net contributor of CO2e.

Figure 3-2: Impact per tonne of waste of EfW with electricity generation and landfill for the different scenarios



<u>**Note**</u>: The emissions accounting in this chart (as in others within the report) excludes biogenic CO_2 emissions, includes a carbon credit for sequestered biogenic carbon (used to assess here the impact of the long-term storage of biogenic carbon in landfill), and includes avoided emission benefits associated with exported energy. Comparative results for EfW with advanced sorting, and EfW with CCUS, are provided within Table 4-4 later in this report.

4.0

Carbon Appraisal of Residual Waste Treatment - Decarbonisation Pathways

4.1 Decarbonisation Technology Options

As outlined in Section 2.0, a host of policy and legislation exists to drive Scotland towards a net zero economy. Given the waste sector has a huge role to play in this effort, here we explore potential technology options to drive this progression and the decarbonisation of existing residual waste treatment infrastructure in Scotland. Four main technology options are assessed below:

- Advanced Sorting (AS);
- Carbon Capture, Utilisation, and Storage (CCUS);
- Heat Recovery; and
- Biostabilisation.

4.1.1 Advanced Sorting (AS)

Successful recycling relies on effective and efficient sorting. However, large quantities of recyclable material currently still end up in the residual waste stream. AS, particularly of plastics, can reduce fossil-derived CO_2 emissions from incineration, as well as reduce emissions by limiting the need for primary materials. Given this, separating these different elements is crucial for recovering valuable materials, minimizing the amount of material sent to landfills, and allowing recyclable materials to find a new purpose. It also supports Scotland in reaching its recycling targets, particularly in areas where these might be more difficult to reach (due to being highly rural, having high flat density within the housing stock, etc.).

It is recognised that it is not practically possible to remove 100% of a material stream, including plastics, from the residual stream, nor to stop recyclable materials from entering the residual stream. This is considered particularly unlikely by 2035 as this would require stark behavioural changes on a national level. It would also require the further development of end markets for the recycled materials, as not all plastics have stable end markets currently, to act as drivers. Moreover, to prevent plastics from entering the residual stream in the first place, they must be designed to be technically recyclable, which is not currently the case for a vast array of plastics.

4.1.1.1 Technical Viability

There is a wide range of sorting and separating technologies on the market today (magnetic, near infra-red (NIR), robotic, sensor-based, induction, etc.). These are used in combination to separate key recyclable material streams, based on key characteristics of the targeted items. Sorting is done across Europe to varying levels of effectiveness. Overall, most technologies are well established across Europe and are relatively low risk. However, certain characteristics of the waste streams can add technical complexity, particularly in relation to plastics.

Plastics fractions contained in complex waste streams may not be easily sortable nor available in sufficient amounts to make mechanical recycling a viable solution from both an economic and environmental standpoint. Currently, only certain types of plastics hold value in being recycled. Black plastics are particularly hard to sort as their colour makes them difficult for machines to spot, plastic films are problematic due to their capacity to jam sorting machinery, and low-density polythene needs to be chemically recycled. Furthermore, alternative options such as chemical recycling also come with technical complexities and other challenges. As such, to achieve recycling targets, a significant advancement on **design for recycling** (alongside other technical and market developments such as a maximisation of source segregation, wash plants, chemical recycling, and stable markets) is required – alongside the development of sorting infrastructure. It is anticipated that the implementation of European legislation set out in Section 2.1.4.1 will greatly assist in ensuring that this is the case by 2035. **Additional infrastructure** would be needed in Scotland to deliver the required sorting capacity. This could be in the form of:

- New stand-alone sorting sites;
- Increasing or adding sorting capacity to existing waste management sites such as transfer stations, material sorting facilities (MRFs), or MBTs; and
- Front end sorting at EfWs and ATTs.

These all will require additional space, either at an existing site (e.g., an EfW), or at an off-site location. Sites for incineration may be spatially constrained so that a straightforward retrofit might not always be possible. Furthermore, incineration plants often treat large quantities of waste so that if the whole of the residual waste stream was to be treated in one location, the size of the facility, and the associated footprint, may be significant. In some circumstances, spatial constraints could be overcome through creative design of the layout of the facility: the type of processes being considered lends themselves reasonably well to 'multi-storey' designs, although this might be expected to increase costs. Thus, there are likely to be operational and technical constraints. There are limitations on the characteristics of the wastes that can be fed to the incinerator itself, the spatial requirement of retrofitting the equipment, and the cost effectiveness of the process.

Another technical implication of sorting is the change in composition of the residual stream, and in turn its calorific value (CV). Both EfWs and ATTs have defined ranges of acceptable CV, and their throughput is dictated (in part) by this (boilers can burn less waste of higher CV, and vice versa). Variable CV levels can lead to combustion irregularities.

4.1.1.2 Potential Costs and Economic Benefits

Costs for AS are highly variable and largely dependent on facility size – with smaller facilities tending to be more expensive on a per tonne basis. The overall balance of costs depends on material revenues and avoided disposal costs – not just the cost of installing and operating sorting processes. Any given site can install as many or as few pieces of sorting equipment as deemed feasible and cost effective, which cannot be easily generalised at a national level across multiple potential plants. Nevertheless, based on industry knowledge, the following costs represent averages for mixed waste sorting across EU Member States, which should act as a reasonable guide on the economics of AS: [59]

- For large (~200kt) facilities, total costs of £30-£40/tonne, not including revenues and disposal (i.e., the potential benefits arising from avoidance of disposal).
- Revenues of £17-£27 per tonne, dependent on quality of recyclable material.

These figures are corroborated by a study by the RWTH Aachen University in Germany, which compared costs for varying levels of sorting. Based on an average conversion rate for the year of publication, costs range between £30 and £44. [60] As each AS technology matures, its yield, efficiency, and reliability will improve, leading to higher throughput and lower operational cost. Scale-up of these technologies also

[59] Costs for the high ambition advanced sorting considered within the 2035 decarbonisation modelling have not been specifically costed, but are not expected to be greatly different from the above costs since higher rates of sorting are achievable by additional passthrough of sorting equipment (i.e., either doubling up on certain equipment, or by multiple passes through individual sort lines). By 2035, even if additional equipment capital cost is needed to achieve AS's higher recovery rates, then revenues may (in any case) be improved due both to the better sorted recyclate and the higher capture rates.
[60] RWTH Aachen University (2017) MBT Calculation. https://urt.fmmr.tuke.sk/content/ustav/linky/projectcalculation2.pdf

means lower capital cost per metric ton and lower fixed costs for labour, maintenance, and overhead. Large scale commercialisation is currently very minimal, which results in higher capital cost per unit (with a relatively high capital intensity of more than $3,000 per metric ton) as well as fixed costs. [61]

Furthermore, transporting, storing, and potentially upgrading intermediates can add significant operational and capital costs. These are increasingly offset by green premiums, but economics still depend on the optimisation of processes and site location—for example, the trade-off between waste proximity and the location of further chemical processing. Policies, such as EPR, can help support the business case for investment. Though, in the future market, developing a business case for such investments may become easier as the market develops

Scaling up of AS would allow for increased economy of scale. It would require significant changes in consumer behaviour, investment in waste collection, and infrastructure upgrades. Material densification, which compresses loose plastics into waste bales of uniform size and shape, can help offset high transportation costs. Other routes to help scale supply require changes in collection processes and consumer participation to expand the supply of plastic waste, improved feedstock management via digital solutions to ensure consistent input and output quality, and technological advances in sortation to improve recovery rates.

Another aspect to consider is the impact of improving source segregation at kerbside, which would decrease the amount of recyclable material within the residual stream. In turn, the demand for AS may decrease, as may the facilities' yields. This may result in decreased revenues, and thus increased overall costs, unless material revenues per tonne rise in future. (However, the sorting cost alone on a per tonne basis would be expected to remain the same.)

4.1.1.3 Impact on Emissions

AS techniques reduce climate change emissions in two ways:

- There are emission benefits from the recycling activity – which results in avoided emissions from the primary production of materials
- For materials that contain fossil carbon, emissions benefits also arise as a consequence of the reduction in this material within the incinerator feedstock.

Plastics are the most significant contributor to the fossil CO_2 emissions arising from the incineration of waste. As such any activity which reduces the amount of plastic in incinerated waste has a significant impact on emissions from those facilities. Sorting technologies have the potential to deliver reasonably substantial carbon emissions reductions, especially in situations where plastics capture through kerbside collections is relatively poor. Moreover, recycling of certain types of plastic, and of plastic films in particular, is somewhat challenging under current market conditions, but this is expected to change in the future as a result of policy drivers in Europe and beyond which will improve the recyclability of these streams. Performance of the technology has therefore been modelled on this basis; in such a situation, capture rates of all forms of plastic are expected to be much improved on the performance seen in existing UK MBT systems.

[61] McKinsey (2022) Advanced Recycling: Opportunities for Growth. https://www.mckinsey.com/industries/chemicals/our-insights/advanced-recycling-opportunities-for-growth

4.1.1.4 Wider Societal Impacts

AS has the potential to create a range of good, sustainable jobs, particularly a wide range of unskilled, technical, and scientific jobs associated with plastics recycling. These include roles such as drivers collecting and transporting the plastics, sorters placing the plastics in the right spot, technicians, machine operators and plant managers operating the facilities, and engineers and scientists planning the compounding process and resins. In addition, when people observe the range of benefits from AS, from environmental protection to sustainable products, it prompts a shift in ideology. Society is then perceived as a "user" rather than "consumer" and starts demanding innovative products with recycled materials.

4.1.1.5 Key Drivers

Higher recyclability reduces the need for virgin materials and fossil fuels. By 2050, if current trends continue, the production of new plastic from fossil fuels could consume 10-13% of the remaining global carbon budget permissible to ensure temperatures rise to no more than 1.5°C above pre-industrial levels as required by the Paris Agreement. Thus, circular economy transitions and the ability to meet key policy and legislations as cited in Section 2.0, are the main drivers for AS.

Motivation to achieve the highest capture rates are also expected where there are financial incentives in place such as DRS reaching at its best 95% as seen in Germany (see Section 2.1.4 for more information on Scotland's DRS scheme). Given this, Provisional Recommendation 13 in the Review led by Colin Church advises the Scottish Government to "immediately strengthen existing requirements for pre-treatment and work with local authorities and industry to apply them to all existing and future incineration facilities to remove as much recyclable material as feasible, with a particular focus on plastics". [62]

It is anticipated that the recycling sector will continue to grow and play a crucial role not only in achieving pivotal decarbonisation targets, but also in meeting the demand for recycled polymers. This demand is growing, primarily because of increased consumer awareness, consumer packaged goods pledges, and regulations. As this demand increases, there will be market drive for more feedstock (in part sourced from AS outputs).

4.1.2 Carbon Capture, Utilisation, and Storage (CCUS)

CCUS is a set of technologies aimed at capturing, transporting and either permanently storing or using CO_2 that would otherwise be released into the atmosphere. In this context, the analysis refers to the potential application of CCUS on EfW and ATT facilities. Facilities have been assessed for their suitability for CCUS based on size and location. This is presented in Appendix A 2.1.2.

4.1.2.1 Technical Viability

There are a variety of different carbon capture techniques, the two main processes are:

[62] Scottish Government (2022) Stop, Sort, Burn Bury? Independent Review of the Role of Incineration in the Waste Hierarchy in Scotland. https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-report/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-report/govscot%3Adocument/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-report.pdf#page=46&zoom=100,92,325

- Post-combustion. This process removes CO_2 from flue gases. The most promising and mature technology is the absorption process based on a chemical solvent, such as monoethanolamine (MEA). This can be retrofitted to existing waste treatment facilities.
- Pre-combustion. This process reacts fuel with oxygen, air, or steam, and after a further catalytic process, removes the CO_2 and uses the hydrogen left over as fuel in a combined cycle gas turbine (CCGT) generating station. Only new fossil fuel power plants can be equipped with this.

For EfW, the most suitable capture technology is post-combustion. Post combustion CO_2 capture is a mature technology having been used effectively for many years outside Scotland; there are already three EfW facilities in Europe incorporating CCUS at a significant scale.[63] However, this technology has not yet been integrated with EfW at a commercial scale in Scotland. After capture, carbon either needs to be utilised by an industry partner or transported and stored. Currently, large scale deployment in Scotland is mostly reliant on the availability of T&S infrastructure. It is possible for the odd industry partnership to emerge, though such a partnership is yet to come to operational fruition in Scotland (and does come with commercial and operational risks).

Retrofitting Capture Units

EfW facilities are built to last, with average lifetimes of 25 years (Table 4-4) This means that those that operate them can take an enduring view on investment. This is a key advantage, with respect to CCUS deployment over many other industrial sectors, which generally have a shorter horizon when considering return on investment. As such, Scotland's relatively young EfW fleet is well placed to retrofit CCUS economically, in the sense that the technology will be attached to an asset for a significant time. Conversely, there are several aspects related to CCUS which make its technical viability less than suitable. To date, no EfW facility has been designed to capture CO_2 and thus, the capture equipment will need to be retrofitted to the already installed national fleet of EfW in Scotland. Given this, application of CCUS is likely impossible in some cases due to spatial constraints at existing EfW's. However, retrofit is in the process of practical application elsewhere.

By 2026, the Fortum Oslo Varme's Klemestrud EfW in Norway is expected to be the world's first EfW with full scale CCS. The technology aims to capture 400kt CO_2/yr, which given the playoff between biogenic and fossil carbon emissions, has the potential to remove up to ~200kt CO_2/yr. As part of this, an effective 9-month pilot project which ended in December 2019 succeeded in capturing 3.5t CO_2/day.

Transport & Storage (T&S), or Utilisation

There is recognition that in terms of practicality, large CO_2 emitters near each other may be able to form a CCUS 'cluster' that can share T&S solutions. This style of joint infrastructure has the benefit of improving the resilience of the CO_2 supply and providing significant economies of scale due to shared infrastructure. Furthermore, significant investment in transportation infrastructure is required to enable large-scale deployment both on and offshore. Pipelines are the most commonplace for transporting substantial quantities of CO_2, with vast tonnes already transported in this way. There is potential for existing oil and gas pipelines to be used or upgraded for this capacity, however this involves an understanding of the extent to which these pipelines are no longer required for their original purpose, as well as analysis of the costs of pipeline decommissioning versus reuse. Scotland's Cluster involves a pipeline running from Grangemouth up to Peterhead, which then plans to pipe and store carbon in the North Sea.

