Greenhouse Gas and Air Quality Impacts of Incineration and Landfill

Report to National Toxic Network

Ann Ballinger

William Shanks

Tamsin Miles

Sophie Degagny

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Prepared by Ann Ballinger, William Shanks, Tamsin Miles, and Sophie Degagny

Approved by

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Dr Chris Sherrington

(Project Director)

Eunomia Research & Consulting Ltd
37 Queen Square
Bristol
BS1 4QS

United Kingdom

Tel: +44 (0)117 9172250
Fax: +44 (0)8717 142942

Web: www.eunomia.co.uk

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1.0 Introduction

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

- Landfill;
- Landfill with pre-treatment and bio-stabilisation;
- Incineration;
- Incineration with pre-treatment;
- Refuse Derived Fuel (RDF) for co-firing in a cement kiln or for export to Malaysia

The report focusses on the following impacts:

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

We have modelled four scenarios to account for variability in waste composition – the variability depending on whether Australia meets its recycling target or not by 2030 – and variability in the marginal electricity generation source.

The report compares the technologies from an Australian perspective, making use of data from other countries in the analysis where data from Australia is not yet available.

The report comprises the following key sections:

- Section 1.0 describes the context and motivation behind this study and gives an overview of the status of incineration technology adoption for each state;
- Section 2.0 describes the residual waste treatment systems compared within the study and describes the scenarios examined;
- Section 3.0 presents the results of the study. It compares the climate change and air quality impacts of the treatment technologies modelled;
- Section 4.0 compares the climate change impacts of incineration to other electricity generation methods; and
- Section 5.0 gives conclusions and recommendations based on the findings of this study.

1.1 Context

There are two large-scale incineration facilities currently under construction in Western Australia and proposals in development for other large-scale facilities across the country.[1] These facilities, which will convert residual waste to electricity using a mass combustion incineration process, will be the first of their type in Australia.[2]

The use of incineration technology is a contentious area of waste management. Incineration is seen by some as a technology to reduce the carbon emissions from residual waste treatment, through diverting waste from landfill and reducing the need to burn fossil fuels in conventional power plants. Those who sell this technology consider it to be the 'missing link in Australia's waste management hierarchy'.[3]

By contrast, opponents of the development of incineration facilities suggest that these facilities do not, in fact, reduce climate change emissions when impacts are properly accounted for - and also emit other pollutants which are damaging to human health. In addition they are concerned that large volumes of ash contaminated with persistent organic pollutants will still have to be landfilled leading to future contamination problems.

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

The study found that "typical UK incinerators, generating only electricity, are unlikely to be emitting a lower quantity of greenhouse gases… than the average gas-fired power station in the UK," and that the convention of 'ignoring' biogenic carbon dioxide – that coming from organic- as opposed to fossil-based materials – is not always appropriate for comparing incineration to landfill, as it does not take into account the time profile of GHG emissions or the sequestration effect of landfill. A more recent study, produced by Eunomia for Client Earth in 2020, considered the potential performance of facilities in 2030. Facilities operating in combined heat and power (CHP) mode performed better than landfill under the conditions modelled in that study, but incinerators generating only electricity did not consistently outperform landfill in the situation where UK authorities met recycling targets.[5] Opportunities to use CHP mode in Australia are likely to be very limited as district heating is not needed; the only opportunities will be linked to industrial heat users. Australian incinerators burning MSW residue are therefore

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[1] Infrastructure Partnerships Australia, Putting Waste to Work, Development a Role for Energy from Waste, p. 3.
[2] Australian Renewable Energy Agency (ARENA), Submission 15, p. 4.
[3] SUEZ Australia & New Zealand, Submission 58, p. 2.
[4] Eunomia Research & Consulting (2006) *A Changing Climate for Energy from Waste?*, 2006
[5] Eunomia (2020) Greenhouse Gas and Air Quality Impacts of Incineration and Landfill, Report for Client Earth

expected to only generate electricity except in some specific industrial heat off-take scenarios.

Other analyses have included that from the UK Without Incineration Network – which made recommendations as to how carbon assessments on incineration facilities should be undertaken, and work by Policy Connect, which made the case for the role of incinerators in reducing climate change emissions, where such facilities utilised carbon capture and storage and operated in CHP mode.[6] Carbon capture and storage (CCS) remains an unproven technology and, like CHP, is not expected to be implemented in the context of Australian incinerator operation. No current Australian incinerator projects propose to use CCS.

Alongside this – as was noted by Zero Waste Europe in 2019 - incineration was excluded from the list of economic activities included by the European Commission within its EU Taxonomy. These are activities that can make a substantial contribution to climate change mitigation, and which do no harm to other environmental objectives such as waste prevention and recycling.[7]

In Australia, looking ahead, it is anticipated that the fossil carbon content (mainly embodied in plastic waste) in the residual waste stream will increase as policies to recycle more food and green waste gather pace and are implemented. However, a significant amount of plastic will remain in the waste stream even if plastic recycling rates improve, because plastic film and other polymers (e.g. PVC) are typically not easily recycled. These changes to the residual waste stream will have a significant impact on the carbon emissions from some waste treatment options, especially in reducing methane emissions from landfill – a far more potent greenhouse gas than CO_2.

A deeper understanding of methane's climate-changing potential has led to an increase in the climate impacts attributed to methane and accounted for in modelling (as approximated by its Global Warming Potential (GWP), the heat absorbed by a gas in the atmosphere divided by the heat that the same mass of carbon dioxide would have absorbed). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The increase in the GWP of methane in the past 10 years means the performance of landfill has worsened with respect to climate change impacts depending on the level or organics diverted from landfill. Organics drive methane (and leachate) production from landfills so high rates of organic waste diversion can result in better emission performance of landfill than incineration.

As well as this, the impacts of carbon dioxide and methane on global warming vary over time. Methane is extremely potent in the first couple of decades after emission but decays or is removed from the atmosphere more quickly than carbon dioxide. This

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[6] UKWIN (2021) Good Practice Guide for Assessing the GHG Impacts of Waste Incineration; Policy Connect (2020) *No Time to Waste: Resources, recovery & the road to net-zero*, July 2020, https://www.policyconnect.org.uk/research/no-time-waste-resources-recovery-road-net-zero

[7] Zero Waste Europe (2019) Waste-to-Energy is not Sustainable Business, the EU says: Policy Briefing

means that the timescale used in the analysis has a critical impact on conclusions: from a 20-year perspective landfill is a less favourable treatment method than from a 100-year perspective. Conversely, while incineration emits carbon dioxide instantaneously, landfill emits greenhouse gases on multi-decadal timescales. For example, 100% of fossil carbon in plastic wastes is permanently stored in a landfill. More than 80% of biogenic carbon from wood and many types of paper is stored for decades in a landfill. Up to 20% of carbon in food scraps is even stored long term in a landfill. This means that impacts of landfill and incinerators are not equivalent when viewed over different timescales, which is critical when considering the urgency of climate change – these points are often omitted from analyses comparing landfill and incineration.

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

1.2 Status of EfW Policy

There is no specific national EfW policy guidance in Australia; each State and Territory is developing its own policy position. However, in some cases the federal government policy documents do make some recommendations on national policy. Commonly, the policy approach limits thermal recovery of energy to residual waste streams which currently have no viable alternative to landfilling; investment in some mechanical biological treatment systems has occurred as a result – this involves the application of mechanical sorting systems which are used to extract recyclables from the residual stream. In addition, the Australian government has funded the largest waste management infrastructure investment in its history with a key focus on plastic reprocessing infrastructure. National plastic and other waste management policies have clearly been designed to provide business and economic support and incentives, particularly for the plastic reprocessing, Refuse Derived Fuel and Waste to Energy Incineration sectors and chemical recycling sectors.[8] Alongside this, a majority of Australian EfW policy documents outline eligibility criteria.

1.2.1 Federal Government

The National Waste Policy Action Plan has set several targets, including achieving an 80% average recovery rate from all waste streams by 2030 and a 50% reduction in organic waste to landfill by 2030. However, it does not differentiate between recovery and recycling. It is then down to States and Territories to implement policies and strategies to get there.

At a federal level, the impetus for the development of the energy from waste sector is being driven by the Clean Energy Finance Corporation (CEFC) supported by the

[8] See https://www.awe.gov.au/environment/protection/waste/publications/plastics-infrastructure-analysis-update

Australian Renewable Energy Agency (ARENA). In 2015 CEFC published a market report entitled "Bioenergy and Energy from Waste". That report identified up to $3.3 billion of potential investment in urban energy from waste – it also noted that generating electricity and heat from waste resources could be cost competitive with other new-build energy generation in terms of capital expenditure but that the technologies were not yet widely deployed in Australia. This was followed in November 2016 by a further CEFC market report entitled "Energy from Waste in Australia: A state by state update" which highlights that *"facilities that turn urban waste into electricity are a major investment opportunity in the Australian energy from waste sector*".

It is noted that – at a federal level – there is some lack of clarity in some documents in respect of the definition of recycling, particularly in relation to plastics. The term is not defined in the recently published Australian Recycling and Waste Reduction Act.[9] Definitions are provided in the slightly earlier Plastics Infrastructure Analysis Update published by the Department of Environment and Energy; the definitions focus on re-processing operations, with a further distinction also being made between such activity and recovery operations.[10] The Circular Economy Roadmap published by Australia's national Science Agency (CSIRO) assumes some feedstock (or chemical) recycling will occur to contribute to future recycling activity; European experience indicates such activities include some recovery options based on current technologies and the extent to which such activity is classified as recycling in Europe is currently unclear. The CSIRO target for plastics recycling in 2030 assumes there is only 50% recycling for plastics, with 80% recovery.[11]

Reflecting these uncertainties, at a state level, many of the representations of the waste hierarchy therefore group together recycling and recovery operations.

1.2.2 State and territory level

At a state and territory government level:

- New South Wales: The NSW Government has recently released its 20-year waste strategy which says *"we will support energy recovery where it makes sense to do so and where it is used to manage residual waste, not as an alternative to recycling"*[12]. Only residual waste from MSW collection systems with FOGO collection and commercial and industrial waste (C&I) generators with effective source separation is eligible for incineration. For other collection systems,

[9] Australian Government (2020) Recycling and Waste Reduction Act, available from https://www.legislation.gov.au/Details/C2020A00119

[10] Envisage Works (2019) Plastics Infrastructure Analysis Update, report for the Department of Environment and Energy

[11] CSIRO (2021) Circular Economy Roadmap for Plastics, Glass, Paper and Tyres

[12] Department of Planning, Industry and Environment, NSW Waste and Sustainable Materials Strategy 2041, 2021, https://www.dpie.nsw.gov.au/__data/assets/pdf_file/0006/385683/NSW-Waste-and-Sustainable-Materials-Strategy-2041.pdf

resource recovery criteria prescribe the percentage of residual waste eligible for energy recovery. Ineligible waste may be recycled or landfilled.
Remanufacture NSW offers funding opportunities to support the NSW resource recovery sectors response to changes brought about by the decision to ban the export of waste plastic, paper, glass, and tyres.

In late 2020, NSW called for registrations of interest to finance and build a new *"integrated waste recovery, reprocessing and energy production facility"* in the planned Parkes Special Activation Precinct (SAP). This was followed in September 2021 by the publication of an Energy from Waste Infrastructure Plan that set out the locations of future capacity of this type, alongside other recommendations for the regulatory environment. Essentially, this policy restricts waste to energy to four regional precincts. These are West Lithgow, Parkes, Richmond Valley and Southern Goulburn.[13]

- Victoria: In February 2020, the government published its 10-year policy on waste and recycling strategy in a document entitled "Recycling Victoria – A new economy". The policy notes that the "*government will encourage investment in appropriate waste to energy facilities that reduce the need for landfill"*. Victorian Government appreciates thermal waste to energy technologies can achieve Victoria's waste to energy goals *"if we have the right number and scale of facilities".* To this end, Recycling Victoria committed to placing a 1 million tonne per year cap on the amount of residual waste that can be sent to thermal WtE in Victoria to 2040. Works' approvals have been granted for prospective projects totalling approximately 950,000 tpa capacity.
  In recent developments, Metropolitan Waste and Resource Recovery Group (MWRRG) is leading a group of 16 councils in Melbourne's southeast to seek proposals for *"a smarter way to deal with household rubbish".* Advanced waste processing solutions will play a significant role in achieving the Victorian Government's target to divert 80% of household rubbish from landfill by 2030.
- Western Australia: The government is focused on transitioning to a "*sustainable, low waste, circular economy model"*. The government's "Waste Avoidance and Recovery Strategy 2030" provides targets and structures for that transition including recovering energy from residual waste streams. Western Australia already has 2 significant incineration projects under construction at Kwinana and East Rockingham. The state government has also developed policy that all metropolitan councils will have FOGO by 2025 to divert organics from landfill.
- South Australia: Following industry consultation in 2019, the EPA published its thermal waste to energy (WtE) position statement in 2020. In keeping with the waste management hierarchy and circular economy objectives, thermal WtE

[13] NSW Government (2021) Energy From Waste Infrastructure Plan - Supporting the NSW Waste and Sustainable Materials Strategy 2041

activities using waste that would otherwise be disposed to landfill are supported once sufficient material resource recovery has been undertaken. For councils with FOGO collection systems, up to 40% (by weight) of MSW total kerbside collection is eligible for levy-free use in incineration. All C&I and C&D waste must go through sorting for resource recovery prior to incineration.

- Queensland: The government has developed an EfW incineration Policy which supports the implementation of the Waste Management and Resource Recovery Strategy as one of its action plans. The Policy does not incentivise or promote incineration but will help to ensure that any incineration facilities developed in Queensland meet technical, environmental, regulatory and community expectations and are in the best interest of Queenslanders. The Policy outlines a preference for industries that produce higher value commodities such as solid or liquid fuels, over the production of electricity and heat, to align with the Queensland Government's biofutures agenda. Incineration can only accept residual waste, which is technically, environmentally, or economically impractical to recycle. This is expected to be further defined in a guideline later this year. The 2050 waste targets suggest that 15% of waste generated could be potential incineration feedstock. A major incineration facility is proposed for Ipswich.
- Tasmania: A draft Waste Action Plan was released by the government in 2019 and provides a framework for the discussion with local government, business, and the community on the best way to address Tasmania's waste and resource recovery challenges. However, Tasmania has got insufficient scale to support thermal EfW for mixed residual waste.
- Australian Capital Territory (ACT): The government has published its Waste to Energy Policy 2020- 2025. Following the waste hierarchy, waste reduction, reuse and recycling of material takes precedence over energy recovery applications. Thermal treatment of waste (including incineration, gasification, and pyrolysis) is not permitted in the ACT. Non-thermal means of energy recovery such as anaerobic digestion or the production of Refuse Derived Fuel (RDF) will be permitted. Landfill gas capture and electricity generation will also continue as best practice management of the ACT's landfills. The ACT has already achieved a 75% recycling rate of organics and is implementing further FOGO systems.
- Northern Territory: Whilst renewable energy represents a key priority for the government, which has set a policy of achieving 50% renewables for electricity supply by 2030, EfW does not seem to be a priority now due to insufficient scale in Northern Territory.

2.0 Methodology

This chapter describes the waste treatment systems, scenarios, assumptions, and modelling methodology used when comparing the climate change and air quality impacts of landfill and incineration. The study focuses on the direct impacts of treating residual waste via these different routes – the indirect impacts associated with the investment in these different routes (such as potential impacts on recycling from investment in incineration or impacts on waste generation) are not considered.

2.1 Approach to the Modelling

The modelling performed in this work compares the emissions of the waste treatment systems described in Section 2.2. The Functional Unit (FU) of this assessment is one tonne of residual waste, meaning the analysis compares the emissions from each system's treatment of one tonne of residual waste. Emissions from transport are not considered for any of the treatment systems.

Methane, carbon dioxide and nitrogen dioxide are the greenhouse gases (GHG) considered in this report. As they have different GWPs, their impacts are converted into carbon dioxide equivalents (CO_2e) using the GWP values (assumptions we have used are presented in section A.1.2.1 of the Technical Appendix).[14]

The GHG emissions analysis uses a 'consumption' approach, meaning all emissions are included regardless of their location. For example, the emissions benefits of recycling are included even where they do not occur in Australia.

2.2 Treatment Systems

This section describes the residual waste treatment options modelled in this study. Each of these treatment practices is a method of disposing of *residual waste*: waste from households and businesses that is not sent to be recycled.

2.2.1 Incineration ('straight')

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

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

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

local homes or industry. Most incineration facilities planned for Australia will generate only electricity, as the demand for heat is lower than is the case in Northern European jurisdictions where incineration is prevalent; however, it is understood that the proposed plant at Maryvale is aiming to use both heat and electricity.

In accounting for the climate change impact of incinerators, the analysis takes into account that the electricity generated by incinerators would likely reduce the requirement for electricity to be generated elsewhere by power plants and other forms of power generation.

A given unit of heat produced by the incinerator can produce different quantities of useful electricity and heat. A high-performance incinerator can convert heat into electricity at an efficiency of up to around 30%, whereas it can produce useful heat at an efficiency of about 85% (gross). This latter value is much higher because no conversion of energy is occurring. Electricity generation efficiency of incinerators is regarded as very low compared to other electricity generation sources.

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

As noted above, the emission of greenhouse gases is near-instantaneous in an incinerator. Landfills, conversely, emit carbon dioxide and methane over several decades- an important consideration given the time imperatives of emissions reduction in this climate crisis.

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

2.2.2 Incineration with Mixed Waste Sorting (MWS)

Advanced mechanical pre-treatment systems use a series of mechanical processes to remove more of the recyclable materials from the residual waste stream. This includes the targeting of dense plastics and plastic film, which is poorly targeted by kerbside collection systems due to its low density. These systems thereby reduce fossil carbon content of the residual stream and increase the material going to recycling, improving the overall ‘climate performance’ of the system. This report examines advanced mechanical pre-treatment in conjunction with incinerators, whereby the final residual stream is combusted to produce energy. Such systems are not currently being considered for development in Australia.

2.2.3 Incineration with Heat production (CHP)

Combined Heat & Power (CHP) is a technology that generates electricity and captures the heat to provide thermal energy—such as steam or hot water—that can be used for space heating, cooling, domestic hot water, or industrial processes. CHP can be located at an individual facility or building or be a district energy or utility resource. CHP is typically located at facilities where there is a need for both electricity and thermal energy.

Nearly two-thirds of the energy used by conventional electricity generation is wasted in the form of heat discharged to the atmosphere. Additional energy is wasted during the distribution of electricity to end users. By capturing and using heat that would otherwise be wasted, and by avoiding distribution losses, CHP can achieve efficiencies of over 80%, compared to 50% for typical technologies (i.e., conventional electricity generation and an on-site boiler). However, few if any incinerators proposed in Australia plan to develop CHP as the need for district heating in Australia is non-existent and industrial heating requirements are low.

2.2.4 Landfill ('straight')

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

The breakdown of organic material that occurs in landfills releases a combination of methane and carbon dioxide, a process that occurs on a timescale of 100+ years. Cells are periodically sealed to limit the escape of gases. Some of the methane produced is oxidised into carbon dioxide by micro-organisms as it rises through the landfill. In Australia and many other countries, a substantial proportion (60 to 70%) of the landfill gas is captured and either combusted to produce electricity, or 'flared' to convert the methane to carbon dioxide before being released into the atmosphere.

Not all the carbon in the material in the landfill is released as carbon dioxide within the 100-year period. While there are significant uncertainties, most analyses estimate (using the approach set out by the IPCC) that at least 50% of the biogenic carbon in the waste – that coming from organic- as opposed to fossil-based materials – remains 'sequestered' (see Section 2.3.1 for a full description of biogenic carbon emissions).[15] In addition, fossil carbon (e.g. most plastics excluding compostable plastics of fossil origin) is not subject to degradation in landfill and thus CO_2 is not emitted from such sources in landfill.

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

2.2.5 Landfill with Advanced Mechanical Biological Treatment (MBT)

This treatment system combines advanced mechanical pre-treatment systems, designed to remove recyclables from the residual stream as above, with aerobic bio-stabilisation

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[15] 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

of the residue from the pre-treatment system. The bio-stabilised residue is then sent to landfill.

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

2.2.6 Refuse Derived Fuel Sent to Co-Incineration

This treatment system involves the production of Refuse Derived Fuel (RDF) or Process Engineered Fuel (PEF) from Municipal Solid Waste and Commercial & Industrial Waste. Because RDF can be made from a variety of materials, there are different techniques to ensure the creation of a homogenous material that can be used as a substitute fossil fuel. The most common way of extracting RDF is to combine mechanical and biological treatments methods. Such methods include, but are not limited to:

- Size screening
- Coarse shredding
- Mechanical separation of metals, plastics, paper, and cards
- Bio drying – use of an aerobic degradation process to generate heat and therefore reduce moisture within the waste

Depending on the particular type of RDF fuel required, further processing equipment might be required. The resulting RDF can be combusted either in existing cement kilns plants in Australia or exported abroad for energy generation. Existing evidence suggests that, at present, coal is the fuel most likely to be displaced; as such, climate impacts (in carbon terms) are similar irrespective of whether the fuel is sent to a cement kiln or for co-combustion. We are using Malaysia as the country the RDF is assumed to be exported to. It is noted that some major cement manufacturers are now replacing fossil fuels with hydrogen. As fuel mixes shift over time to decarbonise, RDF and PEF may start to displace lower carbon fuel like hydrogen instead of fossil fuels.

2.3 General Assumptions Relevant to the GHG Modelling

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

2.3.1 Treatment of Biogenic Carbon Dioxide Emissions

Biogenic carbon emissions are those that originate from organic material like food and garden waste, as opposed to the emissions coming from fossil carbon in oil-derived materials. It is often considered that biogenic carbon emissions need not be incorporated into total emissions, because they are ‘short cycle’, i.e. “only relatively recently absorbed by growing matter”. [16] Note that methane emissions from organic material *are* included because they are considered to be anthropogenic in nature, whereas biogenic CO_2 emissions are in effect viewed as similar to or part of the natural carbon cycle.

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

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

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

The use of such an approach is recommended by authors from the Technical University of Denmark (who developed the EASEWASTE model), and in UK Department for Farming and Rural Affairs’ modelling guidance. [17, 18] Despite often being omitted from similar analyses in the literature, a carbon sequestration credit is included in this analysis. A similar approach was used in the peer-reviewed EU Reference Model on Municipal

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

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

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

Waste as well as Eunomia's work for the Greater London Authority in developing an Environmental Performance Standard for municipal waste treatment. [19,20]

2.3.2 Treatment specific assumptions

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

- Landfill modelling is largely in line with the national methane emissions model used in the Australia's submission to the UNFCCC, apart from a different assumption being used for the fraction of dissolved organic content dissimilated to landfill[21], and the application of the 'sequestration' credit for the storage of biogenic carbon (as described above).
- We assume – in the central case - that landfill gas capture in Australian landfills is in line with that of UK plant such that 62% of the landfill gas is captured. The national waste report[22] confirms that 42% of the landfill gas generated is used for energy generation. Only gas that is captured can be used for energy generation. Typically, around 50-60% of gas captured is used for energy generation, with the rest being flared. Data on the related landfill gas capture rate is not available in the waste report, but the 42% figure suggests relatively high gas capture rates may be being achieved at Australian sites; a 60% energy generation rate (from captured gas) combined with the 42% energy generation figure would imply overall capture rates in the order of 70%. We have used the figure of 62% in the central case - reflecting the uncertainties around measuring gas capture at landfill sites, and likely poorer performance at older landfills. Sensitivity analysis considers the results with gas capture at 70%, reflecting the situation at newer sites with better gas capture.
- Operational data relating to the energy generation performance of Australia's incineration fleet is not available as there are no such plants in Australia. Energy generation efficiencies for proposed facilities were based on data obtained from newer European facilities, which were considered alongside data on the intended energy generation performance of the proposed facilities for Australia.
- Assumptions for the performance of pre-treatment facilities are based on data provided by plant operators, based on facilities operating in Europe and elsewhere.