[63] AVR Duiven and Twence Hengelo in the Netherlands, and Fortum Oslo Varne in Norway

There is significant support for the Scottish Cluster stemming from central Scottish Government (and UK Government), as well as notable private sector engagement. Phase 1 of BEIS's Cluster Sequencing Process placed the Scottish Cluster on a reserve list for Phase 1 funding. If not promoted within this round, the Scottish Cluster will be able to apply to receive funding from the same source at a later time in the second round of funding. EfW's are within scope of this funding for fitting carbon capture and connecting to pipeline projects (assuming the Scottish Cluster is eligible).

Alternatively to the Scottish Cluster, CO_2 can be transported via specialised ships from ports to ports (to be later transported in pipelines), or from ports to offshore storage sites directly. To accommodate CCUS, large scale shipping capacities of 10,000 to 40,000 cubic metres are likely to be required. This is expected to have much in common with the shipment of liquefied petroleum gas (LPG).

As such, location is key for EfW's and ATTs to deploy CCUS, as is the facility's size (to make it commercially viable and competitive when bidding for funding). In Scotland, the ATTs are not considered to be well located for the planned Scottish Cluster pipeline, nor are they near the east coast (which might allow for shipping of captured carbon). As for the EfW's, most are relatively near the pipeline and/or the east coast. Quite optimistically – much like AS – it has been assumed that those large enough (>100ktpa) and well-situated could install CCUS. However, again like AS, the practical ability for technology implementation would need to be assessed on a case-by-case basis, to assess if EfW's have sufficient space, access to funding, and to consider either connection to a major carbon transport pipeline, or to agree contracts for utilisation or shipment options. There are many variables to consider in relation to each EfW's potential business case.

Once CO_2 has been captured and transported, it needs to be stored safely and permanently. Geological storage involves injecting CO_2 underground at depths of around 800m or more, denoting the CO_2 held at many times atmospheric pressure and temperature. Depleted oil and gas reservoirs or deep saline aquifers (an underground layer of saltwater-bearing permeable rock) are well placed to accommodate this injection and have successfully naturally trapped liquids and gases for millennia. The UK benefits from one of the best CO_2 storage potentials of any country in the world, with the continental shelf estimated to be able to store 78 billion tonnes of CO_2, equivalent to 200 years of the UK's annual emissions. Given the maturity of the UK's oil and gas industry, this storage potential is well characterised. In recent years substantial work has been undertaken to understand this storage potential in direct relation to CCUS.

Finally, CO_2 can be utilised in a broad range of applications and is a relatively mature management, particularly in the food and drink sector, primarily in beverage carbonation. The fertiliser industry is also a significant user of CO_2. However, as it captures the CO_2 emitted during ammonia production and reuses it during the urea production process, it is unlikely to require additional CO_2 volumes.[64] It is important to recognise that CO_2 used is not the same as CO_2 avoided, as the use does not necessarily reduce emissions. CO_2 utilisation can provide climate benefits where the application is scalable, uses low-carbon energy, and displaces a product with higher lifecycle emissions. CO_2 derived products that involve permanent carbon retention, such as building materials, can offer larger emissions reductions than products that ultimately release CO_2 to the atmosphere, such as fuels, chemicals and CO_2 enrichment in greenhouses.

Notwithstanding this, emission reductions achieved by utilising and storing CO_2 in products are often not accounted for in many emission reduction policies.

[64] The Fertiliser Institute (2021) *State of the Fertiliser Industry*. Environment and Energy. https://www.tfi.org/our-industry/state-of-industry-archive/2017/environment-energy

4.1.2.2 Potential Costs and Economic Benefits

Whilst cost estimates for CCUS retrofit varies significantly between studies, the following describes assumed best estimates of average cost benchmarks, and a recent, specific example of estimated costs.

Eunomia[65] estimated the capture, transport and storage costs for CCUS (applied to EfW) ranging from £66/tCO_2 to £110/tCO_2. [66] The variation is due to variables such as size, form of transport (pipeline or shipping) and more. It was assumed that EfWs with the ability to utilise onshore pipelines to connect to T&S infrastructure would be developed first and in turn have larger costs associated with being fist movers. Those using liquid/gas ports to ship carbon were assumed to have certain cost savings, benefiting from knowledge and efficiencies already gleaned. Higher costs apply for smaller plants that were more likely to use 'modular' (100kt) CCUS systems and thus achieve lower efficiencies than larger plants using bespoke (specifically sized) CCUS systems.

When considering potential economic benefits, it is important to understand the potential implications of EfW inclusion in the ETS. As outlined in 2.1.5.1, a UK ETS consultation period is currently underway which specifically includes proposals to include EfW and waste incineration within the scope of the UK ETS. It is expected that these outcomes will be published in due course. If the scope is expanded, waste companies will have to buy emission allowances for each tonne of fossil CO_2 they emit (beyond any 'free allowances' which may feature, potentially in the early years). Installation of CCUS which limits emissions into the atmosphere will result in significant economic savings across the sector, linked to the traded price of carbon at the time. As of 9th December 2022, average UK ETS prices across 2022 have been £75/tCO_2. Such price levels may be sufficient to incentivise the lowest cost CCUS systems detailed above, but only in the case that no 'free allowances' are given out, and also only in the case where a credit is payable for biogenic capture and storage (since only the fossil carbon would be liable to the penalty). Nevertheless, future ETS prices may reasonably be expected to increase to trigger investment and behaviour change to achieve the emissions reductions required to meet future national carbon budgets, even the prices seen today may be

Given the high costs associated with CCUS retrofit, this may be a decisive element as to whether this technology continues to be deployed once other sources of funding (see Key Drivers section) are utilised.

4.1.2.3 Impact on Emissions

For retrofitted post-combustion carbon capture, the capture rate is assumed to be around 90% (as was used in this assessment). However, for differing types of CCUS technologies, capture rates typically sit between 90% and 95% .[67] There is a body of evidence suggesting that ultra-high capture rates, defined as CO_2 capture rates equal to or greater than 99%, can be technically achievable and are cost-effective, the CO_2 capture system is sized such that 100% of the CO_2 originating from the combustion of waste is prevented from entering the atmosphere. Though, such high capture rates are generally reserved for solvent-based capture.[68] [69] Recent guidelines published by SEPA for permitting new post-combustion CO_2 capture plants

[65] Eunomia (2021) *CCUS Development Pathway for the EfW Sector*, https://www.eunomia.co.uk/reports-tools/ccus-development-pathway-for-the-efw-sector
[66] Eunomia (2021) *CCUS Development Pathway for the EfW Sector*. https://www.eunomia.co.uk/reports-tools/ccus-development-pathway-for-the-efw-sector/
[67] NEWEST-CCUS (2022) Deliverable D5.3 Report on the technical comparison of the investigated WtE CCUS technologies.
[68] Danaci, D., Bui, M., Petit, C., MacDowell, N., 2021. En Route to Zero Emissions for Power and Industry
[69] NEWEST-CCUS (2022) Report on the technical comparison of the investigated WtE CCUS technologies.

for gas and biomass power plants require a design CO_2 capture rate of at least 95% to be achieved for an environmental permit to be approved. [70]

The total carbon content and the biogenic carbon ratio in the waste feedstock has an important effect on the evaluation of global warming potential. It becomes more relevant in EfW plants with CCUS since biogenic CO_2 emissions removed from the flue gas leads to negative direct emissions. As outlined in Section 2.1.5.2, negative emissions refer to the removal of CO_2 from the atmosphere and permanent or at least long-term storage. This can be achieved through CCUS capturing both the biogenic carbon and fossil carbon from waste emissions. This dynamic is explained in further detail in the Appendix.

However, it is important to highlight that net negative emissions do not constitute a global system benefit. This is owing to resource use and emissions associated with the other life stages of materials and products prior to their end of life. Therefore, although negative emissions can be obtained through CCUS from the perspective of residual waste in isolation, application of the technology relies on materials to be produced and disposed through a linear economy. As such, from the whole system perspective, global CO_2 concentrations are increased with each tonne burned. Decarbonisation on a societal level is thus better achieved through better design for recyclability, and other shifts to circular economy business models. Nevertheless, as long as residual waste exists, arguably CCUS has a role – even if the net negative claim is only applicable when focusing on a discrete part of the material lifecycle.

4.1.2.4 Wider Societal Impacts

CCUS from EfW has the potential to be used to produce low-carbon hydrogen, promoted under the first stage of the EU Hydrogen Strategy (2020-2024). [71] The Scottish Government has also published a draft Hydrogen Action Plan (2021) that further supports the development of a hydrogen economy in Scotland. [72]

From a societal perspective, the potential contribution of CCUS to sustainable growth is high, especially when considering the long-term preservation of jobs. It has been estimated that the UK will need in the region of 53,000 jobs by 2030; of these, 31,000 have been estimated to be required for construction activities. [73] Furthermore, through the North Sea Transition Deal, the execution of offshore infrastructure projects needed for CCUS growth can help deliver up to 40,000 supply chain jobs. Meanwhile, it has been estimated that the Scottish Cluster project could deliver 31,000 jobs in the next decade.[74] Currently, planned construction work by the mid-2020s is to be based in England only, although a portion of further work (by 2030) may be based in Scotland – via the Scottish Cluster project if successful.

4.1.2.5 Key Drivers

A consistent, long-term policy, institutional and regulatory framework, underpinned by multi-year funding, is needed to improve coordination across stakeholders at the national and local levels on the entire

[70] Gibbins, J., & Lucquiaud, M. (2021). BAT Review for New-Build and Retrofit Post-Combustion Carbon Dioxide Capture Using Amine-Based Technologies for Power and CHP Plants Fuelled by Gas and Biomass as an Emerging Technology under the IED for the UK, UKCCSRC Report, Ver.1.0, July 2021. (https://ukccsrc.ac.uk/best-available-technology-bat-information-for-ccs/).
[71] European Commission (2022) Key actions of the EU Hydrogen Strategy. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/key-actions-eu-hydrogen-strategy_en
[72] Scottish Government (2021) Draft Hydrogen Action Plan. https://consult.gov.scot/energy-and-climate-change-directorate/hydrogen-action-plan/#:~:text=On%2010%20November%202021%2C%20the,emissions%20from%20Scotland's%20energy%20system%2C
[73] Serin E et al. (2021) Seizing sustainable growth opportunities from carbon capture, usage and storage in the UK. London: Centre for Climate Change Economics and Policy, Grantham Research Institute on Climate Change and the Environment and Centre for Economic Performance, London School of Economics and Political Science.
[74] Element Energy (2021) CCUS Economics Impact Study: Delivering a roadmap for growth and emissions reductions for Scotland. https://www.scottish-enterprise.com/media/4319/ccus-economic-impact-assessment-report.pdf

portfolio of net-zero solutions and technologies, including CCUS. The Scottish (and UK) Governments are aiming to deliver this by taking a holistic approach, addressing barriers to CCUS investment and capitalising on advantages for sustainable and inclusive growth: infrastructure/ physical capital, knowledge capital/innovation, human, natural and social capital. The UK Government is currently supporting industrial CCUS as part of wider low carbon/ net zero plans. EfW is included in these plans and a number are already linked to various T&S projects. These plans involve developing four T&S projects, each with connected emitters, by 2030 – aiming to capture ~6Mt CO_2 from industrial sources. There is significant funding and business models being developed by BEIS to help deliver this.

4.1.3 Heat Networks

Outlined in law by Heat Networks Scotland Act (2021) and Heat Metering Billing Regulations (2014), 'heat networks' is a term for both district and communal heating systems. (District heating systems are distribution systems which deliver heat from a central source to domestic or non-domestic buildings.) Heat networks are uniquely able to unlock otherwise inaccessible large-scale renewable and recovered heat sources such as waste heat. Such benefits of heat networks have specifically been identified in the Scottish Governments Heat in Buildings Strategy as one of the key strategic zero emissions technologies and under pins the policy and legislation detailed in Section 2.1.5.3.

4.1.3.1 Technical Viability

Technically, the ability to recover heat from incinerators is well established across Europe. It is not a new technology, though almost all EfW's and ATTs operational in Scotland are electricity-only. Once heat is recovered, a heat network is used to distribute the heat to end users. Scotland will need to significantly increase the use of heat networks across Scotland and build an eventually self-sustaining heat networks sector. However, a number of Local Authorities have voiced concern over which third party investors are actively considering investment in the heat network sector. Such a heat network sector would span well beyond the residual waste sector.

Also, different end users have different heat needs – domestic buildings require lower heat than, say, the steel industry. The level of heat received from incinerators is not sufficient to be used in heat-intensive industry (such as steel, glass, etc.). While some industrial sites can use heat from incinerators, for district heating transporting hot water in their pipes, there is a technical limitation on who end users can be – homes, hospitals, pools, libraries, and such are all potential end users. This is owing to the fact all end users need to be connected to the heat network, which is often retrofitted. As with other low and zero emissions heating technologies, this is not always possible especially for many urban buildings, due to issues of space restrictions, heritage issues and costs. However, viability in this sector is demand driven. Given this, the Scottish Government have published research on level of demand in relation to domestic buildings. [75]

Despite this, as stated in 2.1.5.3, there are limited references of heat network retrofit being overly disruptive. All buildings moving towards decarbonised heat systems (such as heat pumps), will require retrofitting, and those that are unable to do so have the potential to link to buildings which have the technology. This is currently the case for several gas CHP networks. Furthermore, there are other means of

[75] Scottish Government (2020) Low carbon heating in domestic buildings – technical feasibility: technical appendix. https://www.gov.scot/publications/technical-feasibility-low-carbon-heating-domestic-buildings-technical-feasibility-appendix-report-scottish-governments-directorate-energy-climate-change/

supplying heat networks with minimal retrofit, for example through the use of high temperature heat pumps.

One example overcoming such challenges is Queens Quay, a brown field regeneration site on the banks of the River Clyde in Glasgow. The scheme plans included the construction of +1000 houses and flats including socially-rented homes, a council-funded care home, a health clinic, a leisure centre and a commercial zone. In fact construction is already underway and the energy centre built, which is currently supplying heat to a number of buildings including council offices, a leisure centre and a care home.

A ZWS feasibility study estimated that fully built a heat network utilising water source heat pumps could deliver almost 20,000 MWh of heat, resulting in an estimated 64% reduction in CO_2/y against the BAU gas boilers scenario.[76] Though this example refers to heat pumps, it gives an insight into the potential emissions savings of heat supplied from incinerators.

The ESA published a EfW Heat Network Directory, which sought to show the heat network potential of EfWs. Table 4-Table 4-1 shows the plants included that are based in Scotland.