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

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

[21] The approach taken here is in line with the standard methodology used by the IPCC and the UK's national methane generation model

[22]

2.4 Scenario – Specific assumptions relevant to the GHG Modelling

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

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

Five scenarios are explored (shown in Table 2-1). A Central scenario, explained in Section 2.4.1.1, uses today's composition of MSW going to landfill and the carbon intensity of electricity and heat provision. Two further sensitivities to the 'Central' scenario are explored in Sections 2.4.1.2 and 2.4.2 respectively: 'Composition sensitivity' examines the residual waste composition if voluntary plastic and food waste recycling targets are met, and 'Electricity sensitivity' examines what would happen if electricity decarbonised more slowly than expected, based on a NSW Environment Protection Agency report.[23] We have also modelled two variants for landfill gas capture, as previously described in Section 2.3.2. The final scenario is where RDF is produced from MSW and sent for co-incineration in a cement plant in Australia or in a coal-fired power station in Malaysia. This scenario is explored in Section 2.4.3.

The technical elements behind each of the columns in Table 2-1 are explained below.

Table 2-1: The scenarios explored in the analysis

Scenario	Electricity marginal	Plastics recycling target	Marginal carbon intensity ($kgCO_2e/kWh$)		Landfill gas capture
			Electricity	Heat	
Central	Renewables & gas	Missed	0.10	0.23	62%
Composition Sensitivity	Renewables & gas	Met	0.10	0.23	62%
Electricity Sensitivity	Gas	Missed	0.40	0.23	62%
Landfill gas capture	Renewables & gas	Missed	0.10	0.23	70%
RDF for co-firing	N/A	Missed	N/A	Displaces coal	62%

[23] Department of Industry, Science, Energy and Resources (2020) *Australia's emissions projections 2020*, December 2020, https://www.industry.gov.au/sites/default/files/2020-12/australias-emissions-projections-2020.pdf

2.4.1 Composition

Composition data for both the residual and recycling streams is a key consideration for the modelling – with outcomes influenced both by total arisings as well as quantities recycled.

In Australia, data on MSW composition is available from the 2020 National Waste Report.[24] The term MSW here applies to household waste and government waste arisings.

Australia has in place a series of recycling targets, the achievement of which is being facilitated by an NGO, the Australian Packaging Covenant Organisation (APCO). Although supported by both government and industry, the 2025 National Packaging Targets (referred to hereafter as the 2025 Targets) are voluntary. They apply to all packaging that is made, used, and sold in Australia. The 2025 Targets are:

- 100% reusable, recyclable, or compostable packaging.
- 70% of plastic packaging being recycled or composted.
- 50% of average recycled content included in packaging (revised from 30% in 2020).
- The phase out of problematic and unnecessary single-use plastics packaging.

It is important to note that the plastics recycling targets are voluntary and that, at the time of writing, Australia is some way off target to achievement, with only relatively modest improvements in recycling being seen in recent years. Waste management is largely the responsibility of Local Councils. It can be assumed that Local Councils that have not declared a Climate Emergency or set a net-zero target date will not, without any forthcoming mandate from federal or state Government to achieve these targets, improve recycling drastically. This would be a continuation of the slow progress seen in the last few years. The plastic packaging recycling rate increased from 16% to 18% only in 2018-19[25], hence it is still a long way off the targeted 70% by 2025.

Therefore, in the Central scenario we have assumed the plastics recycling targets are not met.

The National Waste Policy Action Plan for Australia – published in 2019 – includes a target for 50% of food waste to be diverted from landfill by 2030 and confirms a commitment to ensure that food waste collection services are in place for households and businesses by 2023. Achievement of this target is included within the Central scenario.

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[24] Blue Environment, *National Waste Report 2020*, 2021, https://www.environment.gov.au/protection/waste/national-waste-reports/2020

[25] APCO, *Australian packaging consumption and recycling data 2018–19*, 2021, https://documents.packagingcovenant.org.au/public-documents/Australian%20Packaging%20Consumption%20And%20Recycling%20Data%202018-19

Assumptions regarding the household waste recycling rates are summarised in Table 2-2. The scenarios are described in more detail in the sections that follow.

UK datasets on composition and arisings are relatively more advanced than is the case for Australia. Household composition data are collated from multiple samples into a meta-analysis, and this data was incorporated into the UK analysis undertaken for Client Earth[26]. In contrast, the National Waste Report in Australia is compiled from fewer samples. Commercial waste composition data is somewhat more uncertain in the UK than household, but sufficient data exists to allow for the disaggregation into commercial and industrial waste streams. A similar approach was not possible for Australia as only data on the landfilled waste is available. For commercial and industrial waste, some is masonry waste and timber; much of this material is unlikely to go to incineration due to its size and its low calorific value (in the case of the former). A further significant proportion of the stream is hazardous wastes. The National Waste Report confirms that a significant proportion of the latter stream is contaminated soils and asbestos waste – which are less likely to be sent to incineration. No information on the rest of the stream is provided, but materials could include chemical wastes of variable carbon concentrations. Given the uncertainties associated with quantifying the carbon content of the commercial and industrial wastes, the model focuses on the household stream which is better characterised.

When the hazardous and masonry streams are excluded from the commercial and industrial streams, the following points are noted regarding the composition of material sent to landfill:

- Food waste and plastic waste quantities are lower in the commercial / industrial wastes compared to household;
- Quantities of paper and card are, however, higher.

These impacts are anticipated to cancel each other out to a certain extent, reducing the extent to which commercial residual waste differs from the household stream. It is noted that incinerators in Australia will also accept some waste from the commercial and demolition sector. The composition of this stream is similarly uncertain as significant quantities of it will be masonry. As is the case with the same material in commercial waste, this is unlikely to be sent to incinerators in any significant quantity. No data on the actual composition likely to be sent is, however, available – but it is likely that the material has a lower organic content than that of either household and commercial / industrial wastes.

2.4.1.1 Central scenario

In this scenario it is assumed that the plastic recycling targets are not met - given the slow rate of progress to date, and that the targets are a voluntary commitment. Plastic recycling rates are, however assumed to improve such that capture of these materials

[26] Eunomia, Greenhouse Gas and Air Quality Impacts of Incineration and Landfill, 2021

doubles by 2030. The composition is also modelled assuming the 50% recycling target for food waste is met.

Table 2-2 presents the residual waste composition used in the Central Scenario. The same composition is used in the Electricity Sensitivity, landfill gas capture sensitivity and RDF scenarios. Recycling rates for each scenario are presented in Table 2-5.

Table 2-2 Household residual waste compositions in Central/RDF Scenario

Material stream	Central/RDF
Masonry materials	4.8%
Other ferrous	2.9%
Other aluminium	2.0%
Food	28.1%
Garden	7.3%
Timber	2.0%
Other organic	6.2%
Paper & cardboard	20.8%
Plastic film (other)	4.9%
Dense plastic (other)	8.8%
Glass	5.8%
Textiles, rubber & leather (excl. tyres)	4.4%
Hazardous	0.0%
Other	2.1%

2.4.1.2 Composition sensitivity

Under this scenario, it is assumed that the voluntary recycling target of 70% plastics captured for recycling is met. Since July 1st, mixed plastics — where different types of plastics are bundled together — can no longer be exported. Plastic waste sorted into single resin or polymer types can be exported for another 12 months if exporters are granted a licence by the federal environment department. But next year (2022) that too will be banned, with only plastic that has been sorted and processed into pellets, powder or flakes eligible for export. It is noted there is some confusion at a state level as to the extent to which recovery operations can be interchanged with recycling activity. It is assumed here that no recovery of these fractions occurs, and that all such material is sent to re-processors.

This has an impact on the volume of plastic packaging diverted from the household stream as shown in Table 2-3. Quantities of other types of waste – such as food waste – increase in relative terms as a result of the change.

Table 2-3 Residual waste compositions - Composition Sensitivity

	Composition Sensitivity
Masonry materials	5.1%
Other ferrous	3.1%
Other aluminium	2.1%
Food	30.3%
Garden	7.8%
Timber	2.1%
Other organic	6.7%
Paper & cardboard	22.5%
Plastic film (other)	2.4%
Dense plastic (other)	4.4%
Glass	6.3%
Textiles, rubber & leather (excl. tyres)	4.8%
Hazardous	0.0%
Other	2.3%

A summary of the composition assumed in each scenario is shown in Table 2-4 and a summary of the recycling rates today and in 2030 is presented in Table 2-5.

Table 2-4 Compositions in Central and Composition Sensitivity

Material stream	Scenario	
	Central / electricity sensitivity / landfill gas sensitivity / RDF	Composition Sensitivity
Masonry materials	4.8%	5.1%
Other ferrous	2.9%	3.1%
Other aluminium	2.0%	2.1%
Food	28.1%	30.3%
Garden	7.3%	7.8%
Timber	2.0%	2.1%
Other organic	6.2%	6.7%
Paper & cardboard	20.8%	22.5%
Plastic film (other)	4.9%	2.4%
Dense plastic (other)	8.8%	4.4%
Glass	5.8%	6.3%
Textiles & rubber (excl. tyres)	4.4%	4.8%
Hazardous	0.0%	0.0%

Material stream	Scenario	
	Central / electricity sensitivity / landfill gas sensitivity / RDF	Composition Sensitivity
Other	2.1%	2.3%

Table 2-5 Household waste recycling rates today and in 2030

Material stream	Scenario		
	Current	2030 Plastics Target achieved	2030 Plastics Target missed
Masonry materials	23%	23%	23%
Metals	76%	76%	76%
Ferrous	76%	76%	76%
Non-ferrous	76%	76%	76%
Food	16%	50%	50%
Garden	64%	85%	85%
Timber	22%	22%	22%
Other organic	23%	23%	23%
Paper & cardboard	47%	47%	47%
Plastics	17%	70%	35%
Plastic Film	17%	70%	35%
Dense Plastic	17%	70%	35%
Glass	62%	62%	62%
Textiles & rubber (excl. tyres)	4%	4%	4%
Hazardous	0%	0%	0%
Other	17%	17%	17%

2.4.2 Carbon Intensity of Energy Systems

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

Until relatively recently, Australia was highly reliant on coal for the generation of its electricity. As such, either coal or gas would have been appropriate choices for the marginal source of electricity generation. These assumptions are expected to no longer be applicable in the future however, due to a decarbonising, renewables-fed grid, and the need to decarbonise heat production to meet net-zero targets.

2.4.2.1 Electricity

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

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

The literature defines the long-run marginal factors as considering: [27]

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

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

In the UK, data exist on projections associated with the long-run marginal, which can be used to develop appropriate assumptions for which marginal fuel source is displaced by incineration electricity generation capacity. However, no such data exist for Australia.

The contribution of gas generation is anticipated to increase over the next decade; data from the Department of Industry, Science, Energy and Resources indicates that gas production will increase by 3% by 2030 from current day levels[28]. As a result of this and other changes, electricity production is anticipated to become increasingly decarbonised. Other sources of electricity generation will fill the gap, including (mostly) renewables and power storage. The carbon intensity of these sources is much lower than that of gas.

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

[28] Department of Industry, Science, Energy and Resources, Australia's emissions projections 2020, 2020, https://www.industry.gov.au/sites/default/files/2020-12/australias-emissions-projections-2020.pdf

Data on current and future installed electricity generation capacity for Australia are shown in Table 2-6; this data forms the basis of assumptions made in respect of the marginal fuel source to be displaced by incineration generation capacity[29].

Table 2-6 Assumptions on future installed capacity

Installed capacity	2020	2025	2030
Coal	25	23	19
Gas	19	19	20
Hydro	7	7	7
Wind	8	13	15
Large-scale solar	3	8	8
Mid-scale solar (100kW to 5MW)	<1	1	2
Small-scale solar (<100kW)	12	25	36
Other	4	4	4
Pumped Hydro	1	1	3
Battery storage	<1	3	6
Total	79	104	119

In developing an assumption for the carbon intensity of the marginal source(s) of electricity, the new generation capacity coming online between now and 2030 was considered. Much of this is wind and solar energy, both of which will vary in the amount that can be generated. Incinerators contribute to the baseline energy provision – although they are less likely to be switched on and off in the way that gas and coal generation can be since the waste will typically still need treating. Other than solar and wind, there will be an additional 7 GW of generation capacity added between now and 2030, of which 1 GW is gas, and the rest pumped hydro and storage. Assuming gas CCGT has a carbon intensity of 0.35 kg CO_2e / kWh, if gas contributes 1 GW to the new generation capacity, this implies that the new capacity has a carbon intensity in the region of 0.04 kg CO2e / kWh. A relatively conservative assumption of 0.1 kg CO_2 / kWh was used for the marginal source of electricity, based on the calculation outlined above. Given the uncertainties in this aspect of the modelling, the impact on the results of further decreases in the carbon intensity of the marginal source is discussed.

2.4.2.2 Heat

There are currently no operational incineration facilities operating in CHP mode in Australia and the ones in planning and/or development do not give much information on the potential recovery of heat nor the use for it if it was to be recovered. Local circumstances dictate the marginal source for heat; this is particularly the case in Australia where heat is more likely to be used for industrial purposes given the country's climate.

[29] ibid

In the absence of better data about where CHP will be built and what kind of off-takers will be using it, we assumed that incineration plant operating in CHP mode will be competing with gas. The only currently proposed CHP facility – that at Maryvale - is not felt to be representative of Australia's future EfW capacity operating in CHP mode. This is because energy generation profile will vary across plant and there are no strong drivers for CHP nationally in Australia.

2.4.3 RDF Co-firing

Co-combustion involves the use of RDF as a fuel in combination with another fuel. Although other fossil fuels can be used, the combination of RDF and coal has been used by electric utilities because the two fuels are ordinarily burned in a similar manner, using the same generic equipment. The RDF can either be produced at the power plant site or be shipped from another, generally nearby location. It is more frequently produced at another location. Co-firing can permit authorities to avoid the substantial cost of building a new dedicated MSW combustion facility.

Where RDF is co-combusted with coal, the use of RDF for power production is assumed to displace the use of coal, with emissions benefits accounted for accordingly. Impacts of co-firing RDF in a cement kiln in Australia or in a coal plant in Malaysia are expected to be similar, only difference would be the transport of the RDF which would be comparatively small.

Current utility plants have been optimised for the fuel they use so switching to RDF will most likely lower the efficiency of the boiler by about 2-3%[30] and the utility will lose power generating capacity.

[30] MccGowin, C.R., 1991, *Alternate Fuel Cofiring with coal in utility boilers*, EPR proceedings: 1991 conference on waste tyres as a utility fuel, EPRI GS-7538

3.0 Results

This chapter presents the climate change and air quality impacts of the treatment options in question.

3.1 Greenhouse Gas Impact

3.1.1 Results for Household Waste

The carbon impacts of the different waste treatment systems for household waste are summarised in Table 3-1; a more detailed breakdown of these results is provided in Technical Appendix Section A.1.3.

Table 3-1 Summary of Results for Household Waste

Waste treatment system	Climate Change Impacts - GHG impact (tCO2e/t)			
	Central	Composition sensitivity	Electricity sensitivity	Landfill gas sensitivity
Incineration (electricity only)	0.210	0.033	-0.044	0.210
Incineration (CHP)	0.051	-0.096	-0.146	0.051
Incineration (MWS)	-0.304	-0.248	-0.389	-0.304
Landfill	0.283	0.305	0.257	0.176
Landfill (MBT)	-0.252	-0.141	-0.225	-0.261
RDF	-0.505	N/A	N/A	N/A

Results are also shown graphically in the figures below: Figure 3-1 shows the impacts of the Central scenario and Figure 3-2 the Composition Sensitivity scenario, whilst Figure 3-3 presents results from the Electricity Sensitivity scenario.