Table 4-1: Heat Network Directory for Scottish Facilities[77]

Facility	Annual Heat (MWh_th)	Annual Availability (%)	Maximum efficiency with maximum heat export (%)	Heat off take supplied currently
Dunbar	135,517	91	16.4	No
GRREC	119,574	91	27.9	No
Millerhill	155,200	89	59	No, but currently negotiating an agreement

While Table 4- provides the maximum efficiency of heat export, actual heat offtake which might be beneficially utilised in practice can be much lower. The Dunbar facility is a good case in point on this issue. A recent planning variation application included a 'heat and power plan' which states the following:[78]

> *"An average and diversified peak heat demand of 2.21 MWth and 5.38 MWth respectively has been estimated for consumers which could viably be connected to a district heating network. These consumers comprise a planned industrial development, a planned residential development, and several public buildings. Alternative potential heat consumers within a radius of 10km of the Facility were identified and analysed but were discounted for inclusion in a district heating network on grounds of location, technical feasibility, or the expressed intentions of the owners."*

While the maximum heat export efficiency for Dunbar is stated within the ESA document (and Table 4-Table 4-) as 16.4%, the average heat offtake for consumers who could viably be connected (2.21 MWth) equates to a heat utilisation efficiency of 2%. This low value raising questions of cost effectiveness of a Dunbar district heating network and means we do not include heat recovery from Dunbar within the pathway modelling (described from Section 4.24.2 below). It also serves to flag that heat offtake efficiencies

[76] Zero Waste Scotland (2020) Investment opportunities 'heating up' for district network.
https://zerowastescotland.org.uk/content/investment-opportunities-%E2%80%98heating-up%E2%80%99-district-network
[77] ESA (2021) Energy from Waste (EfW) Heat Network Directory.
https://www.esauk.org/application/files/9916/4677/0451/ESA_Heat_Network_Directory_2022-5.pdf
[78] Fichtner Consulting Engineers (2022) Viridor Dunbar Waste Services Ltd - Heat and Power Plan,
https://www.sepa.org.uk/media/594285/appendix-e-dunbar-erf-heat-and-power-plan-2021-ver4_redacted.pdf

in practice may not be especially high (yet the heat recovery pathway modelling assumes heat utilisation efficiency of 20% for EfW facilities, and 13% for ATTs, as is detailed in Appendix A 2.1.3).

Another assessment of heat network potential is the First National Assessment of Potential Heat Network Zones (FNA), based on the Scotland Heat Map. This automated assessment focuses on heat demand density, offering an initial assessment of areas of Scotland which are most suited to heat networks based on this demand. It does not yet consider the presence of existing networks or other aspects such as the economic viability, technical detail or stakeholder input. It also does not consider the feasibility of EfW heat contributions (set against other sources of heat).

4.1.3.2 Potential Costs and Economic Benefits

In wider support of developing heat networks, a range of key funding and support mechanisms are available. The Heat Networks Delivery Plan which set ambitious targets for the amount of heat to be supplied to heat networks, 2.6 Terawatt hours (TWh) of output by 2027 and 6TWh of output by 2030 (3% and 8% respectively of current heat supply). The Plan allocated funding under Scotland's £300 million Heat Network Fund, to enable and support the development of new, and expansion of existing heat networks in Scotland. [79] [80] Furthermore, the Heat Network Support Unit which of works with the public sector to identify, support and develop heat network projects to capital readiness through expert advice and grant funding. This funding can be used towards developing feasibility studies and Outline Business Cases, and for the procurement of technical, financial and legal advisors. [81]

Benefits from the increased use of heat networks could include reductions in energy cost and greenhouse gas emissions, of which CO_2 is a major contributor, through allowing the exploitation of lower CO_2 and higher efficiency forms of generation. These could include the use of CHP, biomass, heat pumps, waste heat and low-grade heat sources. This will be a potential key driver for achieving Scotland's statutory GHG emissions reduction targets.

4.1.3.3 Impact on Emissions

Heat networks have the potential to deliver emissions savings. However, the extent of those savings depends on two elements:

- The fuel (or the method of heat generation) used in the heat network itself; and
- The emission associated with the alternative sources of heat that would have been used in the absence of the network.

The incineration of residual waste results in relatively high emissions compared to some other forms of heat generation that could be used in a heat network (such as a centralised heat pump system fuelled with relatively low-carbon electricity). However, in general, heat decarbonisation is progressing at a slower pace than that of electricity decarbonisation. Gas is expected to be the fuel offset for domestic heating systems in many cases for some time to come – and this may also be the case for many industrial heat systems. By generating heat and power simultaneously from the same fuel, CHP can reduce carbon emissions by up to 30% compared to the separate generation of heat through a gas-fired boiler and an electricity power

[79] Scottish Government (2022) Heat networks delivery plan, https://www.gov.scot/publications/heat-networks-delivery-plan/
[80] Scottish Government (2022) Heat network fund: application guidance. https://www.gov.scot/publications/heat-network-fund-application-guidance/pages/overview/
[81] Heat network support: Scotland (2022) Heat network support unit. https://www.heatnetworksupport.scot/heat-network-support-unit/

station. [82] As such, climate change benefits from heat generated at incinerators are anticipated to continue for longer than is the case for electricity generated at the same type of plant. Emissions benefits are nonetheless expected to decline over time, in the same way as has already been seen for electricity, but at a slower pace. As such, heat should be seen as a transition technology towards achieving net zero targets where incineration is the source of the heat being generated.

4.1.3.4 Wider Societal Impacts

Heat networks provide a way to reduce heating bills for customers both domestically and commercially. Given the current energy crisis, the capacity to deliver affordable heat nationally, will become increasingly important.

Conversely, its original consultation BEIS estimated that the total annual cost of regulating the heat network market will be approximately £6.5m per year. If these costs solely fell on heat networks, then assuming costs would then be recovered through heating bills, it would lead to an additional £10 or more per heat network consumer bill per year. An additional £10 or more to each heat network consumer bill per year would create risks to the competitiveness of the market, create issues of affordability for heat network consumers and have impacts on suppliers. A proposal for Ofgem and Citizens Advice's total ongoing costs of regulating and performing consumer advocacy functions in the heat networks, gas, and electricity markets being spread evenly across heat network, gas, and electricity consumers, it was estimated that heat network, gas and electricity consumers would pay £1.40 per year towards the costs of heat network, gas, and electricity regulation. This amounts to an additional £0.10 per gas and electricity consumer per year compared to what they currently pay for Ofgem's gas and electricity regulation and Citizens Advice's consumer advocacy functions. If applied estimates of the average gas bill, this represents a 0.02% increase.

In addition, heat networks can contribute to other local aims such as those relating to fuel poverty, cost reduction, regeneration, local jobs and growth. In particular, heat networks can provide cheaper heat for residents at risk of fuel poverty.

4.1.3.5 Key Drivers

Heat networks form an important element of Scotland's plan to reduce overall carbon, as well as a significant investment opportunity across distribution, generation, storage, controls and customer interface. Though the market is growing, currently only around 1.5% of Scottish heat demand is provided by heat networks. [83] The CCC estimates that with government support, this should rise to 18% by 2050 to help meet Net Zero targets. As outlined in Section 2.1.5.3, the Heat Network (Scotland) Act sets ambitious targets for 120,000 and 400,00 additional homes being connected to heat networks by 2027 and 2030 respectively. Whilst this does not directly support EfW's connecting to heat networks, it supports the development of the networks to which EfW's would need to connect – if well placed and able to switch away from being electricity-only.

As an initial step in achieving this, the Scottish Government will consider the introduction of a requirement to provide information when formally requested with relevant authorities and licenced heat network providers. This is sought to be applied to potential heat suppliers, for the type of heat source where heat can be cost effectively recovered and supplied. Furthermore, the Scottish Government will work with

[82] BEIS (2020) Combined Heat and Power. https://www.gov.uk/guidance/combined-heat-and-power
[83] Scottish Federation of Housing Association (2022) New assessment identifies potential heat network zones in Scotland. https://www.sfha.co.uk/news/news-category/sfha-news/news-article/new-assessment-identifies-potential-heat-networks-zones-in-scotland#:~:text=In%20Scotland%2C%20heat%20networks%20currently,heating%20our%20homes%20and%20buildings.

stakeholders to further develop proposals for consultation on the provision of information on potential waste heat sources and any further measures considered necessary to increase the utilisation of surplus or waste heat. This consultation will include which potential heat suppliers would be in scope of any proposals. [84]

The wider market growth is already supported by strong government commitments through the Heat Networks Fund, which is soon to be expected to receive funding for heat networks using heat from incinerators, and the Heat Networks Support Unit. [85] In addition, in Scotland's Heat and Buildings Strategy the Scottish Government committed to investing at least £200 million of capital funding to support decarbonisation of social housing, as well as at least £200 million in the Scottish public sector estate to improve and reduce energy use and install zero emissions heating systems. [86] Overall, an estimated £33 billion is likely needed. Furthermore, the New Build Heat Standard scoping consultation sought views on proposals to introduce a set of regulations which would require net homes (consented from 2024), to solely use zero GHG emission systems. [87] The update to this consultation also included the ban of direct emission heating systems in both domestic and non-domestic new builds. [88]

4.1.4 Biostabilisation

Biostabilisation happens at MBT facilities with integrated bio-treatment: here advanced mechanical pre-treatment systems, designed to remove recyclables from the residual stream as above, are combined with aerobic bio-stabilisation of the residue from the pre-treatment system. 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.

This is not a new technology or process, and there are examples of its successful deployment across Europe. However, historically in the UK, biostabilisation has not seen similar success and thus it is not as widely used in Scotland.

Scottish legislation states biostabilisation as the second acceptable practice (alongside EfW) to achieve a designated level of biostability that allows waste to be landfilled under the Scottish landfill ban.

In the short-term, as landfill rates in Scotland are anticipated to remain relatively significant, the biostabilisation of waste is more significant. However, when looking out to 2035 (and beyond) – when almost all residual waste will be diverted from landfill – the carbon impact of biostabilisation is likely to be notably less significant at the national level. Drying and stabilising organic wastes remaining within the residual stream is not necessary if it is to be incinerated. However, Scotland has remote and rural locations that may not be feasibly served by EfW or ATT facilities, and landfill usage may still be required. It is in these types of exceptional areas where bespoke assessments of the potential benefits of biostabilisation should be considered, on a case-by-case basis.

[84] Scottish Government (2022) Heat networks delivery plan. https://www.gov.scot/publications/heat-networks-delivery-plan/pages/7/
[85] Scottish Government (2022) Launch of the Heat Network Support Unit. https://www.heatnetworksupport.scot/2022/09/28/hnsu-first-blog-post/
[86] Scottish Government (2021) Heat in buildings strategy: achieving net zero emissions in Scotland's buildings. https://www.gov.scot/publications/heat-buildings-strategy-achieving-net-zero-emissions-scotlands-buildings/
[87] Scottish Government (2021) New build heat standard: scoping consultation. https://consult.gov.scot/energy-and-climate-change-directorate/new-build-heat-standard/
[88] Scottish Government (2022) New build heat standard consultation: part II. https://consult.gov.scot/energy-and-climate-change-directorate/new-build-heat-standard-part-two/

4.2 Overview of Pathways

This study evaluated the potential for decarbonising the residual waste infrastructure emissions through a series of technological changes, namely AS, heat recovery, CCUS and biostabilisation. These have been combined to generate four future pathways scenarios. These are introduced in Table 4-2.

Table 4-2: Overview of the modelled pathways

Pathway 1: Advanced Sorting	This pathway includes the addition of AS to 100% of the waste that was going directly to EfW plants in the baseline. It also involves improved MBT efficiencies for all the operating MBTs.
Pathway 2: Advanced Sorting and Heat Recovery	This pathway includes AS as detailed in pathway 1 plus the benefit associated with the implementation of heat recovery in 5 facilities (Millerhill, GRREC, Aberdeen, Dundee and Earls Gate).
Pathway 3: Advanced Sorting and CCUS	This pathway includes AS as detailed in pathway 1 plus the benefit associated with the implementation of CCUS in the relevant facilities, as detailed in the Appendix A 2.1.2.
Pathway 4: Advanced Sorting, Heat Recovery and CCUS	This scenario sums up the assumptions detailed for pathways 1, 2 and 3.
Biostabilisation	This scenario assesses the benefit of biostabilisation. Due to the increase in EfW capacity, and the anticipated decrease in amount of residual waste sent to landfill by 2035, the impact of this technology is discussed separately to the first four pathways in Section 4.4.

The technologies necessary to achieve these pathways are described in Section 4.1.

The assumptions used in the pathways model are detailed in Appendix A 2.1. The main assumptions behind the modelling of each technology are also reported in Table 4-3.

Table 4-3: Main assumptions behind the modelling of the technology options

Technology	Approach to modelling	Potential constraints – not considered in the model
Advanced sorting	• We assume that the technology can be applied to all waste that is going to incineration • We assume that the same capture efficiencies of AS can be applied to all MBT facilities	• Barriers to technical implementation are relatively few assuming the material can be in practice recycled – the main issue may be cost, especially when considering smaller facilities. But the technology is likely to be cheaper than CCUS • We have not considered local constraints that might exist and prevent some flow of waste from being sorted, especially in the case of rural areas/islands • With respect to existing MBT facilities, in practice it might not be possible to retrofit the required technology to meet the same capture rates as AS • We have not considered the potential viability of business cases for such as investment.
CCUS	• This is assumed to be fitted on all plants meeting the following criteria: minimum annual capacity of 100,000 tonnes and located close to a potential Scottish CCUS project, as these will be priority facilities for receiving CCUS. Others may follow but they are less likely to have advanced by 2035. For those further away from the pipelines, the costs of implementing CCUS will likely be higher	• In practice, there may be technical restrictions at a given site that prevent the retrofit of CCUS (such as insufficient space for the equipment) • We have not considered the potential viability of individual business cases for such as investment.
Heat Recovery	• We modelled heat recovery for those facilities where the Scottish Government heat networks team indicated that heat offtake would most likely occur in the near term – Millerhill, Aberdeen Recycling & Energy Recovery (NESS), GRREC, Dundee and Earls Gate	• We have been somewhat conservative with heat recovery deployment – more research on each incineration facility's potential for heat recovery is needed, as the available literature has not specifically evaluated this

4.3 Decarbonisation Pathway Modelling Results

4.3.1 Net Carbon Emissions for Each Pathway

Figure 4-1 shows the emissions associated with the baseline and the pathways, described in Table 4-2, for each scenario considered (BAU, BES-F and BES-P), described in Section 3.3.1. A more detailed breakdown of these results is provided in Appendix A 3.2.

Figure 4-1: Carbon emissions associated with the baseline and the pathways for each scenario

Note: The negative emissions in the Pathway results are primarily driven by the carbon benefits associated with the extraction of recyclables through advanced sorting (as is included in all Pathways), and CCUS in Pathways 3 and 4. Biogenic CO2 emitted to atmosphere is not accounted, while a credit is applied for capture of biogenic carbon in the CCUS pathways.