Figure 3-1 GHG impacts - Central scenario

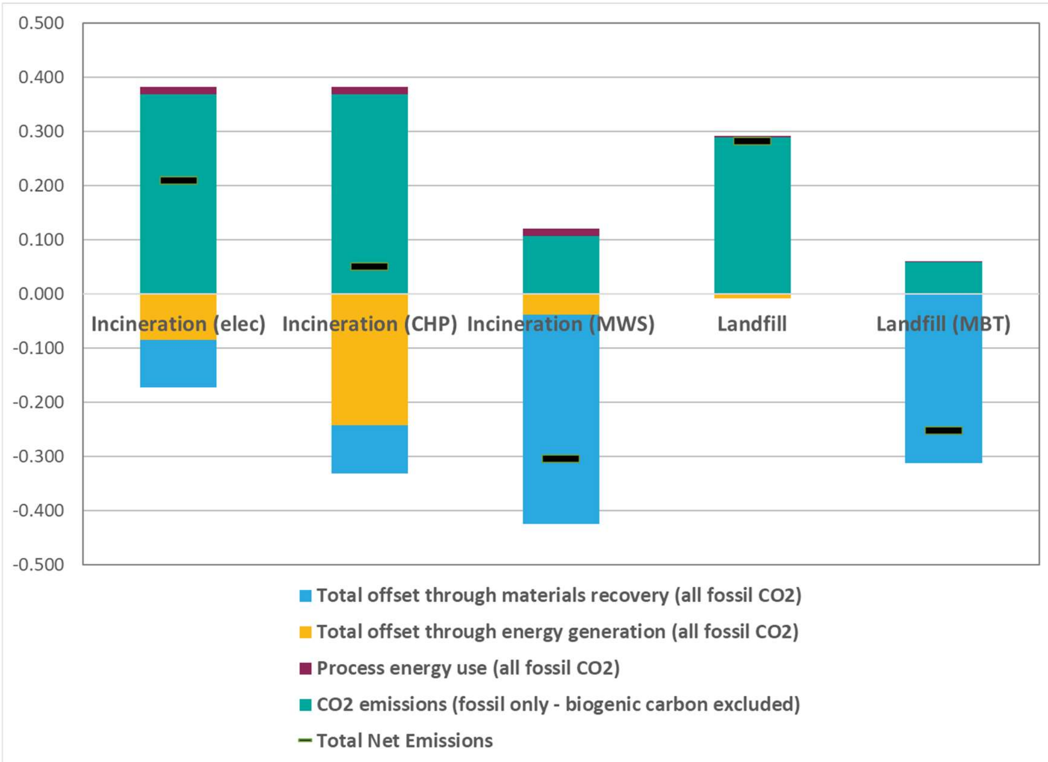


Figure 3-2 GHG impacts - Composition Sensitivity scenario

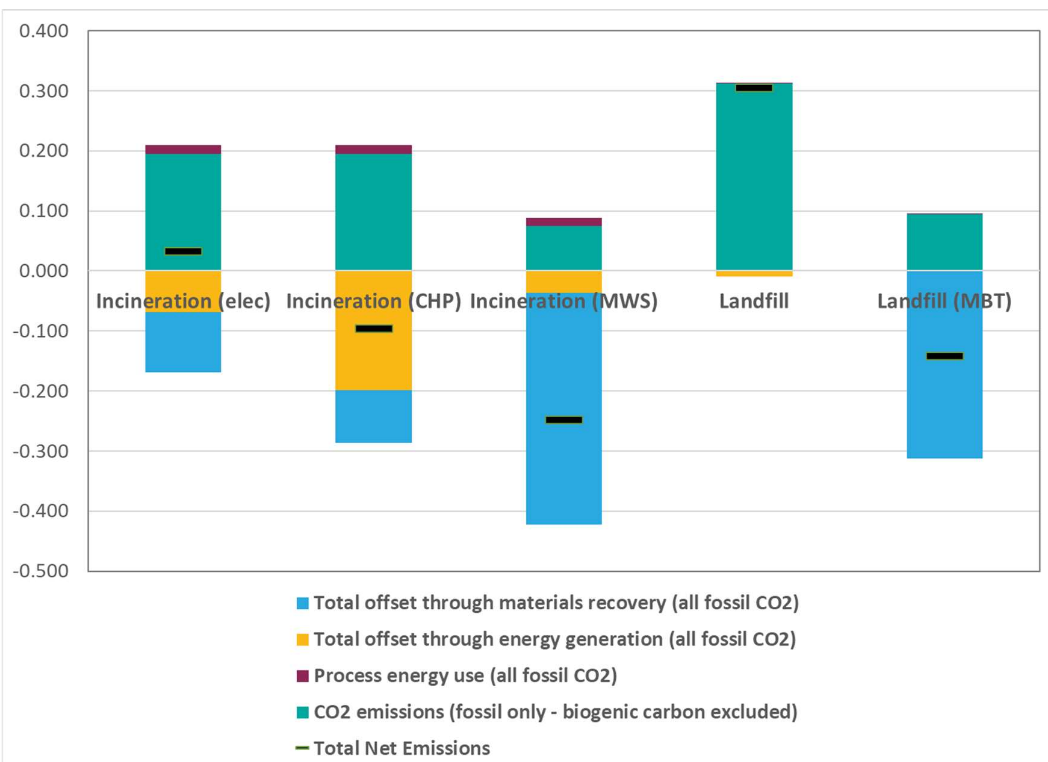


Figure 3-3 GHG impacts - Electricity Sensitivity scenario

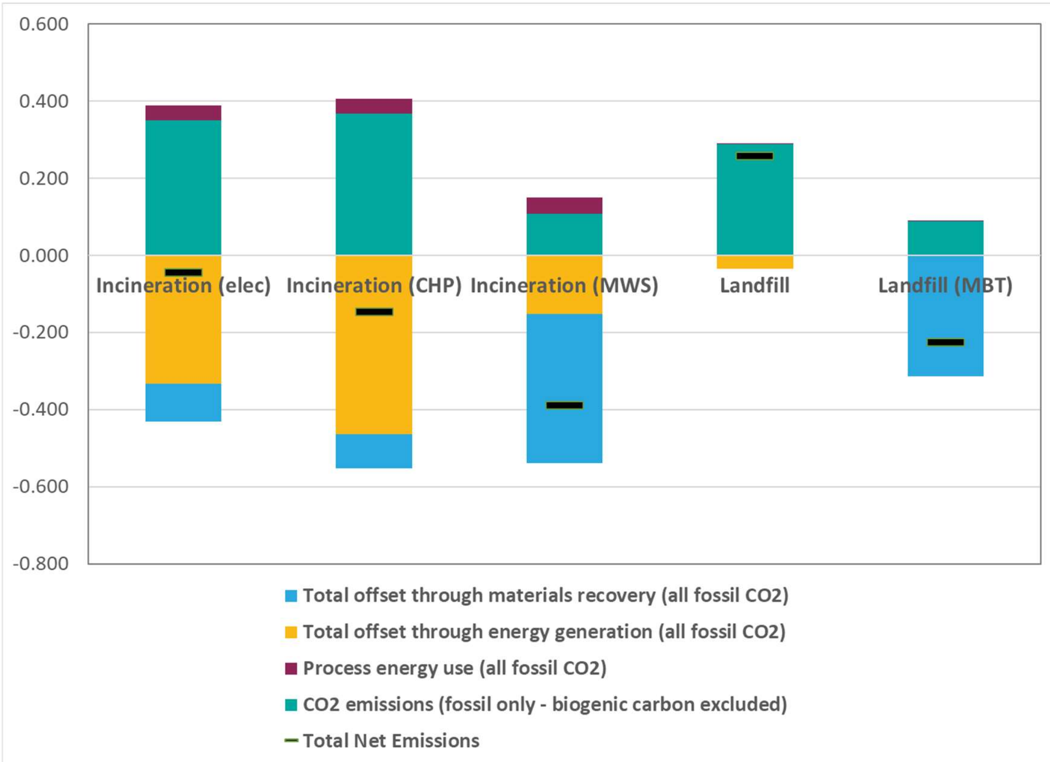
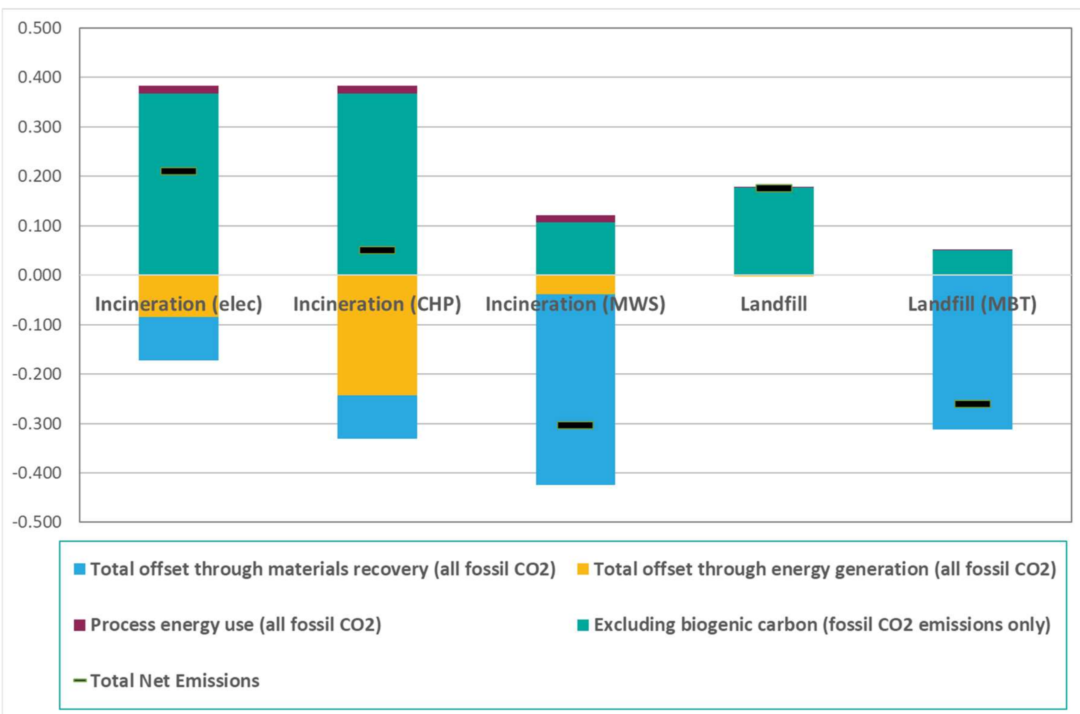


Figure 3-4: GHG Impacts – Landfill Gas Sensitivity



Under the first three scenarios, the results indicate that incineration performs better than landfill. This is the case even when plastics recycling performance is relatively poor, and progress has been made decarbonising the electricity grid, both of which occur under the central scenario. However, data shown in Figure 3-1 - showing the central case - confirms that incinerators benefit, in 2030, from an emissions benefit of 0.085 tonnes CO2e associated with the generation of electricity. This benefit is anticipated to disappear at some point between 2030 and 2050, assuming Australia achieves its national climate change target. In the absence of that credit, most of the climate change benefit of incineration over that of landfill will disappear.

The data on landfill gas capture – whilst also highly uncertain – also suggests that some sites may capture more landfill gas than has been modelled in the central case, as is discussed in Section 2.3.2. The fourth scenario considers this outcome and assumes 70% of landfill gas is captured; under this scenario landfill performs better than incineration where the plastics recycling targets are not met.

Household waste in Australia has a relatively high organic content compared to that of the UK and this worsens the performance of landfill. UK datasets on composition and arisings are relatively more advanced than is the case for Australia. Household composition data are collated from multiple samples into a meta-analysis, and this data was incorporated into the UK analysis undertaken for Client Earth[31]. In contrast, the National Waste Report in Australia is compiled from fewer samples. Commercial waste composition data is somewhat more uncertain in the UK than household, but sufficient data exists to allow for the disaggregation into commercial and industrial waste streams. A similar approach was not possible for Australia, and hence the decision was taken to focus on the household waste only.

The inclusion of commercial waste in the final composition data for Australia is anticipated to result in an increase in the fossil carbon content, given that the proportion of food waste is much lower in this stream than is the case in the household waste. This impact is somewhat mitigated by the increase in paper content for the commercial and industrial waste stream relative to that of household residual waste. Alongside this, some construction and demolition waste is also expected to be sent to incineration, which would also further decrease the organic content; however, the composition of this stream is also uncertain.[32] An increase in the fossil carbon content would be expected to bring the performance of incineration and landfill closer together – particularly in the case where the voluntary plastics recycling targets are not met.

Results therefore suggest that for incineration to continue to clearly out-perform landfill in the future throughout the lifetime of the facility, it is important for Australia to meet the targets for plastic recycling – given uncertainties in the data on both composition and landfill gas capture, and the declining importance of benefits from energy

[31] Eunomia, Greenhouse Gas and Air Quality Impacts of Incineration and Landfill, 2021
[32] Much of this stream is masonry which will not be sent to incineration due to its low calorific value

generation at incinerators. Where the plastics recycling target is met – modelled for household waste in the composition sensitivity scenario – landfill is unlikely to perform better than incineration. For household waste, landfill impacts are 0.3 tonne CO_2e per tonne of waste in this scenario, whereas incineration with electricity only results in an impact of less than 0.05 tonne CO_2e.

The need to meet these targets is less critical in the situation where Australia makes less progress in decarbonising electricity supplies – as is implied by the Electricity Sensitivity scenario (shown in Figure 3-3). However, such a situation would be a result of the country making significantly less progress in meeting its overall climate change emissions reduction goals.

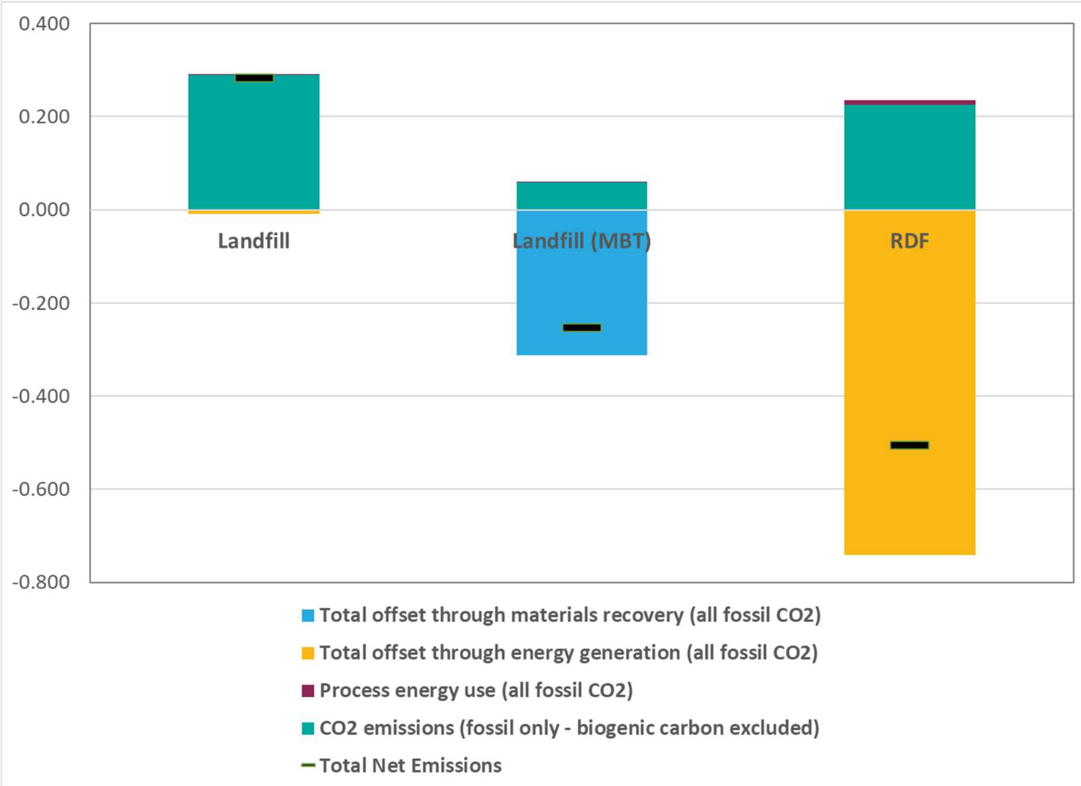
Results show here that incineration facilities operating in CHP mode will out-perform those generating only electricity in all scenarios. This improved performance is, however, dependent on those facilities generating and utilising a significant amount of heat, and this heat being used to displace gas (or other similarly carbon intense fuels). The latter is considered likely to be the case for the foreseeable future in Australia, but generation efficiencies are somewhat uncertain given that most proposed facilities at present are not expected to operate in CHP mode. However, adoption of CHP incinerators in Australia is not anticipated due to very low heating demand.

If Australia fails to meet its voluntary recycling targets for plastics, an alternative approach would be to incorporate mixed waste sorting technologies alongside incineration facilities. Such an approach would ensure that incineration does not contribute as much to climate change emissions in the future: net climate change results are less than zero for the scenario with incineration (MWS) in all cases because of the additional benefits associated with recycling which is incorporated into this treatment system. However, it should also be noted that a similar result would be achieved by authorities developing bio-stabilisation plant alongside the existing landfill capacity. Such an approach would require less financial investment than developing a network of incineration facilities across the country.

3.1.2 RDF Scenario

Figure 3-5 shows the impacts of the RDF scenario compared to landfill. These results exclude the consideration of transport impacts, as these have not been included within the system boundaries of the other treatment systems. Transport impacts associated with the waste being sent for treatment in Malaysia are estimated to be 0.15 tonnes CO2e per tonne of waste treated. Approximately a third of this impact is associated with road transport; the shipping impacts - when considered per km of travel, per tonne of waste - are much smaller than those per km of road travel.

Figure 3-5 The GHG impacts of the landfill scenarios compared to the RDF scenario



Under this scenario, RDF performs significantly better than landfill, largely due to its power production credit, i.e., the emissions reduction brought about by avoided power production using coal elsewhere. The results also suggest that the RDF scenario performs better than that of the household waste scenarios set out in Section 3.1.1. The improved performance occurs as a result of the RDF being assumed to displace coal in the scenario – which is a relatively carbon-intense fuel. This is anticipated to be a reasonable assumption in many cases for the foreseeable future for the destinations likely to receive RDF produced by Australian facilities. However, it is noted that the cement industry is also taking steps to decarbonise its operations, and that in many countries, fuels other than coal are being used – such as biomass rich feedstocks and hydrogen. Where this is the case, the benefits attributed here will not be seen – and relative performance will more closely reflect that of the incineration options modelled elsewhere in the study.