Following the carbon accounting conventions described in Section 3.3.1, Figure 4-1 indicates that, under the baseline scenarios, residual waste infrastructure is a net contributor to carbon emissions, i.e. the residual waste treatment technologies contribute to the total lifecycle emissions of the materials considered. By contrast, under each scenario of each Pathway option, the emissions benefits from recycling, benefits from avoided energy generation and from biogenic carbon capture are such that these outweigh the direct emissions from the treatment processes – leading to net negative emissions. However, it should be noted that negative emissions are shown because of narrow system boundaries considered in this analysis. In particular, the scope of this work considers only part of the lifecycle of the materials/products that become waste, as it only includes the emissions associated with their end-of-life treatment, i.e.[89]:

[89] As described in the introduction to the modelling approach in Section 3.3.1.3.3.1

- Direct emissions generated from the waste treatment and energy use at facilities;
- Credits associated with recovered recyclables through MBT and AS;
- Credits associated with avoided energy and heat production; and
- Credits associated with storage of biogenic carbon through CCUS.

The assessment, therefore, excludes from scope climate-impacting emissions which are relevant in a full life cycle assessment of materials or products - such as the emissions associated with product manufacture and use. This is explained further in Section 4.3.2.

Furthermore, as described in Section 3.3.1, as per convention in waste LCAs, we have also excluded direct emissions of biogenic CO_2. This is only considered in the analysis through credits applied for long-term sequestration in accordance with the assumptions described in Appendix A 1.1.6.2 and A 2.1.2 accordingly). If biogenic CO_2 emissions were included in the analysis[90], all pathways would result in a net contribution to climate change and there would be no net negative results. Again, this is an output relating to system boundaries and methodological choices that are made where the LCA methodology is applied to residual waste systems.

Considering the three scenarios included in this work, BAU, BES-P and BES-F, which differ for the amount of recycling happening at kerbside, as described in Appendix A 1.1.4, Figure 4-1 shows that the impact of Pathway technology interventions applied to the BES-P and BES-F scenarios give reduced net benefits as compared to the BAU scenario. This happens because the kerbside recycling rates of the BES-P and BES-F scenarios are higher than in the BAU scenario. The recycling emission credits associated with source separated recycling however are not considered in this work (and source separated recycling benefits are obviously higher in the BES-F and BES-P scenarios), while at the same time higher kerbside recycling leaves less material to be available for recycling through AS and MBT, leading to lower modelled residual waste benefits for these scenarios. Considering the BES-P in particular, given that a significant proportion of plastic is already captured through source separation, the emissions benefit associated with plastic recycling through AS and MBT (associated with removing plastics from residual waste) is lower than those in the BAU and BES-F scenarios.

The results obtained for each Pathway option are discussed below:

- **Pathway 1** explores the effect of implementing advanced pre-sorting prior to incineration. AS generates a carbon benefit from extracting plastic and other materials for recycling (credited within our analysis since this is a carbon benefit attributable to the policy) whilst also avoiding emissions from incinerating it. The contribution from avoided emissions is derived particularly from extracting plastics, given their high fossil carbon content emitted as CO_2 when burnt, and metals, given their high recycling carbon benefits. Combined with the benefits from the energy generated from waste, these contributions are sufficient to outweigh the direct emissions from combusting waste, hence the CO_2 emissions are reduced and become negative within the analysis. In addition to this, AS reduces the amount of waste going to EfWs of about 18% (equivalent to ca. 260k tonnes of waste per annum which would be sent for recycling instead). Such a significant swing in residual waste volumes has significant implications on pipeline EfW facilities in particular. The possibility of any future advanced pre-sort policies in Scotland needs to be taken into account by facilities seeking financial close, to avoid and limit future redundancy in Scottish EfW capacity;
- **Pathway 2** includes AS plus the contribution of heat recovery from some of the modelled facilities. Five out of the 10 EfW and ATT facilities considered have been modelled as operating in CHP mode. The additional average[91] decrease in emissions beyond AS is ca. -21% from Pathway 1. This relatively low decrease is also due to the fact that the marginal heat sources in the future are set to

[90] This is a convention that is receiving increased attention and debate, especially when dealing with biogenic materials that are less evidently on a short carbon cycle, such as wood or paper sourced from not properly managed forests.
[91] Average calculated including both household and C&I waste and all the scenarios BAU, BES-F, BES-P

decarbonise to a certain extent, making the impact of heat recovery relatively minimal. It is important to highlight that as marginal heat decarbonises, the benefits associated with heat recovery will also decline over time (beyond 2035). For this reason, EfW CHP to heat networks can be considered a transition technology, the benefit of which declines over time as energy system decarbonisation progresses.

  - The average decrease in emissions of -21% (-16ktCO_2e) from Pathway 1 has been calculated considering the efficiency of the plants operating in CHP mode described in Appendix A 2.1.3 (20% for EfW and 13% for ATT). If these plants were operating in heat only mode with an efficiency of 85%, with no electricity generation, an average decrease in total emissions of 97% (-75ktCO_2e) in comparison to Pathway 1 has been calculated;

- **Pathway 3**: In the third pathway, AS and CCUS are considered. Due to the location and size of the facilities we modelled, we considered that only certain facilities in Scotland are in a position to adopt CCUS technology. CCUS offers the possibility to give significant additional GHG reductions, bringing an average decrease of ca. –421% from Pathway 1. One driver for this decrease in emissions is the fact that some biogenic emissions, which are typically ignored in life cycle assessments, are instead captured and stored, bringing additional carbon credits to this pathway. The results shown here do not capture the benefits of future recycling activity occurring through the recycling taking place here (e.g. through AS)– which would help keep materials in circulation for longer, thereby supporting a circular economy and the longer term decarbonisation of materials production. By contrast incineration - even with the use of CCUS - would lock out the benefits of giving materials a new life;
- **Pathway 4**: In the fourth pathway, the benefits of heat recovery from the five facilities considered as summed up to the emissions in Pathway 3. This thusly combines the impact of AS, CCUS and heat recovery. The relative average decrease in emission however is ca. -3% compared to the emissions calculated for Pathway 3.

When observing these results, it is important to reflect on the assumptions behind the model, in particular:

- The recycling rates of plastics predicted at kerbside and those of AS, shown in Appendices A 1.1.4 and A 2.1.1 respectively, both require parallel policies to work as effectively as possible, such as a push for design for recyclability and policies to improve markets and demand for recyclates of plastics that are currently unrecycled;
- It is assumed that 100% of the waste that goes to incineration facilities is subject to advanced sorting, which will be more expensive for smaller and rural incineration facilities (if the sorting is not done in centralised facilities);
- MBTs are assumed to be upgraded to reach the same sorting efficiencies as those of AS plant, which may not be possible due to constrains in existing facilities (such as floor space or other reasons);
- It is assumed that all sorting occurs at a rate that – based on our understanding of current industry standards – is realistic best efforts across all the relevant material streams. Again, due to other constraints such as size and costs, this may not be feasibly deployed across all facilities;
- For CCUS, we have similarly not considered the constraints associated with retrofitting the equipment needed, as there might not be enough space for this to be possible.

We have therefore been relatively optimistic in modelling these pathways options, with the exclusion of heat recovery which has only been applied just to the five facilities most likely to adopt it in the close future. The results obtained can therefore be seen as the highest reasonably achievable. The aim of this work was to show high-level benefits of each pathway, but a more detailed site-specific assessment is recommended, and this would need to consider all technical constraints, particularly those in the more rural areas.

Alongside emissions, other implications from the large-scale deployment of the technologies and pathways discussed in this section require consideration. A number of these aspects are collated in Table 4-4.

Table 4-4: Further parameters to consider when comparing options available to decarbonise incineration facilities in Scotland

Parameter	Unit	Landfill	EfW Electric only	Advanced Sorting	CCUS	Heat Recovery
First year available	Year	-	-	2020s	2030's	2020s
Equipment Lifetime	Years	-	-	15-20	25	25
Combined Cost (excluding EfW cost)	£/t	-	-	0-50[92]	60-110	30-120[93]
CO_2 per tonne of waste treated[94]	tCO_2eq/t waste	BAU = 0.320 BES-F = 0.301 BES-P = 0.351	BAU = 0.351 BES-F = 0.386 BES-P = 0.228	BAU = -0.079 BES-F = -0.088 BES-P = -0.068	BAU = -0.419 BES-F = -0.417 BES-P = -0.457	BAU = 0.270 BES-F = 0.298 BES-P = 0.156
Waste heat suitable for re-use95	MWh/year (at 20% heat efficiency)		-	-	-	268,070

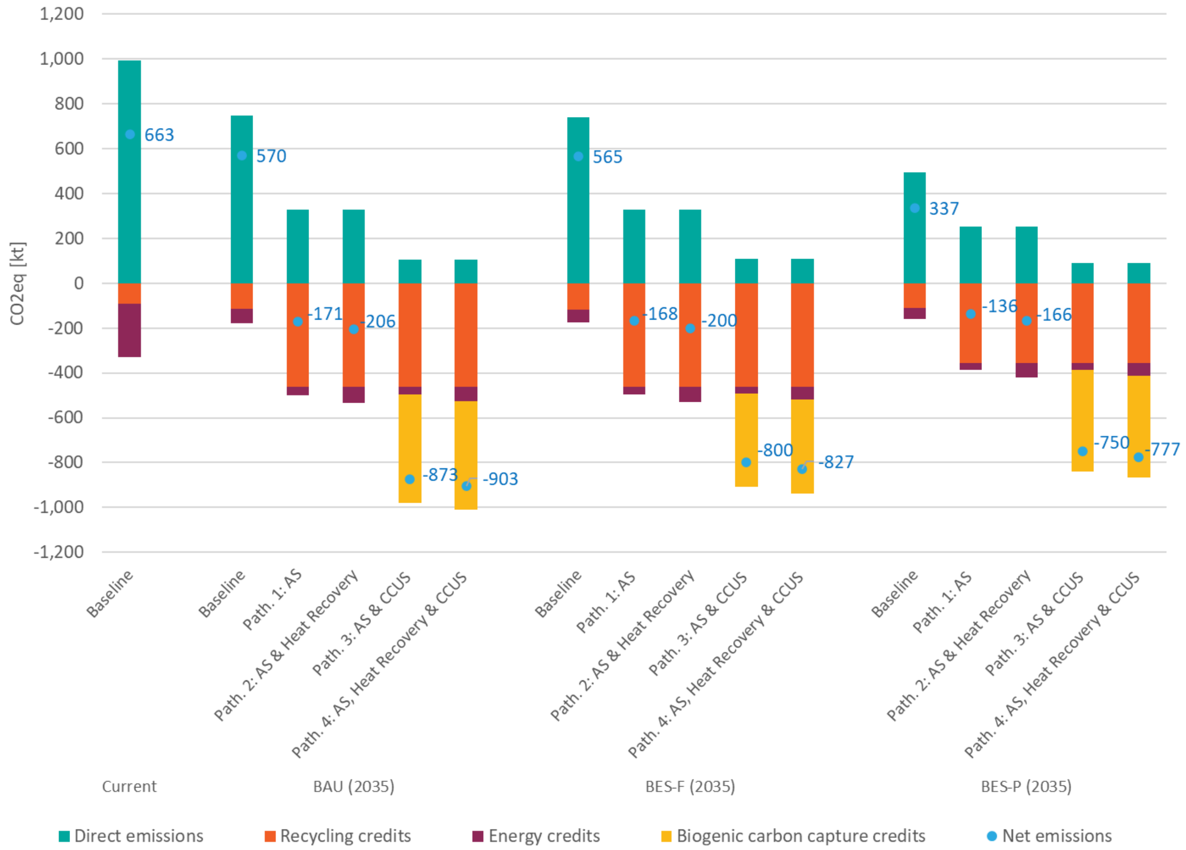
4.3.2 Results Split by Direct Emissions and Carbon Benefits and Credits

Figure 4-2 shows the carbon emissions associated with the baseline and the pathways for each scenario split by direct emissions and carbon credits.

In the results of Pathway 1, the recycling credits associated with the deployment of AS (together with improved sorting efficiencies for MBTs) are shown, together with the reduction in direct emissions associated with the lower amount of material that is incinerated in comparison to the baseline. In the results of Pathway 2, it is possible to observe the increase in energy credits associated with the deployment of heat networks in five of the 10 EfWs and ATT considered. Finally, the credits associated with the capture and storage of biogenic carbon can be observed in the results shown for Pathway 3 and 4, together with the reduction of direct emissions resulting from the capture of fossil carbon.

[92] Costs per tonne are very sensitive to revenue and avoided disposal assumptions, and the range in net costs can therefore be high. The cost range provided here should be considered as indicative based on expert judgement only.
[93] Derived from analyses based on BEIS research into heat network investment: BEIS Heat Networks Investment Project. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/691643/Heat_Network_Case_Study_Brochure.pdf
Costs are referred to as 'investment costs' and are therefore assumed to not any include operational costs that may be incurred. Furthermore, as this cost applies to the development of a heat network, the investment may be covered by more parties involved, not just one facility
[94] Including EfW [where relevant], excluding biogenic carbon emissions credit applied for stored biogenic CO_2
[95] The amount of waste going to the Millerhill, Aberdeen, GRREC, Dundee and Earls Gate (from which the heat available is calculated) is proportional to the facilities' capacity and the total amount of waste going to EFW. Excluding Lerwick EfW. The heat generated is calculated considering the efficiency of the facilities and a calorific value per tonne of waste equal to 2.78 MWh/ tonne

Figure 4-2: Carbon emissions associated with the baseline and the pathways for each scenario, split by direct emissions and carbon credits



Note: The modelling undertaken for landfill did not separate direct emissions and energy credit, and the net figure only is included in the direct emissions. This implication only affects the current baseline, since there is almost no direct landfill by 2035 (apart from a fixed 1% of C&I waste which is assumed to be still directed to landfill).

A point to note from the above chart is that Scotland's national emissions inventory considers only direct emissions, without offsets, and the accounting is done on a territorial emissions basis. National inventory emissions associated with Scottish waste management are therefore expected to relate closely to the teal bars within the chart alone – and therefore are likely to remain positive even in spite of new decarbonisation policies, hampering Scotland's ability to meet its net zero target. It is not possible here to determine the extent to which changes in energy benefits or recycling benefits might impact on direct emissions occurring from the energy or materials sectors in Scotland, though it is to be expected that a large part of the recycling benefits might only reduce emissions overseas (and so not reduce territorial emissions in Scotland). Neither is it certain if and how biogenic carbon capture credits should be accounted within the national inventories (for instance it is reasonable to consider that food exists on a short carbon cycle and thus capture of associated CO_2 can be thought of as an emission reduction, but wood and paper should only be considered this way if from sustainable sources). The flag must simply be raised that waste decarbonisation technologies considered within this report can contribute quite significantly to global decarbonisation, but that not all the benefit would be picked up within Scotland's national emissions account. Further nuance to emissions accounting principles are also discussed in the next section below.

4.3.3 Results Including Production Emissions

The scope of what is included in this analysis generates a picture that is not representative of the whole life cycle of a material or product. A focus solely on residual waste emissions is a somewhat arbitrary accounting methodology for focussing on the impacts of waste systems. As was indicated above this excludes the emissions associated with other life cycle stages of materials, which ultimately become waste sent for residual treatment. In particular, entirely ignoring production emissions would fail to recognise the impact of the resources that are - in effect - consumed by residual treatments such as incineration and ATT. Such treatment systems prevent materials from staying in circulation for longer, and do not fully reflect the benefits that occur via recycling in respect of decarbonising material production. To reflect this picture more fully, we have generated a graph that shows the carbon emissions associated with the baseline and the pathways for each scenario including materials production emissions, and this is shown in Figure 4-3.

Figure 4-3: Carbon emissions associated with the baseline and the pathways for each Scenario Including Material Production Emissions

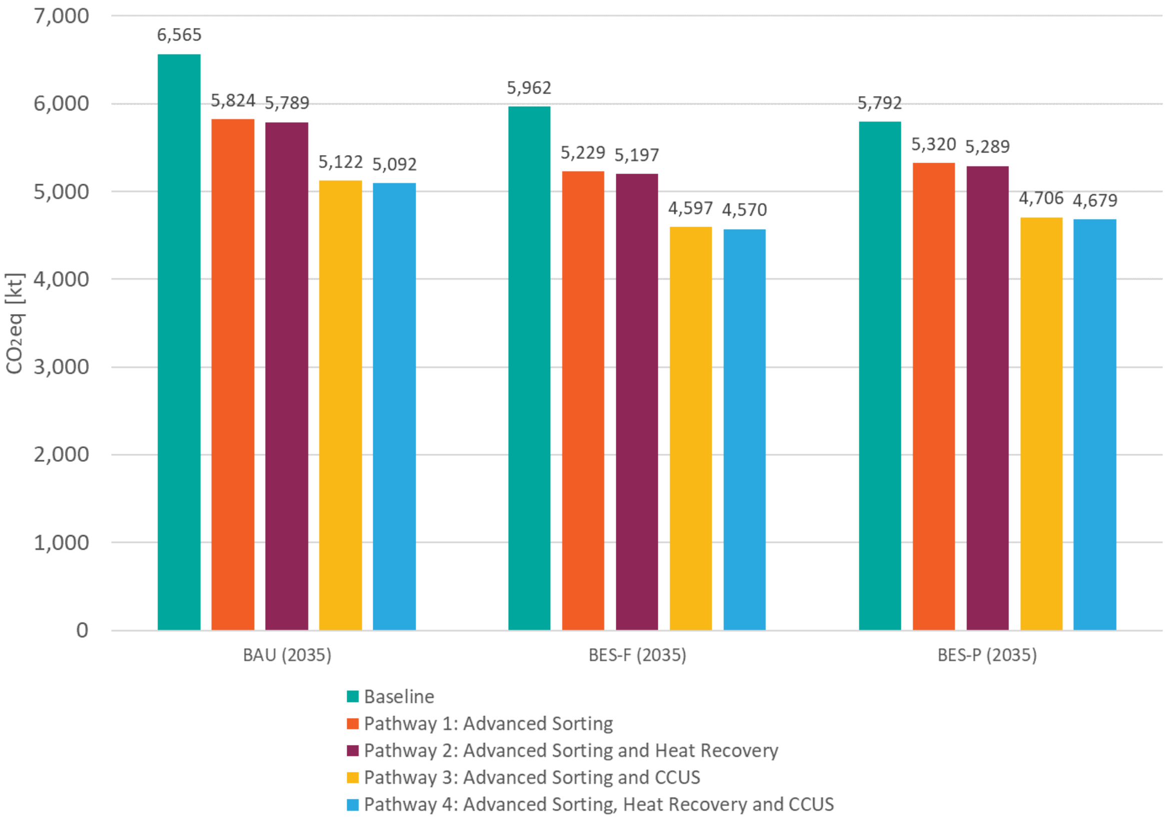


Figure 4-3 shows the emissions associated with the production of materials that eventually become the waste that has to be treated, alongside the waste treatment impacts, When such impacts are included, the carbon impact of all the scenarios for all the pathways is positive (i.e., showing a net contribution to climate change) and impacts associated with materials production are shown as being significantly higher than the carbon benefits occurring through the residual waste pathways as presented in the analysis above. The graph illustrates the need to fully consider the decarbonisation of materials production, which means prioritising waste prevention, reuse and recycling activities over waste disposal. End-of-life benefits arising from techniques like CCUS therefore need to be seen in the wider waste and resources systems context, as shown on this graph.

4.3.4 Summary Comment on the Results

Overall, while we have only modelled residual waste GHG emissions (plus an additional version of the results with production emissions included), the implications are that a strong policy ambition for implementation of AS (alongside design for recycling improvements which are desirable and irrespectively expected to occur for plastics) could already deliver significant benefits in respect of decarbonisation of the waste sector. This is particularly relevant given the fact that AS is a commercially proven and existing technology and has relatively lower technical risks compared to CCUS. AS also allows for materials to be kept in circulation for longer, therefore further supporting the circular economy.

4.4 Biostabilisation Assessment

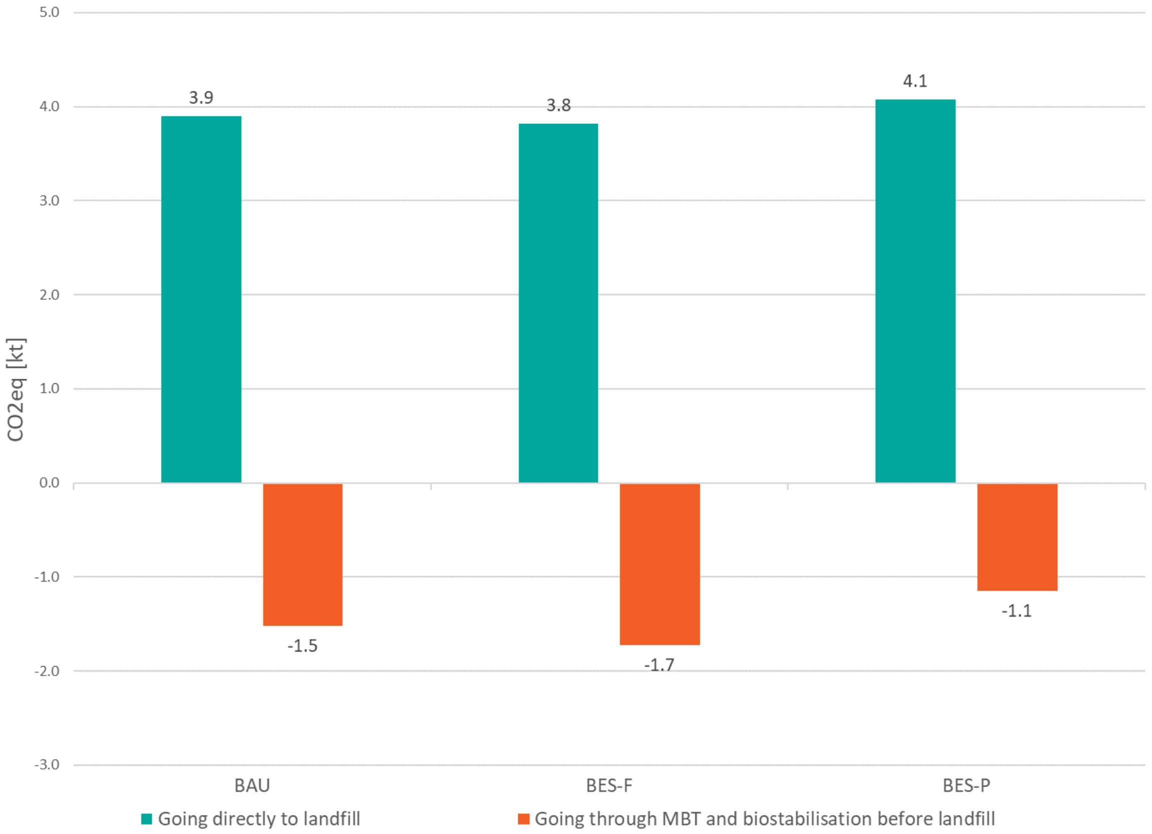
Biostabilisation was originally listed as one of the technology options that would have been included in the decarbonisation pathways modelled in this work. However, due to the anticipated over capacity of incinerators in 2035 based on other modelling work[96], its uptake is expected to be limited in 2035 – as for the most part, Scotland will have transitioned away from landfill. However, considering geographically remote areas, there may be opportunities in some outlying communities where investment in an EfW facility might be less likely, or access may be limited (or expensive) due to distance. We, therefore, carried out an analysis to evaluate the impact of biostabilisation for a reference 10 kt HH residual waste, following two distinct treatment options:

- Send the waste directly to landfill without any treatment;
- Pre-sort the waste and bio-stabilise it in an MBT facility before sending it to landfill.

All of the scenarios (BAU, BES-F and BES-P) have been compared, with kerbside capture rates of each described in Appendix A 1.1.4. The MBT capture rates that have been considered are equivalent to those of AS and are described in Appendix A 2.1.1. (Note: these “advanced sorting” capture rates are higher than assumed within the Ricardo ‘Biostabilisation’ report to Zero Waste Scotland, and therefore the carbon benefits in our modelling will be higher than those of Ricardo.[97]) The carbon impact of these scenarios is shown in Figure 4-4. A more detailed breakdown of these results is provided in Appendix A 3.3.

[96] Ricardo for Scottish Government on behalf of the Independent Review of the role of Incineration in the Waste Hierarchy of Scotland, Incineration Review Capacity Analysis, April 2022, https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/incineration-review-capacity-analysis/incineration-review-capacity-analysis/govscot%3Adocument/incineration-review-capacity-analysis.pdf
[97] Ricardo (22 July 2022) “Alternative Residual Waste Treatment - Biostabilisation", draft report for Zero Waste Scotland, Issue 2, unpublished at time of writing.

Figure 4-4: Carbon emissions associated with 10kt of HH residual waste sent directly to landfill or previously pre-treated



The following considerations can be made on the results:

- Sending waste to landfill without pre-treatment is a net contributor to emissions (0.390 tCO_2e/t for BAU, 0.381 tCO_2e/t for BES-F and 0.408 tCO_2e/t for BES-P)[98];
- Pre-treating waste has a double benefit:
    - The impact of landfill per tonne of waste decreases:
        - BAU: 0.390 tCO_2e/t for non biostabilised waste versus 0.074 tCO_2e/t for biostabilised waste;
        - BES-F: 0.381 tCO_2e/t for non biostabilised waste versus 0.075 tCO_2e/t for biostabilised waste;
        - BES-P: 0.408 tCO_2e/t for non biostabilised waste versus 0.075 tCO_2e/t for biostabilised waste;
    - The captured recyclables account for recycling credits, which bring to overall negative emissions;
- The total impact associated with the BES-P scenario is higher compared to the BES-F scenario because of two main reasons:
    - The carbon impact of the landfilled waste is higher in the BES-P because of the higher percentage of food waste;
    - The recycling credits associated with the BES-P are lower because there is less plastic to be captured at the MBT facility, as more plastic has been captured at kerbside (for which recycling credits are not in scope of this analysis). If the recycling credits associated with

[98] As per the overall pathways results, these do not include recycling credits associated with kerbside collected materials.

material captured at kerbside were considered, the impact of this scenario would decrease (as it would for the other scenarios).

5.0

Conclusions

5.1 Aim and Scope of Assessment

As part of the wider Independent Incineration Review, the potential routes to decarbonise the residual waste treatment sector within Scotland have been assessed. This report builds on work already published and will feed into further work as part of the Review. The policy landscape influencing Scotland informed the assessment, including Scottish, UK and EU policy developments.

Residual waste covers HH and (HH-like) C&I wastes. Three future scenarios were assessed to demonstrate the variation of high and low levels of recycling (i.e., business-as usual [BAU] and two Best Efforts scenarios [BES]), and the impact of composition depending on whether plastic or food was removed more or less (i.e., the BES-F scenario that targets removal of more food waste, and BES-P scenario that targets removal of more plastic waste).

The waste treatment options include operational infrastructure as well as those in the pipeline that are considered likely to be developed, and cover a range of end-destinations for residual waste: EfWs, ATTs, MBTs, landfills, and exports.

Non-permitted infrastructure is not in scope of this assessment, neither are carbon emissions or benefits not directly linked to the residual waste sector. For example, the benefits of increased recycling at kerbside collections are not in scope nor included in the figures provided.

5.2 Assessment Outcomes

The single most cost-efficient and effective method to reduce direct emissions from the residual sector across all scenarios (BAU, BES-F, and BES-P) was the implementation of **AS,** as demonstrated in Pathway 1. Alongside reduction of EfW's direct emissions, AS has the further benefit of emissions savings from additional recycling recovered from residual waste.

AS here refers to having sufficient total sorting capacity operating at currently known 'best in class' efficiencies. It is considered to be an optimistic yet technically achievable pathway; the sorting technologies assumed to be used are proven (operating at commercial scale in Europe) and offer relatively little technical risk.

There are some policies already in place to support the deployment of AS, although it would require investment. Costs for AS are highly variable and largely dependent on facility size – with smaller facilities tending to be more expensive on a per tonne basis. The net costs also depend on material revenues and avoided disposal costs – not just the cost of installing and operating sorting processes. For large facilities, cost indications gathered for this report suggested a range of £30-40/tonne operating costs, with revenues of £17-27/tonne (and not accounting avoided disposal savings).

The more that plastics are captured before entering the residual stream – e.g., via DRS or at kerbside – the lower the impact residual waste sorting will have. The BES-P scenario assumes that a significant proportion of plastic (but certainly not all of it) is already captured at kerbside, so the emissions benefit associated with plastic recycling through AS and MBT (associated with removing plastics from residual waste) is lower than that in the BES-F and BAU scenarios. However, for the level of impact modelled to become reality, a higher proportion of plastic currently placed on the market would need to become feasibly recyclable – i.e., more of the plastics in circulation needs to be designed so as to remove technical and commercial barriers currently associated with recycling it. The implementation of policies focussed on **design for recyclability** and EPR -alongside private sector support to enable the necessary changes – will be key elements in ensuring the potential of increased sorting and recycling plastics is fully realised. With the new UK EPR scheme expected from 2024, this is anticipated to be a key enabler.

This report provides an initial assessment of the national picture, confirming the anticipated impact of sending all of Scotland's residual waste to high-efficiency sorting facilities. The practical ability to implement this on the ground – given Scotland's geography – would need to be assessed further (as this is not in scope of this work).