3.2 Air Quality Impacts

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

3.2.1 The literature on air quality impacts of incineration

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

Much of the information in the literature on this topic is not specific to Australia, as the country does not currently have any existing incineration infrastructure. However, a recent peer reviewed, global meta-analysis of all available health studies involving incinerators undertaken by the Australian Public Health Association in 2019 considered the literature on the public health impacts of incineration, considering data from facilities around the world (including those from the UK).[33] The review confirmed that a range of adverse health effects were identified from the literature, including significant associations with some neoplasia, congenital anomalies, infant deaths and miscarriage. The report noted that impacts were particularly associated with older facilities, although the authors suggested that this might be in part due to there having been less time for impacts to become prevalent in the data from newer sites. It recommended that:

- Since there has been insufficient time for health effects of newer technology to emerge, a precautionary approach to licensing and monitoring incinerators must continue.
- As a condition of applying for a licence to build waste incinerators, independent third-party conducted baseline population studies and long-term surveillance cohort studies be mandated to measure the longitudinal and emerging effects of the incinerator's presence on the local community and the environment.
- Health and safety standards for workers should be enshrined in law and should include regular health checks and exposure monitoring.
- In countries that have ratified the Stockholm Convention, incinerators should be designed to meet the Convention guidelines.
- Facility upgrades and regular maintenance schedules for incinerators must be adhered to.
- New incinerators should be located away from areas of food production.
- Food grown near an incinerator should be avoided.

In the UK context, studies on this topic include that undertaken by Enviros *et al.* on behalf of Defra (who approve incinerator proposals in the UK) in 2003. That study focussed primarily on an examination of epidemiological studies looking specifically at incinerators.[34] It found relatively few studies of this nature, with those that did exist relating to older facilities with higher emissions. Even today there is relatively little in the way of research specifically focused on incinerators and health impacts: a study in the academic literature published this year and focussing on similar literature concluded

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[33] Tait P, Brew J, Che A, Costanzo A, Danyluk A, Davis M, Khalaf A, McMohan K, Watson A and Bowles D (2019) The Health Impacts of Incineration: A Systematic Review, *Australian and New Zealand Journal of Public Health*, 44(10), pp40-48

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

there was "*a dearth of health studies related to the impacts of exposure to WtE emissions*".[35] No conclusions based on very limited epidemiological studies in the UK can therefore be drawn.

Later, the Health Protection Agency, which subsequently became part of Public Health England, undertook its own research of the literature, and concluded:[36]

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

That study focused primarily on the potential carcinogenic effects of pollution from incinerators including emissions of dioxins, with some consideration of the impact of particulate pollution. The study did not consider the impact of NO_x emissions. The potential relative impact of the various pollutants is discussed in Section 3.2.3, where government data on the health impacts is used to evaluate the relative impacts. This type of assessment suggest that NO_x emissions make the most significant contribution to the total health impacts from incinerators. NOx emissions were also omitted from the scope of the recent review of the health impacts of incineration facilities undertaken by the Australian Public Health Association, cited above. The reason for the exclusion is that the studies consider analyses from the academic literature, and NOx emissions from incinerators specifically are not a focus of the academic research on epidemiological impacts of this type of facility.

The Health Protection Agency study was the basis of the Public Health England statement on the health impacts of incinerators, which was published in 2009 but withdrawn in 2019.[37] Around the time of its withdrawal, PHE released another study. The research in this case was undertaken by Imperial College and focussed only on foetal abnormalities. This informed a subsequent position statement produced by PHE, which indicated that emissions from incineration were not felt to result in significant harm to health.[38]

A recent study undertaken by Air Quality Consultants for the GLA was one of the first to attempt to quantify the impact on health of both particulate and NO_x pollution from incineration. The authors concluded that 15 deaths of London residents per year were associated with emissions of nitrogen oxides and particulate matter from the city's five

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[35] Cole-Hunter T et al (2020) The health impacts of Waste-to-Energy emissions: A systematic review of the literature, *Environ. Res. Lett*, article in press
[36] Health Protection Agency (2010) The Impact on Health from Municipal Waste Incinerators
[37] Health Protection Agency (2010) The Impact on Health from Municipal Waste Incinerators
[38] https://www.gov.uk/government/publications/municipal-waste-incinerators-emissions-impact-on-health/phe-statement-on-modern-municipal-waste-incinerators-mwi-study

EfW facilities.[39] That analysis also used government datasets to establish the anticipated health impacts of the pollution from these facilities.

It is important to note that existing evaluations of the impact of pollution on health are likely to be relatively conservative, with the assessment reflecting only those impacts where the data is most robust. The current data used by the UK government to assess the health effects of pollution does not include any consideration of the emerging evidence with regards to the health impacts, such as the links between NO_x pollution and dementia and mental health issues.[40] Elsewhere, other papers confirm there is a lack of evidence regarding the threat to health posed by emissions of superfine particles emitted by facilities such as incinerators.[41]

Other studies have also considered the health impacts of POP contaminated residues associated with the bottom ash and fly ash arising from incinerators – currently not well studied in the academic literature.[42]

3.2.2 Approach to the modelling

The UK government has developed a dataset which considers the impacts upon human health associated with the emission of key air pollutants. The data are based on the estimated costs to society of these emissions occurring, including the financial costs associated with ill health such as hospital admissions related to respiratory illness. The dataset has been developed for use when assessing relatively small impacts on air quality occurring as a result of government policy.[43]

In the absence of Australia specific information on the health impact from incineration and pollution, other authors have used the UK data to consider potential impacts. As an example, in a report prepared for the NSW Environment Protection Agency, standard UK data is used to derive a methodology to calculate how changes in particulate emissions impacts the costs to society.[44] The same approach has therefore been used in the assessment of air pollution impacts of waste facilities undertaken here. Such

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

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

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

[42] IPEN (2020) Toxic ash poisons our food chain, available at: https://ipen.org/sites/default/files/documents/ipen-toxic-fly-ash-in-food-v2_3-en.pdf

[43] See Appraisal Toolkit Spreadsheet 2021, available at https://www.gov.uk/government/publications/assess-the-impact-of-air-quality

[44] NSW Environment Protection Agency (2013) Methodology for valuing the health impacts of changes in particle emissions – Final report, available at https://www.epa.nsw.gov.au/~/media/EPA/Corporate%20Site/resources/air/HealthPartEmiss.ashx

assessments are considered to sit alongside the epidemiological research which was recently undertaken in Australia by the Australian Public Health Association (previously cited in Section 3.2.1 – as this gives the fullest coverage of the potential health impacts associated with pollution from incinerators.

Caution is needed when applying the UK's damage cost dataset to Australia as there are differences in population density between the two countries. Australia is in large part less densely populated than the UK. However, it is expected the incinerators will largely be sited in the more densely populated urban areas of the country, so the dataset can be applied in a similar way to the UK.

The UK dataset is only a guide for the potential impacts on human health. Ideally, a proper analysis is needed for Australia to consider specific population density and point sources of pollution. This is important for those states such as NSW that have a policy to site incinerators in regional areas. Impacts on agriculture, water, forests and tourism especially will need to be considered.

For landfill, emissions are largely related to landfill gas management, and this has been modelled in line with assumed performance of Australian facilities as described previously.

For Australia's incinerators, performance of plant is not yet clear as facilities are not operational, and at varying points in terms of their development. States may take a different approach when considering the emissions performance of that are developed within each jurisdiction.

The updated NSW EfW Policy Statement, with respect to the management of air quality emissions from waste treatment facilities states that it will:[45]

> *…ensure that all NSW energy from waste facilities, wherever they operate, are subject to strict new air quality and operating standards to help protect our environment and human health. NSW has air emission standards that meet and exceed world best practice.*

In Queensland, the potential environmental impacts of EfW facilities are expected to be managed in accordance with the Waste Incineration BREF[46] which are a series of European reference documents that provide guidance on best available techniques (BAT) for a range of industrial processes regulated by the Industrial Emissions Directive 2010/75/EU.

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[45] NSW Environment Protection Authority, NSW Energy from Waste Policy Statement, 2021, https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/waste/21p2938-energy-from-waste-policy-statement.pdf?la=en&hash=34A8524D2D3869F006A690078594057EBC437214

[46] Office of Resource Recovery, Department of Environment and Science, Energy from Waste Policy Queensland, 2020, https://www.qld.gov.au/__data/assets/pdf_file/0020/118433/energy-from-waste-policy.pdf

These statements suggest that Australian waste incinerators may be developed using BAT for managing air emissions. This is not typically the case for UK plant, which typically use the lower performing Selective Non-Catalytic Reduction techniques to reduce NOx emissions. Although this ensures that such facilities just meet the emissions limits in the European Industrial Emissions Directive for this pollutant, the performance is not in line with BAT, as other techniques are available which considerably reduce NOx pollution from these levels. Such approaches are, however, starting to be used on UK facilities – particularly where such plant is developed in dense urban areas such as London. The modelling therefore compares the performance of both approaches.

Table 3-2 presents the current UK damage cost dataset, with the data presented in terms of the financial impact per tonne of pollutant emitted. Three data points are developed for each pollutant, reflecting the uncertainties surrounding the evaluation of these impacts. The values for NO_x and PM2.5 are based specifically on the waste sector and the values for SO_x, NH_3 and VOCs are national figures. We have used the 2020 UK values, converted to Australian dollars, and inflated into 2030 prices. It is noted that a number of pollutants are excluded from this list, such as dioxins, furans and POPs. Data on these other pollutants is less robust; the exclusion of these impacts from the dataset should not, however, be taken to mean that no potential for harm exists. The evidence base for some of these other pollutants is discussed in more detail in Section 3.2.1.

Table 3-2 Damage cost data – health impacts of air pollution

Pollutant	Damage cost for air pollution health impacts, $ / tonne of pollutant		
	Low Sensitivity	Central	High Sensitivity
NH_3	$2,844	$14,816	$45,753
VOCs	$103	$191	$383
PM2.5	$29,544	$138,434	$404,748
SO_x	$5,410	$24,359	$70,332
NO_x	$1,240	$13,202	$50,185

Source: Defra Air Quality Appraisal Damage Costs Toolkit 2021 (exchange rate £1.00 = AUD$1.87)

The upper and lower bounds of the range reflect different approaches to considering the following key impacts:[47]

- The assumed health impact for a given amount of particulate pollution;
- The amount of time before the chronic health impact of particulate pollution is felt;
- The valuation of a life lost as a result of the negative health impacts of air pollution.

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

This dataset has been applied to data on the pollution releases from waste treatment facilities which are, for the most part, derived from information submitted from some example facilities during the application for an environmental permit (these data are given in Appendix A.1.2.4).

UK operators do publish annual performance reports for specific facilities which sometimes include pollutant emissions data. Where such data exists, this is taken from continuous monitoring outputs for the pollutants included within the analysis – and so includes consideration of emissions occurring under the abnormal operation of the facility. However, not all reports contain this information and there is no central repository of the pollution monitoring data, or the associated datasets regarding the amount of exhaust air produced by facilities (the latter being needed to ascertain the emission of pollutant in kg or tonnes, to which the damage cost data can then be applied). It is therefore difficult to ascertain either the typical performance of UK facilities in respect of emissions to air of the key pollutants, or what is best practice.

The assessment uses the "central" damage cost data point. The climate change impacts assessment considers the avoided carbon emissions associated with the energy generated at waste facilities. This is appropriate for the climate change impacts, which are global emissions. However, air pollution impacts are local, making the adjustment to account for avoided emissions less useful. The air quality impacts of different forms of electricity generation are discussed further in Section 0. Benefits occurring as a result of avoided emissions from energy generation and recycling are therefore excluded, as these would occur in different locations to that of the waste treatment facility. In the case of the recycling impacts, these might occur in multiple locations, and, in some cases outside of the UK.

It is also important to note that the above dataset does not include consideration of the health impacts associated with dioxins or furans. Such impacts are of considerable concern to some stakeholders due to their potential to cause hormone disruption and cancer. Eunomia has previously undertaken analysis of the health impacts from incineration relating to these pollutants, using a different dataset developed for the European Environment Agency. This indicates that the impact of emitting one tonne of dioxin is associated with a damage cost of €28m (value in 2010 prices).[48]

Although the impact per tonne of pollution is large, the results of the analysis of incinerator pollution using these data typically show that the impact of this pollution is negligible, as quantities of dioxin emitted are very small. However, such analyses use the data provided by incinerator operators showing the operation of facilities under optimal conditions. Emissions, and therefore health impacts, can be much higher under plant shut down and start up, and may also rise where operational issues occur such as stack bypass, stack cleaning, ESP failure and ESP operating above 2000C . Unlike pollutants

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

such as NO_x and particulates which are subject to continuous monitoring, dioxin levels are only assessed at particular points in the year. Comparison of short term sampling and long term sampling has found that short term sampling can underestimate dioxin emissions by up to 50 fold.[49] There is thus greater uncertainty regarding on-going emissions levels and the associated health risks.

3.2.3 Results: Air quality comparison of waste treatment facilities

Table 3-3 presents the air quality impacts of waste treatment systems modelled as described in Section 3.2.2, with the impacts measured using UK governments dataset to monetise the pollution impacts, as discussed in Section 3.2.2. The table shows the impacts modelled using the central values from the damage cost dataset previously shown in Table 3-2.

The results show that ammonia emissions have the most significant impact on human health for landfill facilities. The use of pre-treatment/ bio-stabilisation reduces the impact of landfill waste. The analysis suggests that, for a landfill facility treating 400,000 tonnes of waste per annum, the cost to society of the human health impacts would be in the order of AUS $4m for landfill facilities without any bio-stabilisation.

The air pollution impact of incineration is higher than that of landfill where emissions are considered on the basis of impacts to human health as modelled by the use of damage costs. Emissions of NO_x account for the most significant contribution to health impacts from incineration according to our analysis. For facilities using typical systems for abating this pollutant that are used in the UK treating 400,000 tonnes per annum, this equates to annual impacts of AUS $13.6m. However, these impacts can be reduced with improved abatement systems as was previously discussed; where these are used the emissions and thus impacts are reduced by more than a third. Emissions reductions also occur where pre-treatment systems are used in combination with incineration. Where this approach is used, emissions are reduced by two thirds, compared to NO_x emissions levels seen where typical UK abatement equipment is used. Clearly further emissions reductions are possible where improved abatement systems are combined with pre-treatment systems.

As was previously discussed in Section 3.2.2, evidence is emerging of other health impacts not currently considered within the analysis. In addition, there are some uncertainties in the attribution of health impacts where the evidence is more robust – whilst no damage cost data is available for some other pollutants with the potential to cause harm, such as dioxins. It is therefore likely that the analysis in Table 3-3 underestimates the health impacts of pollution arising from all waste management systems. Table 3-4 therefore shows the results of the air pollution assessment where the "high" damage cost dataset is used to evaluate the health impacts of the pollutants included within the analysis. Where this data is used to consider the health impacts of

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[49] De Fré R, Wevers M (1998) Underestimation in dioxin emission inventories, Organohalogen Compd, 36, pp17–20

the treatment systems, health impacts from a typical incinerator rise to $132 per tonne, with landfills resulting in comparable impacts of $37 per tonne of waste treated.

Table 3-3 Air quality impacts of waste treatment systems – central case

	Air Quality Impacts, $ per tonne of waste treated[1]				
	Landfill	Landfill with bio-stabilisation	Incineration		Incineration with pre-treatment[2]
			Typical	Low NO_x	
NH_3	$7.27	$2.93			
PM2.5	$0.23	$0.04	$9.18	$9.18	$1.07
SO_x	$0.32	$0.05	$8.08	$8.08	$0.75
NO_x	$2.05	$0.14	$17.51	$3.84	$8.65
TOTALS	**$9.87**	**$3.16**	**$34.77**	**$21.10**	**$10.47**

Notes

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

Table 3-4 Air quality impacts of waste treatment systems – high sensitivity

	Air Quality Impacts, $ per tonne of waste treated[1]				
	Landfill	Landfill with bio-stabilisation	Incineration		Incineration with pre-treatment[2]
			Typical	Low NO_x	
NH_3	$22.45	$9.05			
PM2.5	$0.46	$0.08	$18.41	$18.41	$2.15
SO_x	$0.94	$0.15	$23.62	$23.62	$2.19
NO_x	$5.92	$0.40	$50.56	$11.09	$24.98
TOTALS	**$37.52**	**$12.01**	**$132.17**	**$80.21**	**$39.80**

Notes

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

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

4.0 Comparing Electricity Generation Methods

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

4.1 Approach to the Modelling

The basis of comparison is the amount of carbon dioxide equivalent produced per unit of electricity produced (kgCO_2e/kWh). This section also compares the impact of grid marginal source in 'Central' and 'Electricity Sensitivity' scenarios (see Table 2-1) on the results. Incineration as a form of energy generation is compared with both fossil fuel generation:

- CCGT;
- coal power plants, still in use in Australia although its contribution to total generation is declining;

and low carbon generation:

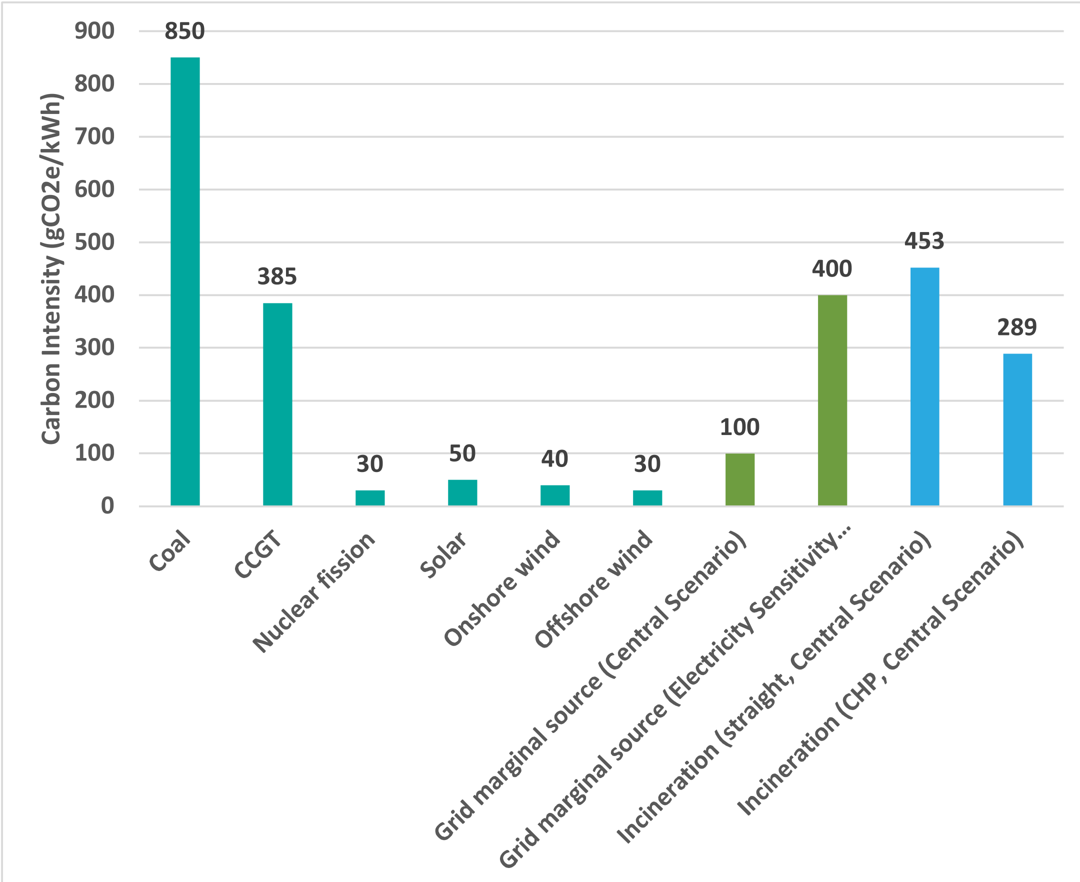
- wind;
- solar; and
- nuclear fission.

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

4.2 Results: Comparing Electricity Generation Methods

Figure 4-1 shows the carbon dioxide equivalent emissions per unit of electricity generated for incineration (electricity-only and CHP modes), fossil fuel, and low carbon generation. The Central and Electricity Sensitivity grid marginal source carbon intensities are also shown.

Figure 4-1 GHG emissions of electricity generation



These results confirm that incineration plants generating only electricity produce power that is more carbon intensive than CCGT, renewables and, most importantly, the marginal source of electricity in both scenarios considered within the analysis. Performance improves for CHP plant; in this case, the power generation is of a lower carbon than that of the electricity sensitivity scenario, considering the beneficial credit for heat generation. However, even where CHP is concerned, the carbon intensity of power generation is much higher than renewables or future grid electricity (assuming in the latter case, reasonable progress towards decarbonisation of the grid occurs). It is important to note that CHP performance in this case is based on reasonably high utilisation of both electricity and heat; if less heat is utilised, the performance will deteriorate. Emissions from incineration consider only the fossil CO_2 emissions associated with the generation of energy at the facility; emissions from burning organic waste such as food and paper are not included.[50] Energy generated at a waste

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[50] This is in line with the conventional approach for undertaking the life cycle assessment of waste treatment systems, as is set out in Section 2.3.1.

incinerator also results in an additional 470 g CO_2 emissions per kWh of electricity for each of the scenarios considered above.

Results presented above include consideration of auxiliary fuels used within the energy generation process for all treatment systems. As such, impacts for wind energy are slightly above 0 g CO_2e / kWh electricity.

Many energy generation facilities are now considering the application of carbon capture and storage to reduce carbon emissions associated with energy generation. Where applied, this would result in an emissions reduction of around 90%. The technology is being actively considered in Australia for coal fired power plants; application of the same technology is also being considered for incineration facilities in Europe, alongside other types of power plant. However, this technology remains unproven and other major industrial operators in Australia have not been able to even partially fulfil their carbon capture commitments.

5.0 Conclusions and Recommendations

The analysis considered a range of scenarios, testing the impact of changes to electricity generation, plastics recycling, and landfill gas capture technology performance. When the anticipated performance of Australian incineration facilities is modelled considering only household waste, GHG emissions performance of incineration is poorer than landfill in 2030 in areas with high landfill gas capture. However, results suggest that incineration performs better than landfill (without pre-treatment) under three out of four of the scenarios considered here. This is the case even when plastics recycling performance is behind target, and progress has been made decarbonising the electricity grid.

There is also some uncertainty surrounding composition of waste actually accepted for treatment at incineration facilities due to a lack of data on the composition of commercial and industrial wastes as well as for construction and demolition waste. The available data indicate that quantities of organic material will probably be lower in the actual material accepted for treatment at incineration facilities – worsening the case for incineration relative to landfill.

Given the uncertainties in the data on both composition and landfill gas capture, for incineration to continue to clearly out-perform landfill in the future with regards to the climate change impacts, it is important for Australia to meet the targets for plastic recycling which appears unlikely on current trends. Where this situation occurs, landfill without pre-treatment is less likely to perform better than incineration even where the grid significantly decarbonises unless improvements on food waste reduction as well as food waste recycling outperform current assumptions. Results of organics diversion in some Australian regions such as the ACT (75%) suggest it is likely that the 50% national organics diversion target could be met and exceeded by 2030.

Further analysis of the results confirms that climate change emissions from incinerators will increase as the electricity grid decarbonises. Incinerators benefit, in 2030, from an emissions credit of 0.085 tonnes CO_2e associated with the generation of electricity. This benefit is anticipated to disappear at some point between 2030 and 2050, assuming regions achieve their climate change reduction targets. In the absence of that credit, most of the climate change benefit of incineration over that of landfill will disappear in the situation where plastics recycling rates do not meet the target. The need to meet the plastics recycling targets is less critical in the situation where Australia makes much less progress in decarbonising electricity supplies as incinerator energy will displace fossil fuels instead of renewables. However, such a situation would be a result of the country making significantly less progress in meeting its overall climate change emissions reduction goals.

Incineration facilities operating in CHP mode out-perform those generating only electricity in all scenarios. This improved performance is, however, dependent on those facilities generating and utilising a significant amount of heat, and this heat being used to displace gas (or other similarly carbon intense fuels). The latter is considered likely to be the case for the foreseeable future in Australia, but most proposed facilities are not expected to operate in CHP mode.