Deployment of **CCUS** is the next largest contributor to the reduction of forecast direct carbon emissions from residual waste, as is shown in Pathway 3. It is also the single largest net contributor to the decarbonisation of residual waste, when considering biogenic capture credits alongside the reductions in direct emissions. However, CCUS only decarbonises EfWs; it does not directly support keeping materials in circulation for longer nor promote a more circular economy (unlike AS). This assessment also takes an optimistic approach of the forecast level of deployment across the Scottish EfW fleet (broadly aligned with the CCC's modelled Tailwinds scenario).

Compared to AS, CCUS comes with greater risks and costs. Carbon capture itself is a proven technology, though a commercial scale carbon capture unit has not yet been deployed on a Scottish (or UK) incinerator. Furthermore, there are as yet no operational pipelines or storage options.

There is, however, significant support stemming from central UK Government and Scottish Government, as well as notable private sector engagement. The Scottish Cluster is currently in reserve to receive funding from BEIS, and – if not successful this round – can still apply to receive funding from the same source, the Cluster Sequencing Process, in the second round of funding. This Process also seeks to financially support selected emitters in fitting carbon capture and connecting to successful pipeline projects. EfWs are within scope of this funding.

As such, location is key for EfWs and ATTs to deploy CCUS, as is the facility's size (to make it commercially viable and competitive when bidding for funding). In Scotland, the ATTs are not considered to be well located for the Scottish Cluster, nor are they near the east coast (which might allow for shipping or direct piping of captured carbon). As for the EfWs, most are relatively near the pipeline and/or the east coast. Quite optimistically – much like AS – it has been assumed that those large enough (>100ktpa) and well-situated would install carbon capture. However, again like AS, the practical ability for technology implementation would need to be assessed on a case-by-case basis, to assess if EfWs have sufficient space, the right business case, and to consider either connection to a major carbon transport pipeline, or to agree contracts for utilisation or shipment options. There are many variables to consider in relation to the business case for each EfW.

Heat recovery, compared to CCUS and AS, resulted in a relatively lower impact on emissions (Pathway 2). This is in part due to assuming that only five facilities – Millerhill, GRREC, Aberdeen, Dundee and Earls Gate – out of 10 implement heat recovery and connect to heat networks. There is policy support for the development of heat networks generally, including funding such as the £300 million Heat Network Fund (some of which is supporting networks using heat from EfWs). However, unlike CCUS and AS, there is a less targeted focus on residual waste treatment facilities being the source of this heat. There is also a large investment requirement for these networks, and extensive retrofitting may not always be suitable or feasible (e.g., for highly dispersed demographics, or around heritage sites). Nonetheless, it must be acknowledged that the ability to retrofit is a potential barrier for all decarbonisation options discussed here, to varying extents.

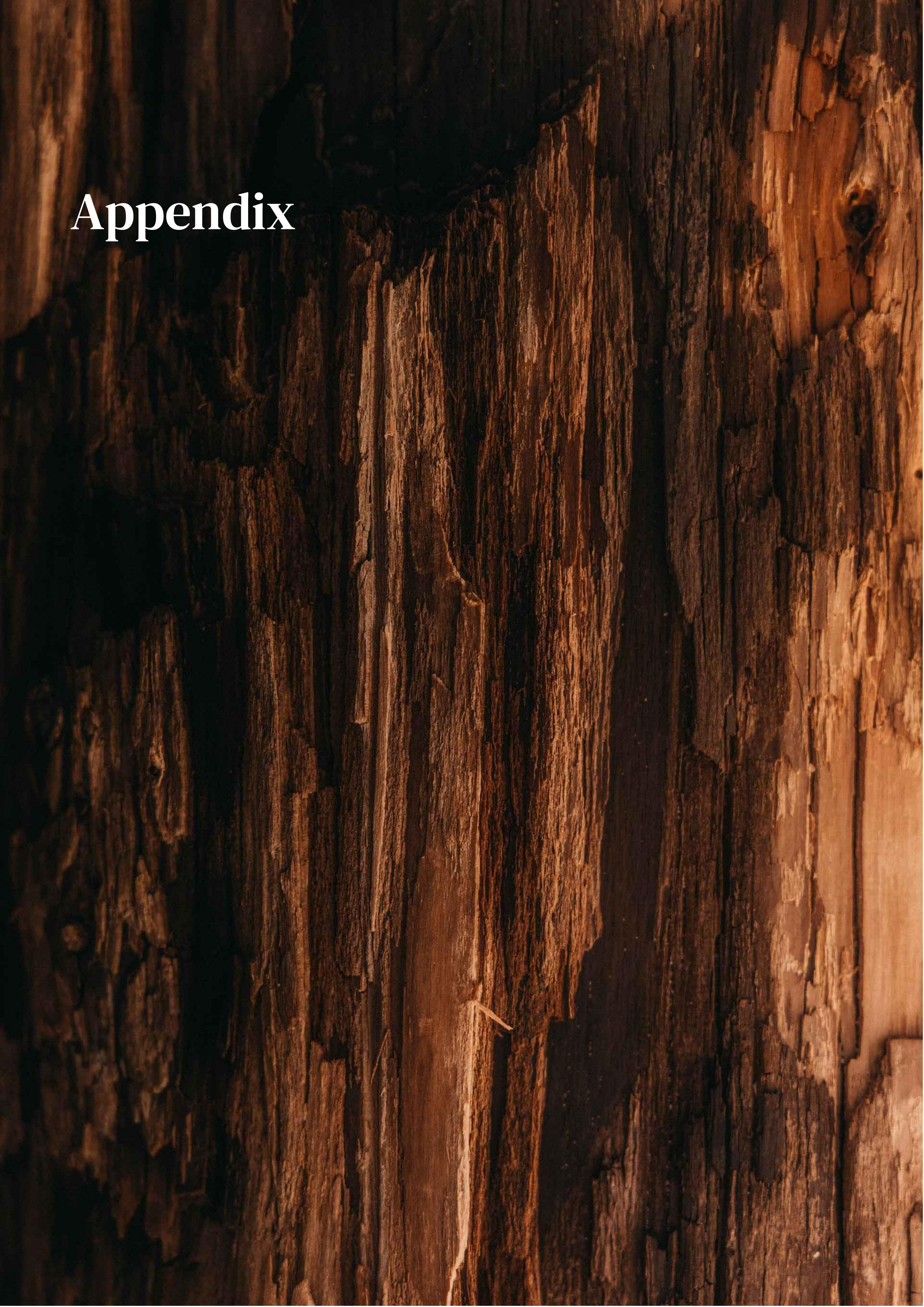
Additionally, as the marginal heat sources decarbonise, the comparative benefits associated with heat recovery from EfW will also decline over time (beyond 2035). For this reason, heat networks as a decarbonisation approach for EfW can in part be considered a transition technology, the benefit of which declines over time as low carbon heat costs reduce and becomes more readily available, and energy system decarbonisation progresses.

A further pathway demonstrates the potential impact of **biostabilisation** by sending 10kt of HH waste either directly to landfill or via an MBT where biostabilisation occurs. This was assessed to help demonstrate the potential benefit of this solution were it to be applied to rural and sparsely populated areas of Scotland that may not be well served by EfW or ATT facilities. In such areas, landfill usage may still be required in small quantities. The pathway showed a decrease in emissions (and possibility for net negative emissions, depending on accounting principles) for all three scenarios when stabilisation at MBTs occurs as pre-treatment. The total impact associated with the BES-P scenario is higher compared to the BES-F scenario, for two reasons. Firstly, BES-P has a higher proportion of food waste in its composition, increasing the impact of biostabilisation. Secondly, BES-P has a lower proportion of plastic in its composition, reducing the additional recycling benefits gained from sorting at the MBT.

In summary, to reduce direct emissions from the residual waste sector and promote a more circular economy, AS is identified as the most significant and readily deployable decarbonisation pathway modelled. It comes at a lower cost and risk compared to other technologies, is less dependent on public funding, and can be deployed imminently (albeit with greater effect as recyclability design improves). However, the largest net carbon reduction overall – including the benefits of capturing biogenic carbon – stems from the introduction of CCUS, across the majority of the Scottish EfW fleet. This level of impact modelled within this study is considered to be optimistic and will require the successful deployment of the Scottish Cluster in order to be fully achieved. Heat networks do have the benefit of energy benefits gained for EfW, although the impact of this will reduce as low carbon heat sources become more prominent. Nevertheless, the use and purpose of heat networks spans beyond the scope of the residual waste sector and this report. Finally, as the use of landfills for residual waste decreases into the future, the effect of decarbonisation technologies that impact landfill - such as biostabilisation – also reduces. However, where landfill use is unavoidable (e.g., due to geographical constraints), such technologies should still be considered.

Overall, this report outlines potential sequencing priorities and impacts from deployment of residual waste infrastructure decarbonisation technologies. Even so, the magnitude of the decarbonisation challenge required across the Scottish economy is immense. It should therefore be considered that all of these options – plus further core policies geared towards zero waste and the circular economy – are all vitally important to help Scotland achieve Net Zero by 2045.

Appendix



A 1.0 Baseline Carbon Appraisal - Assumptions and Results

A 1.1 Key Assumptions

A 1.1.1 Waste inputs and Flow

The following assumptions have been made with respect to how the waste flows through the various treatment facilities:

- No AS is assumed to be present in any of the baseline scenarios;
- A reduction in weight of 20% due to removal of moisture is assumed in MBT facilities, which is applied on top of kerbside recycling removal. The amount of recycling removed is dependent on the MBT capture rates described in Table 5-9, for the baseline, and Table 5-10Table 5-10, for the pathways;
- GRREC and Levenseat MBT facilities are assumed to directly feed their own ATT plants. The rest of the waste that is sorted by other MBT facilities is assumed to be directed to EfW plants;
- In the 2035 scenarios, it is assumed that a fixed 1% of C&I waste that is not pre-treated in an MBT is directed to landfill;
- The waste that is exported to England is assumed not to be pre-treated (no extraction of recyclables before export);
- The waste that is exported out of the UK is pre-treated to extract recyclables, according to the MBT capture rates described in Table 5-9. However, it is assumed that the waste that is exported is treated in separate facilities, and does not "occupy" the capacity of the MBT plants that are considered in this work;
- When generating the waste flows for the different scenarios, the following priority list has been used to determine to which destination the waste is sent to (i.e. the capacities are filled in sequentially up to their modelled capacity):
    1. MBT/Bio and MBT/RDF, and consequentially
        1.1. Recycling
        1.2. EfW and ATT (biodried waste) and landfill (biostabilised waste)
    2. EfW (no MBT treatment)
    3. ATT (no MBT treatment) - note: this flow is equal to zero as there is no waste going directly to ATT, as the only two existing ATT plants considered are fed by their respective MBT
    4. Exports to the UK
    5. Exports out of the UK
    6. Landfill (no MBT treatment)

- The model has been completed on a national level: the waste considered flows wherever there is capacity available, irrespective of the geographical location where is produced.

A 1.1.2 List of facilities

The complete list of operational facilities and those in the pipeline as presented in the analysis completed by Ricardo[99] is shown in Table 5-1. The list of facilities that have been considered in the model is an extract from those listed and includes all the operational facilities, those in construction plus those fully consented when necessary to meet the predicted waste tonnages: it is assumed that some of the facility will not come online due to overcapacity considering the amount of residual waste to be treated, as detailed in the footnotes. The modelled capacity for the facilities that have not been considered in this model has been set to 0.

Table 5-1: List of residual waste treatment facilities in Scotland

Facility name	Operational or pipeline?	Technology Type	Operational (start) date (assumed for future facilities)	Assumed closure date	Modelled capacity 2020 (t)	Modelled capacity 2035 (t)
DERL (MVV Baldovie)	Operational	EfW	1994	2028	92,000	-
Dunbar ERF	Operational	EfW	2019	2059	310,000	372,000
Dundee ERF	Operational	EfW	2021	2061	-	110,000
Lerwick EfW	Operational	EfW	2000	2040	23,000	23,000
Millerhill	Operational	EfW	2019	2059	155,000	155,000
GRREC	Operational	MBT and ATT	2019	2039	120,000[100]	120,000[100]
Levenseat	Operational	MRF and ATT	2018	2038	160,000[100]	160,000[100]
Eco Deco Dumfries	Operational	MBT	2006	2036	15,300[100]	15,300[100]
Dalinlongart Compost	Operational	Composting / MBT	2001	2031	13,000	-
Moleigh	Operational	Composting / MBT	1998	2028	3,000	-
Lingerton Compost	Operational	Composting / MBT	2001	2031	24,000	-
Earls Gate Energy Centre	Pipeline – In Construction	EfW	2023	>2035	-	201,000

[99] Ricardo for Scottish Government on behalf of the Independent Review of the role of Incineration in the Waste Hierarchy of Scotland, Incineration Review Capacity Analysis, April 2022, https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/incineration-review-capacity-analysis/incineration-review-capacity-analysis/govscot%3Adocument/incineration-review-capacity-analysis.pdf

[100] Modelled capacity takes into account the expected pre-treatment and waste reduction from the consented capacity by SEPA

Aberdeen Recycling & Energy Recovery (NESS)	Pipeline – In Construction	EfW	2022	>2035	-	127,500
Westfield EfW	Pipeline – In Construction	EfW	2025	>2035	-	212,500
Oldhall EfW (Dover Yard)	Pipeline – Fully Consented	EfW	(2026)[101]	(>2035)	-	0
South Clyde EfW (Fortum)	Pipeline – Fully Consented	EfW	(2026)[101]	(>2035)	-	0
Drumgray ERC (FCC)	Pipeline – Fully Consented	EfW	2026	>2035	-	255,000
Glenfarg EfW (Binn Group)	Pipeline – Planning Granted	EfW	(2025) [101]	(>2035)	-	0
Inverurie (Agile Energy Recovery)	Pipeline – Planning Granted	EfW	(2027) [101]	(>2035)	-	0
Levenseat 2	Pipeline – Planning Granted	EfW	(2027) [101]	(>2035)	-	0
Killoch EfW	Pipeline – Planning Granted	EfW	(2027) [101]	(>2035)	-	0
Avondale MRF/MBT	Pipeline – Fully Consented	MRF / MBT	2026	>2035	-	60,000[100]
Avondale EfW	Pipeline – Planning Granted	EfW	(2027) [101]	(>2035)	-	0

A 1.1.3 Composition

Due to the lack of availability of data detailing the total waste composition in Scotland (including residual and recycling), this has been derived from Waste and Resources Action Programme (WRAP's) 2017 National Household Waste Composition[102] and the National Commercial Waste Composition[103] reports. This is reported in Table 5-2 .

[101] It is assumed that this facility will not come online due to overcapacity considering the amount of residual waste to be treated

[102] WRAP, 2019, Bristol, National Household Waste Composition 2017, prepared by Eunomia Research & Consulting Ltd. https://wrap.org.uk/sites/default/files/2021-10/WRAP-national-household-waste-comparison-2017.pdf

[103] WRAP, 2019, National municipal commercial waste composition, England 2017, Prepared by Eunomia Research & Consulting Ltd. https://wrap.org.uk/sites/default/files/2020-11/WRAP-National%20municipal%20commercial%20waste%20composition_%20England%202017.pdf

Table 5-2: Total waste composition for household and commercial used in the model

Waste Stream	Household total composition (%)	Commercial total composition (%)
Paper	10.95%	33.47%
Card	6.47%	5.95%
Plastic Film	3.36%	7.08%
Dense Plastic	5.93%	8.01%
Textiles	4.73%	2.07%
Wood	3.83%	4.61%
Nappies & sanitary	3.69%	0.70%
Other misc. combustible	3.88%	3.73%
Other misc. non-combustible	5.90%	1.47%
Glass	6.86%	6.59%
Ferrous	2.46%	2.39%
Aluminium	1.29%	0.73%
WEEE	1.81%	0.66%
Potentially hazardous	0.40%	0.26%
Garden waste	17.06%	2.04%
Kitchen waste	18.19%	17.93%
Other putrescibles	2.26%	0.41%
Fines	0.93%	1.91%

A 1.1.4 Kerbside capture rates

The kerbside capture rates for each scenario are derived assuming that the total HH and commercial overall waste compositions, detailed in Table 5-2, do not change over time. Recycling capture rates at kerbside and at MBT facilities were developed using Eunomia's expertise on current and BESs and using the recycling targets detailed in Table 5-3. Improvements in recycling rates are not uniform across materials because some streams are harder to separate, reprocess or sell than others. It was therefore necessary to make different assumptions about the individual waste streams. These assumptions 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, taking into account the policy landscape for Scotland that is set out in Section 2.0. It is important to note that there is less data available on recycling rates for commercial waste, although this may improve in coming years as a result of the Environment Bill which, in the UK, could result in the collection of more arisings data.

Kerbside capture rates are summarised in Table 5-3. It is assumed that 100% of what is captured is recycled.

Table 5-3: Kerbside capture rates

Waste Stream	Current		BAU		BES-F		BES-P	
	HH (%)	C&I (%)	HH (%)	C&I (%)	HH (%)	C&I (%)	HH (%)	C&I (%)
Paper	49%	81%	56%	81%	56%	81%	56%	81%
Card	62%	77%	69%	77%	69%	77%	69%	77%
Plastic Film	7%	7%	41%	41%	41%	41%	68%	63%
Dense Plastic	25%	25%	41%	41%	41%	41%	68%	63%
Textiles	25%	25%	32%	25%	32%	25%	32%	25%
Wood	73%	61%	79%	61%	79%	61%	79%	61%
Nappies & sanitary	1%	6%	8%	6%	8%	6%	8%	6%
Other misc. combustible	3%	41%	10%	41%	10%	41%	10%	41%
Other misc. non-combustible	45%	11%	52%	11%	52%	11%	52%	11%
Glass	68%	81%	75%	81%	75%	81%	75%	81%
Ferrous	52%	31%	59%	31%	59%	31%	59%	31%
Aluminium	42%	51%	72%[104]	72%[104]	72%	72%	72%	72%
WEEE	56%	51%	62%	51%	62%	51%	62%	51%
Potentially hazardous	17%	1%	24%	1%	24%	1%	24%	1%
Garden waste	80%	88%	87%	88%	87%	88%	87%	88%
Kitchen waste	14%	51%	21%	51%	45%	70%	32%	52%
Other putrescibles	0%	11%	7%	11%	7%	11%	7%	11%
Fines	0%	41%	7%	41%	7%	41%	7%	41%

It is important to highlight that when considering plastics, both film and rigid, assumptions on recyclability, sorting and yield rates, in the current and future scenarios, have been made to derive a value that is reflective of the fact that 100% of what is captured is recycled. In particular,

[104] This is based on an assumed deposit scheme which could bring up to 80% of aluminium, with 90% recycling

Table 5-4 shows the assumed kerbside collection rates and recyclability for both HH and commercial streams.

Table 5-4: Kerbside collection rate and recyclability of rigid plastic and films

Plastic waste	Current	BAU	BES-F	BES-P
Kerbside collection rate - Rigids	45%	45%	45%	75%[105]
Kerbside collection rate - Films	45%	45%	45%	75%[105]
Recyclability - Rigids	55%	90%	90%	90%
Recyclability - Films	15%	90%	90%	90%

A future combined recyclability-sorting efficiency-yield of 90% has been assumed for 2035. This is the best-case scenario which involves significant improvement in design for recyclability and consequential improvements in sorting and recycling yield efficiencies, and an uptake of plastic recyclates in the market that would justify this level of recycling.

A 1.1.5 Emission factors

Table 5-5Table 5-5 shows the benefits associated with recycling of waste sorted through MBT or AS (note advance sorting only happens in the decarbonisation pathways).

The recycling credits associated with kerbside recycling have not been included in the analysis.

Table 5-5: Recycling benefits of material sorted with MBT or Advanced Sorting

Waste streams	t CO_2e/t
Paper	-0.30
Card	-0.10
Plastic Film	-1.17
Dense Plastic	-1.60
Textiles	-3.28
Wood	-0.40
Other misc. non-combustible	-0.23
Glass	-0.23
Ferrous	-1.80
Aluminium	-8.70

[105] A collection rate of 70% for commercial plastic has been assumed to meet the recycling target detailed in the Ricardo report

WEEE	-1.10
Garden waste	-0.02
Kitchen waste	-0.17
Other putrescibles	-0.17

A 1.1.6 Emissions from Waste Treatment

A 1.1.6.1 Energy and Heat Marginals

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 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). In the case of heat provision, the counterfactual source tends to be natural gas, which meets a large majority of UK buildings' heat demand. 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.

The following assumptions on energy and heat marginals were made for this work:

- Electricity: The marginal electricity emissions intensity as forecast by BEIS for the years 2020 and 2035 was used: 0.270 kgCO_2e/kWh and 0.041 kgCO_2e/kWh respectively[106];
- Heat: The marginal associated with heat generation in the 2020 scenario is 0.202 kgCO_2e/kWh, and this is equivalent to the emissions associated with natural gas[107]. In the future scenarios, in the absence of relevant sources, we have assumed a decarbonisation of heat for domestic use of 40% and of heat for industrial use of 5%, bringing to an emission factor equal to 0.157 kgCO_2e/kWh.

A 1.1.6.2 Landfill

The parameters that have been used to determine the emissions factors associated with landfill are described in Table 5-6Table .

Table 5-6: General assumptions used in landfill modelling

Assumption	Value
Proportion of biogenic carbon stored (100 years)	52%
Composition of landfill gas	50% methane / 50% carbon dioxide

[106] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal#full-publication-update-history
[107] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022

Landfill gas use	60% used to generate electricity / 40% flared
Landfill gas capture rate	60%
Gas engine efficiency	35%
GWP100 of methane	34
GWP N_2O	265
Time horizon of methane emissions	100 years

Landfill modelling is largely in line with the national methane emissions model used in the UK's submission to the United Nations Framework Convention on Climate Change (UNFCCC), apart from the application of the 'sequestration' credit for the storage of biogenic carbon (un-emitted carbon that otherwise would in effect be assumed to be emitted as biogenic CO_2). In fact not all the carbon in the waste sent to landfill is released as carbon dioxide within the 100-year period that is considered in this work. 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'[108]. 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. In this way, landfills act as an imperfect 'carbon capture and storage' facility. In contrast, all of the biogenic and fossil CO_2 emissions are released from incineration at the point of combustion.

A 1.1.6.3 Energy and Heat generation of EfW and ATT plants

The following assumptions on the energy generation of EfW plants have been made:

- In the current and future (BAU, BES-P and BES-F) baseline scenarios, it is assumed that only Lerwick operates in heat only mode and all other plants are operating as electricity only (there are no plants operating in CHP mode);
- The energy generation efficiency of existing EfW plants was calculated from the data reported under Freedom of Information request raised to the Scottish government on the topic[109]. EfW efficiencies used in the model are summarise in Table 5-7.

Table 5-7: Average energy generation efficiencies of EfW

Operating Mode	Energy generation efficiency 2020	Energy generation efficiency 2035
Electricity only	25%	28%
Heat only (Lerwick)	66%	66%

[108] 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
[109] https://www.gov.scot/publications/foi-202200294973/

The energy generation efficiencies used for the ATT plants are presented in Table 5-8. These were calculated from the data reported under Freedom of Information request raised to the Scottish government on the topic[109].

Table 5-8: Average energy generation efficiencies of ATT

Operating Mode	Energy generation efficiency 2020	Energy generation efficiency 2035
Electricity only	13%	13%

A 1.1.6.4 Capture rates of MBT facilities

Key assumptions for MBT facilities include the recycling capture rates for the recycling streams recovered as part of the mechanical sorting processes. The assumed capture rates of the MBT facilities for all the baseline scenarios are summarised in Table 5-9. It is assumed that 100% of what is captured is recycled.

Table 5-9: Capture rates at MBT facilities (in the baseline)

Waste Stream	Current		BAU		BES	
	HH (%)	C&I (%)	HH (%)	C&I (%)	HH (%)	C&I (%)
Dense Plastic[110]	0%	0%	25%	25%	25%	25%
Ferrous	75%	75%	75%	75%	75%	75%
Aluminium	40%	40%	40%	40%	40%	40%

A 2.0 Decarbonisation Pathways Carbon Appraisal - Assumptions and Results

A 2.1 Key Assumptions

A 2.1.1 Advanced Sorting

Advanced mechanical pre-treatment systems use a series of mechanical processes to remove recyclable materials from the residual waste stream. This includes the targeting of dense plastics

[110] Assumptions on recyclability, sorting and yield rates for dense plastics, in the current and future scenarios, have been made to derive a value that is reflective of the fact that 100% of what is captured is recycled.

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. All of the pathways examine advanced mechanical pre-treatment in conjunction with EfW plants. In the pathways where AS is included, it is assumed that 100% of the waste that was previously going directly to EfW plants in the baseline is now treated by AS before being directed to incineration. Moreover, it is assumed that the capture rates of the operating MBTs are also increased to replicate those of the AS systems.

The assumed capture rates of AS are summarised in Table 5-10. It is assumed that 100% of what is captured is recycled.

Table 5-10: Advanced sorting capture rates

Waste Stream	Sorting capture rates 2035	
	HH (%)	C&I (%)
Paper	50%	50%
Card	45%	45%
Plastic Film	70%	70%
Dense Plastic	70%	70%
Ferrous	85%	85%
Aluminium	85%	85%

It is important to highlight that, similarly to the kerbside capture rates, when considering plastics, both film and rigid, assumptions on recyclability, sorting and yield rates have been made to derive a value that is reflective of the fact that 100% of what is captured is recycled. This includes a future combined recyclability-sorting efficiency-yield of 90% for all plastics in 2035. This is the best-case scenario which involves significant improvement in design for recyclability and consequential improvements in sorting and recycling yield efficiencies, and an uptake of plastic recyclates in the market that would justify this level of recycling.

A 2.1.2 CCUS

In Table 5-11 the list of EfW plants that will potentially be operating in 2035 is reported. In the table, the facilities which have potential for CCUS are highlighted, and have been determined according to the following assumptions:

- Minimum annual capacity of 100,000 tonnes
- Located close to a potential Scottish CCUS cluster project

An efficiency in carbon capture of 90% was assumed[111].

Table 5-11: List of EfW facilities with CCUS and efficiency of CO_2 capture

Facility name	Operational or pipeline?	Modelled capacity 2035 (t)	CCUS?	Efficiency of CO_2 capture
Dunbar ERF	Operational	372,000	✓	90%
Dundee ERF	Operational	110,000	✓	90%
Lerwick EfW	Operational	23,000	x	
Millerhill	Operational	155,000	✓	90%
GRREC ATT	Operational	85,200	x	
Levenseat ATT	Operational	113,600	x	
Earls Gate Energy Centre	Pipeline – In Construction	201,000	✓	90%
Aberdeen Recycling & Energy Recovery (NESS)	Pipeline – In Construction	127,500	✓	90%
Westfield EfW	Pipeline – In Construction	212,500	✓	90%
Drumgray ERC (FCC)	Pipeline – Fully Consented	255,000	✓	90%

The capture and compression of CO_2 incurs an energy loss (additional parasitic load) in the form of the provision of steam and power. The size of this loss will depend on the efficiency of the capture process. The efficiency of the plants with CCUS has been reduced to account for this, as detailed in Table 5-12.

Table 5-12: Efficiency of EfW with integrated CCUS

Operating Mode		Energy Generation Efficiency
Electricity only	Electricity	25%
CHP	Electricity	19%
	Heat	16%

The decrease in efficiency was calculated using the specific power consumption per tonne of CO_2 captured[112]. In case of electricity only EfW, it was assumed that the heat consumption required for CO_2 capture would be supplied from another source, while for CHP operating EfW, the heat consumption was deducted from the heat recovered during combustion.

[111] For a solvent based CO_2 capture (35%MEA) with 90% CCR - extracted from Report on the technical comparison of the investigated WtE CCUS technologies, NEWEST-CCUS, July 2022
[112] For a solvent based CO_2 capture (35%MEA) with 90% CCR - extracted from Report on the technical comparison of the investigated WtE CCUS technologies, NEWEST-CCUS, July 2022

A 2.1.3 Heat Recovery

Following discussions with the Scottish Government heat networks team, it was agreed that the facilities that would most likely develop heat networks in the near term are Millerhill, Aberdeen Recycling & Energy Recovery (NESS), GRREC, Dundee and Earls Gate Energy Centre. These have been modelled as operating in CHP mode in the pathways that include heat recovery. The efficiencies of the four EfW plants (Millerhill, Aberdeen, Dundee, and Earls Gate Energy Centre) and the ATT plant (GRREC) operating in CHP mode that have been used in the model are detailed in Table 5-13 and Table 5-15. Due to the lack of actual data on the potential efficiencies of these plants, the values used are based on average best practices observed in other plants in the UK and the efficiencies of the plants operating in electricity generation mode only[113].

Table 5-13: Efficiencies of EfW plants with heat recovery (operating as CHP)

Operating Mode		Energy generation efficiency
CHP	Electricity	20%
	Heat	20%

Table 5-14: Efficiencies of ATT plants with heat recovery (operating as CHP)

Operating Mode		Energy generation efficiency
CHP	Electricity	13%
	Heat	13%

A 3.0 Carbon Emissions Results

A 3.1 Baseline emissions

A detailed breakdown of the GHG impacts of each technology for each scenario of the baseline is given in Table 5-15.

Table 5-15: Baseline - Detailed breakdown of greenhouse gas emissions by technology for each scenario

Technology option	Waste composition	Current ($ktCO_2e$)	BAU ($ktCO_2e$)	BES-F ($ktCO_2e$)	BES-P ($ktCO_2e$)

[113] If the plants were operating in heat only mode, overall efficiency for heat would be higher. Other countries also present higher CHP efficiencies, however due to the lack of actual data for the plants considered, the values used are based on average best practices observed in other plants in the UK and the efficiencies of the plants operating in electricity generation mode only

Recycling	recycling (post MBT)	-35	-48	-52	-45
EfW ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated	25	86	94	64
EfW HEAT ONLY - MBT pre-treated (biodried)	pre-treated	0	0	0	0
EfW ELECTRICITY ONLY - No MBT treatment	direct	137	427	408	241
EfW HEAT ONLY - No MBT treatment	direct	1	1	2	0
ATT ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated	116	102	112	75
Exports to England	direct	61	0	0	0
Exports out of UK	pre-treated	31	0	0	0
Landfill - MBT pre-treated (biostabilised)	pre-treated	3	0	0	0
Landfill - No MBT treatment	direct	324	1	1	1
Total		**663**	**570**	**565**	**337**

A 3.2 Pathways emissions

A detailed breakdown of the GHG impacts of each technology across each pathway is given in Table 5-16, Table 5-17, Table 5-18 and Table 5-19Table 5-19.

Table 5-16: Pathway 1 (Advanced Sorting) - Detailed breakdown of greenhouse gas emissions by technology for each scenario

Technology option	Waste composition	BAU (ktCO$_2$e)	BES-F (ktCO$_2$e)	BES-P (ktCO$_2$e)
Recycling	recycling (post adv sorting) + recycling (post MBT)	-451	-449	-343
EfW ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	44	48	37
EfW CHP - MBT pre-treated (biodried)	pre-treated (MBT)	0	0	0
EfW HEAT ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	0	0	0

EfW ELECTRICITY ONLY - No MBT treatment	advanced sorted	183	175	125
EfW CHP - No MBT treatment	advanced sorted	0	0	0
EfW HEAT ONLY - No MBT treatment	advanced sorted	0	0	-1
ATT ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	52	57	44
ATT CHP - MBT pre-treated (biodried)	pre-treated (MBT)	0	0	0
Exports to England	direct	0	0	0
Exports out of UK	direct	0	0	0
Landfill - MBT pre-treated (biostabilised)	pre-treated (MBT)	0	0	0
Landfill - No MBT treatment	direct	1	1	1
Total		**-171**	**-168**	**-136**

Table 5-17: Pathway 2 (Advanced Sorting and Heat Recovery) - Detailed breakdown of greenhouse gas emissions by technology for each scenario

Technology option	Waste composition	BAU (ktCO$_2$e)	BES-F (ktCO$_2$e)	BES-P (ktCO$_2$e)
Recycling	recycling (post adv sorting) + recycling (post MBT)	-451	-449	-343
EfW ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	26	28	22
EfW CHP - MBT pre-treated (biodried)	pre-treated (MBT)	13	15	11
EfW HEAT ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	0	0	0
EfW ELECTRICITY ONLY - No MBT treatment	advanced sorted	107	102	73
EfW CHP - No MBT treatment	advanced sorted	50	49	30
EfW HEAT ONLY - No MBT treatment	advanced sorted	0	0	-1
ATT ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	30	33	25

ATT CHP - MBT pre-treated (biodried)	pre-treated (MBT)	18	20	15
Exports to England	direct	0	0	0
Exports out of UK	direct	0	0	0
Landfill - MBT pre-treated (biostabilised)	pre-treated (MBT)	0	0	0
Landfill - No MBT treatment	direct	1	1	1
Total		**-206**	**-200**	**-166**

Table 5-18: Pathway 3 (Advanced Sorting and CCUS) - Detailed breakdown of greenhouse gas emissions by technology for each scenario

Technology option	Waste composition	BAU (ktCO$_2$e)	BES-F (ktCO$_2$e)	BES-P (ktCO$_2$e)
Recycling	recycling (post adv sorting) + recycling (post MBT)	-451	-449	-343
EfW ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	-70	-67	-75
EfW CHP - MBT pre-treated (biodried)	pre-treated (MBT)	0	0	0
EfW HEAT ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	0	0	0
EfW ELECTRICITY ONLY - No MBT treatment	advanced sorted	-405	-342	-377
EfW CHP - No MBT treatment	advanced sorted	0	0	0
EfW HEAT ONLY - No MBT treatment	advanced sorted	0	0	-1
ATT ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	52	57	44
ATT CHP - MBT pre-treated (biodried)	pre-treated (MBT)	0	0	0
Exports to England	direct	0	0	0
Exports out of UK	direct	0	0	0
Landfill - MBT pre-treated (biostabilised)	pre-treated (MBT)	0	0	0
Landfill - No MBT treatment	direct	1	1	1

Total	**-873**	**-800**	**-750**

Table 5-19: Pathway 4 (Advanced Sorting. Heat Recovery and CCUS) - Detailed breakdown of greenhouse gas emissions by technology for each scenario

Technology option	Waste composition	BAU (ktCO$_2$e)	BES-F (ktCO$_2$e)	BES-P (ktCO$_2$e)
Recycling	recycling (post adv sorting) + recycling (post MBT)	-451	-449	-343
EfW ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	-41	-39	-44
EfW CHP - MBT pre-treated (biodried)	pre-treated (MBT)	-33	-32	-35
EfW HEAT ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	0	0	0
EfW ELECTRICITY ONLY - No MBT treatment	advanced sorted	-237	-201	-221
EfW CHP - No MBT treatment	advanced sorted	-189	-161	-174
EfW HEAT ONLY - No MBT treatment	advanced sorted	0	0	-1
ATT ELECTRICITY ONLY - MBT pre-treated (biodried)	pre-treated (MBT)	30	33	25
ATT CHP - MBT pre-treated (biodried)	pre-treated (MBT)	18	20	15
Exports to England	direct	0	0	0
Exports out of UK	direct	0	0	0
Landfill - MBT pre-treated (biostabilised)	pre-treated (MBT)	0	0	0
Landfill - No MBT treatment	direct	1	1	1
Total		**-903**	**-827**	**-777**

A 3.3 Biostabilisation emissions

A breakdown of the GHG impacts comparing the scenarios described in Section 4.4 is given in Table 5-20 and Table 5-21.

Table 5-20: GHG emissions associated with 10kt of residual household waste landfilled without biostabilisation

Technology option	Waste composition	BAU (ktCO$_2$e)	BES-F (ktCO$_2$e)	BES-P (ktCO$_2$e)
Landfill - No MBT treatment	direct	3.9	3.8	4.1
Total		**3.9**	**3.8**	**4.1**

Table 5-21: GHG emissions associated with 10kt of residual household waste landfilled after MBT and biostabilisation

Technology option	Waste composition	BAU (ktCO$_2$e)	BES-F (ktCO$_2$e)	BES-P (ktCO$_2$e)
Recycling	recycling (post MBT)	-2.1	-2.3	-1.8
Landfill - MBT pre-treated (biostabilised)	pre-treated (MBT)	0.6	0.6	0.6
Total		**-1.5**	**-1.7**	**-1.2**

A 4.0 REA Methodology & Outcomes

Research questions were defined to help inform and guide the assessment conducted. These questions were in part answered via an initial review of the evidence: a REA was undertaken. This informed a wide range of the research questions and informed the delivery of many of the tasks. Nearly 100 sources were included in the REA, which covered;

- Baseline Carbon of existing infrastructure - GHG emissions
- Baseline Carbon of existing infrastructure - Types and volumes of waste
- Current and Future Policy for Decarbonisation
- Heat Networks - Energy potential of heat networks, opportunities, issues, efficiency, regulations
- CCUS – Opportunities, issues, efficiency, and regulations
- Other Potential Decarbonisation Technologies
- Treatment Options:
    - Incinerators
    - Gasification

    - Pyrolysis
    - Landfill
    - Cement Kilns
    - MBT
    - Biostabilisation
    - RDF Export
    - Heat recovery
    - Heat networks
- Decarbonisation of transport
- Removal of plastic from the residual waste stream by sorting
- Systematic changes

Sources were ranked low, medium or high based on their relevance to the research, with the key data, statistics and information being pulled out and included within the main body of this report.

A 4.1 Call for Evidence Responses

Between December 2021 and February 2022, the Scottish Government launched a Call for Evidence to seek data and information in the context of Scotland's waste management ambitions, in particular to gather stakeholders evidence with respect to the capacity required to manage residual waste, the economic, environmental and social trade-offs of the residual waste management options and the potential improvements to existing residual waste treatment facilities in terms of carbon performance and societal impact [114]. The Scottish Government received 57 responses, which have been summarised in the evidence document published in April 2022[115].

The evidence document, together with the research completed by Ricardo[116] which has formed the baseline data on tonnages, recycling rates and facilities' capacities used in this work, was used to generate provisional recommendations to the Scottish Government as part of the wider independent Review[117].

[114] https://consult.gov.scot/environment-forestry/incineration-review-call-for-evidence/#:~:text=The%20deadline%20for%20responses%20to,for%20Evidence%20is%20through%20CitizenSpace.
[115] https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-evidence-document/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-evidence-document/govscot%3Adocument/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-evidence-document.pdf
[116] Ricardo for Scottish Government on behalf of the Independent Review of the role of Incineration in the Waste Hierarchy of Scotland, Incineration Review Capacity Analysis, April 2022, https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/incineration-review-capacity-analysis/incineration-review-capacity-analysis/govscot%3Adocument/incineration-review-capacity-analysis.pdf
[117] https://www.gov.scot/binaries/content/documents/govscot/publications/independent-report/2022/05/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland/documents/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-report/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-report/govscot%3Adocument/stop-sort-burn-bury-independent-review-role-incineration-waste-hierarchy-scotland-report.pdf

Some of the questions and responses raised as part of the Call for Evidence, and the related provisional recommendations raised to the Scottish Government, have been highlighted below as relevant for this work.

A 4.1.1.1 Waste composition

Most responses provided to the Call for Evidence[115] on what data are needed to improve the capacity analysis included these points:

- *Detailed waste composition analysis from local authorities;*
- *Expanding analysis beyond 2025 and incorporating a scenario for banning all biodegradable waste rather than just municipal; and*
- *Waste reduction considerations, as well as analysis of impact of EPR requirements and the DRS.*

The second provisional recommendation[117] of the Review states the following:

> *The Scottish Government should develop better waste management data, especially around the composition of all types of waste […].*

As part of the analysis conducted in this work, the waste composition has been derived from the WRAP's 2017 National Household Waste Composition[118] and the National Commercial Waste Composition[119] reports as detailed in Appendix A 1.1.3, which was completed for England in 2017. We therefore agree with the need for a detailed waste composition analysis, as this will affect the emissions associated with the waste treatment facilities that have been evaluated in this work.

A 4.1.1.2 Improving carbon performance of existing residual waste treatment facilities

The key considerations highlighted in the Call for Evidence responses[115] on this topic include:

- *Prioritise recycling and reuse, these are preferable economically, environmentally, and socially;*
- *A strategic approach is needed to decarbonise the sector aided by the development of a residual waste reduction plan;*
- *Measures to decarbonise residual waste are reliant in part on the success of policy drivers elsewhere in the system;*
- *A more transparent reporting of the carbon emissions of incineration is required.*

This has partly translated into the first provisional recommendation of the Review[117] which states:

> *Scottish Government should rapidly seek further reductions in the proportion of recyclable materials in the residual waste stream. […]*

[118] WRAP, 2019, Bristol, National Household Waste Composition 2017, prepared by Eunomia Research & Consulting Ltd. https://wrap.org.uk/sites/default/files/2021-10/WRAP-national-household-waste-comparison-2017.pdf
[119] WRAP, 2019, National municipal commercial waste composition, England 2017, Prepared by Eunomia Research & Consulting Ltd. https://wrap.org.uk/sites/default/files/2020-11/WRAP-National%20municipal%20commercial%20waste%20composition_%20England%202017.pdf

And the 13th provisional recommendation:

> *(Provisional) The Scottish Government should immediately strengthen existing requirements for pre-treatment and work with local authorities and industry to apply them to all existing and future incineration facilities to remove as much recyclable material as feasible, with a particular focus on plastics.*

As shown in the results of this work, the removal of recyclables such as plastics and metals from the residual waste stream, in particular through AS facilities, has a significant impact on the total emissions associated with residual waste management. Thanks to the credits associated with recycling and the lower impact of incineration, when plastics are removed from the stream, net negative emissions can be achieved. This result however is reliant on the success of other policy drivers, such as improved design for recyclability of plastics, and high capture rates of certain waste streams, such as aluminium, trough, for instance, deposit schemes.

A 4.1.1.3 Heat recovery

The 14th provisional recommendation to the Scottish Government states[117]:

> *(Provisional) The Scottish Government and local authorities should continue to work with industry to deploy combined heat and power for as many existing incineration facilities as possible*

The responses to the Call for Evidence[115] partly touched on heat, and raised multiple differing views among stakeholders, such as[120]:

- *There are examples of heat networks and district heating that function very well[121] ;*
- *There is a need to be careful about sources of heat in the future as lifespan of housing is longer than that of an incineration plant[121];*
- *Heat networks based on incinerators are expensive and unreliable for the communities forced to use them;*
- *Concerns that incinerators have little or no chance of low-cost heat and no community incentive payment as the windfarm operators provide;*
- *Costs where residents may be tied into paying above market price for their heating;*
- *(Potential of heat networks to) provide low and stable cost heat, including in communities suffering fuel poverty.*

As part of this work, we analysed the potential decarbonisation effect associated with running five out of the 10 EfW and ATT in CHP mode. The decrease in total emission was measured as -12% (in comparison to a scenario that included just AS), as detailed in Section 4.3. This relatively low decrease is due to the fact that the marginal heat sources in the future are set to decarbonise, making the impact of heat recovery relatively minimal in the future. The potential for heat networks however should be evaluated considering the local conditions around each incinerator, with particular focus on potential use of heat for industrial use, including considerations on costs and likely timescale for the technology development. Heat networks

[120] These points have been raised by stakeholders during the Call for Evidence review and are reported without modifications: these do not reflect the results concluded in this report in any way
[121] Note: this comment was raised as part of the stakeholder engagements events carried out during the Review

however can be considered a transition technology, the benefit of which declines over time as energy system decarbonisation progresses.

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