In areas of Australia that fail to meet the voluntary recycling targets for plastics via collection of these materials at the kerbside, authorities will achieve more substantial GHG emission reductions through investment in bio-stabilisation systems with advanced pre-treatment – aimed at sending outputs to landfill - than from investment in new incineration capacity. Such an approach would require less financial investment than that required for incineration. If new incineration capacity is developed in such areas – without the development of carbon capture and storage - the additional development of advanced pre-treatment capacity will be required (for the removal of plastics) to ensure climate change benefits over landfill continue throughout the plant's lifetime. Without advanced pre-treatment, both landfill and incineration are likely to be net emitters of GHGs(once commercial waste is considered) and will therefore be incompatible for local authorities wishing to meet a net zero carbon target. Investment in advanced pre-treatment systems will result in an increase in recycling rates from householders and businesses – and could help ensure the plastics recycling target is met in these areas.

The RDF scenarios perform significantly better than landfill in the situation where coal is assumed to be the fuel displaced. It is noted that the cement industry is also taking steps to decarbonise its operations, and that in many countries, fuels other than coal are being used – such as biomass rich feedstocks. Where this is the case, the benefits attributed here will not be seen, and the performance of the RDF scenarios will more closely resemble that of the situation for residual waste.

Incineration cannot be considered a 'green' or low carbon source of electricity, as the emissions per kWh of energy produced are higher than CCGT, renewables, and the likely aggregated future marginal source of electricity in Australia. The carbon intensity deficit of residual waste incinerators will increase as the electricity grid decarbonises. The use of incineration is therefore also incompatible with the achievement of local net zero climate change targets in respect of emissions from energy generation, unless coupled with carbon capture and storage. This technology is not yet commercially viable, and its use will considerably increase the cost of waste treatment.

Incineration makes a more significant negative contribution to local air quality than landfill where facilities only just meet the emissions limits defined by the European Industrial Emissions Directive. These impacts can, however, be mitigated to a significant extent by appropriate abatement equipment. Even where best available techniques are used, incineration is anticipated to perform worse than landfill in this respect. However, further emissions reduction is possible where pre-treatment is used.

All analyses of this type are subject to some uncertainty; impacts of some aspects of waste management such as landfill gas management being particularly difficult to quantify. Improvements in Australia's environmental data systems would, however, reduce some of the uncertainties in this analysis. In particular, better data is needed on residual waste composition (particularly for commercial waste), the future marginal sources of electricity generation, landfill gas capture and data on the health impacts of pollution emitted in Australia.

Appendices

A.1.0 Technical Appendix

A.1.1 Key assumptions used in the modelling

A.1.1.1 Material assumptions

Table 5-1 shows avoided carbon emissions from material recycling. These values consider the impurity of the recycling streams. These figures come from Eunomia's work with multiple industry players.

Table 5-1 Avoided impacts of material recycling

Material	tCO_2e/t
Plastics (PET)	2.2
Plastics (HDPE)	1.7
Plastic film (LLDPE/LDPE)	1.8
Dense plastic (PP)	1.5
Dense plastic (PS)	2.3
Paper assumed low grade (no benefit)	0.0
Glass	0.2
Ferrous (steel)	1.8
Nonferrous (aluminium)	8.6

Eunomia uses its in-house waste treatment modelling tool (Atropos) to derive residual waste stream properties, shown in Table 5-2.

Table 5-2 Properties of residual waste material streams.

Material	Moisture	Carbon	Proportion of biogenic C	Embodied energy (MJ/tonne)
Masonry materials	20%	17%	50%	14.400
Other ferrous	5%	0%	0%	0.000
Other aluminium	5%	0%	0%	0.000
Food	70%	13%	100%	4.500
Garden	55%	18%	100%	7.650
Timber	17%	32%	100%	14.940
Other organic	70%	0%	100%	4.500
Paper & cardboard	20%	31%	100%	14.400
Plastic film (Other)	15%	67%	0%	38.793
Dense plastic (Other)	5%	66%	0%	31.907
Glass	5%	0%	0%	1.406
Textiles & rubber (excl. tyres)	20%	30%	50%	6.300
Hazardous	5%	0%	0%	0.000

Material	Moisture	Carbon	Proportion of biogenic C	Embodied energy (MJ/tonne)
Other	70%	13%	100%	4.200

A.1.1.2 Composition Assumptions

The residual waste composition is affected by the amount of material captured from it through recycling schemes operated by local councils. Table 5-3 presents the household arisings composition taken from the National Waste Report 2020 (2018/19 data).

Table 5-3 Household arisings compositions in 2018

Material	Waste to landfill	Recycling	Total
Masonry materials	4%	2%	3%
Other ferrous	2%	10%	5%
Other aluminium	1%	7%	4%
Food	36%	10%	25%
Garden	13%	34%	22%
Timber	1%	1%	1%
Other organic	5%	2%	4%
Paper & cardboard	16%	20%	18%
Plastic film (Other)	5%	1%	3%
Dense plastic (Other)	8%	3%	6%
Glass	4%	10%	7%
Textiles, rubber & leather (excl. tyres)	3%	0%	2%
Hazardous	0%	0%	0%
Other	2%	0%	1%

A.1.2 Treatment-specific key assumptions

A.1.2.1 Landfill

Eunomia’s landfill model is aligned for the most part with the national inventory model produced by Australia in its submission to the UNFCCC. However, the model deviates from Australia’s national model in respect of the assumption used for the fraction of dissimilable degradable carbon. The national model uses varying fractions for different waste streams. By contrast, Eunomia’s model uses a factor of 0.5 for all types of waste. Degradation conditions in landfill are imperfect, and as such it only occurs in situations where ingress of water occurs and starts the degradation process. It is unclear why the factor should vary in Australian landfills compared to other countries, or why different factors should be used for different types of waste. The approach used in our model is in alignment with the IPCC standard landfill model.

Other key assumptions for landfill are shown in Table 5-4.

Table 5-4 General assumptions used in landfill modelling.

	Assumption
Proportion of biogenic carbon stored (100 years)	54%
Proportion of carbon to methane/carbon dioxide	50% methane / 50% carbon dioxide
Landfill gas use	60% used for electricity / 40% flared
Landfill gas capture rate – central case	62%
Landfill gas capture rate – sensitivity	70%
Gas engine efficiency	35%
GWP100 of methane	34
GWP N_2O	265
Time horizon of methane emissions	100 years

A.1.2.2 Incineration

There are currently no operational incineration facilities operating in CHP mode in Australia. Efficiency data for the Maryvale facility – a proposed facility which is expected to operate in CHP mode - did not provide separate data for electricity and heat. The assumptions have therefore been developed in Table 5-5, based on a relatively efficient incinerator, that is not too focussed on heat production (the latter being the case with plants in Nordic areas).

Table 5-5 Energy generation efficiencies of EfW.

Operating mode	Energy type	Gross generation efficiency
Electricity-only	Electricity	29%
CHP	Electricity	25%
	Heat	25%

Table 5-6 Materials extraction from bottom ash residues. Material is recycled at a rate of 90%.

Metal	Extraction rate
Ferrous	70%
Non-ferrous	30%

A.1.2.3 Pre-treatment

Table 5-7 Recycling Capture rates – Pre-sorting Treatment[51]

Material	Capture rate
Masonry materials	0%
Ferrous metal	87%
Non-ferrous metal	55%
Food	0%
Garden	0%
Timber	0%
Other organic	0%
Paper & cardboard	75%
Plastic Film	67%
Dense Plastic	80%
Glass	73%
Textiles, rubber & leather (excl. tyres)	0%
Hazardous	0%
Other	0%
Notes: capture rates represent the proportion of material removed for recycling from the residual waste accepted at the pre-treatment plant	

Table 5-8 Organic carbon loss of biogenic carbon compounds in bio-stabilisation of residual waste for landfill.

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

A.1.2.4 Air Quality Impacts

Data on the air pollution emissions from waste treatment facilities is presented in Table 5-9.

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

Table 5-9: Emissions to Air from Waste Treatment Facilities

	Emissions, g pollutant/tonne of waste treated[52] [53]				
	Landfill	Landfill / biostabilisation	Incineration		Incineration with pre-treatment
			Typical	Low NO_x	
NH_3	495	191	15	15	15
VOCs	1	55	55	55	55
PM2.5	1	22	30	30	30
SO_x	4	2.5	40	40	40
NO_x	40	3	1000	200	1000

A.1.3 Results

Detailed breakdown of the GHG impacts of each technology across each scenario is given in tables below.

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

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

Table 5-10 GHG impacts of landfill without pre-treatment

	GHG impact (tCO2e/t)			
Scenario	**Central**	**Composition Sensitivity**	**Electricity Sensitivity**	**Landfill gas sensitivity**
Electricity marginal	**Renewables & Gas**	**Renewables & Gas**	**Gas**	**Renewables & gas**
Plastics recycling target	**Missed**	**Met**	**Missed**	**Missed**
Electricity marginal intensity	**0.10 kgCO2e/kWh**	**0.10 kgCO2e/kWh**	**0.40 kgCO2e/kWh**	**0.10 kgCO2e/kWh**
Heat marginal intensity	**0.23 kgCO2e/kWh**	**0.23 kgCO2e/kWh**	**0.23 kgCO2e/kWh**	**0.23 kgCO2e/kWh**
Landfill gas capture	**62%**	**62%**	**62%**	**70%**
Total	0.283	0.305	0.257	0.176
Direct process emissions				
Excluding biogenic carbon (fossil CO_2 emissions only)	0.290	0.313	0.290	0.177
Inputs & offsets				
Process energy use (all fossil CO_2)	0.002	0.002	0.002	0.002
Total offset through energy generation (all fossil CO_2)	-0.009	-0.009	-0.034	-0.003
Total offset through materials recovery (all fossil CO_2)	0.000	0.000	0.000	0.000

Table 5-11 GHG impacts of landfill with pre-treatment

	GHG impact (tCO2e/t)			
Scenario	**Central**	**Composition Sensitivity**	**Electricity Sensitivity**	**Landfill gas sensitivity**
Electricity marginal	**Renewables & Gas**	**Renewables & Gas**	**Gas**	**Renewables & gas**
Plastics recycling target	**Missed**	**Met**	**Missed**	**Missed**
Electricity marginal intensity	**0.10 kgCO2e/kWh**	**0.10 kgCO2e/kWh**	**0.40 kgCO2e/kWh**	**0.10 kgCO2e/kWh**
Heat marginal intensity	**0.23 kgCO2e/kWh**	**0.23 kgCO2e/kWh**	**0.23 kgCO2e/kWh**	**0.23 kgCO2e/kWh**
Landfill gas capture	**62%**	**62%**	**62%**	**70%**
Total	-0.252	-0.141	-0.225	**-0.261**
Excluding biogenic carbon (fossil CO_2 emissions only)	0.059	0.095	0.088	0.051
Process energy use (all fossil CO_2)	0.001	0.001	0.001	0.001
Total offset through energy generation (all fossil CO_2)	-0.001	-0.001	-0.003	-0.001
Total offset through materials recovery (all fossil CO_2)	-0.311	-0.236	-0.311	-0.311

Table 5-12 GHG impacts of electricity-only incineration (no pre-treatment)

	GHG impact (tCO_2e/t)			
Scenario	Central	Composition Sensitivity	Electricity Sensitivity	Landfill gas sensitivity
Electricity marginal	Renewables & Gas	Renewables & Gas	Gas	Renewables & gas
Recycling target	Missed	Met	Missed	Missed
Electricity marginal intensity	0.10 kgCO2e/kWh	0.10 kgCO2e/kWh	0.40 kgCO2e/kWh	0.10 kgCO2e/kWh
Heat marginal intensity	0.23 kgCO2e/kWh	0.23 kgCO2e/kWh	0.23 kgCO2e/kWh	0.23 kgCO2e/kWh
Total	0.210	0.033	-0.044	0.210
Direct process emissions				
Excluding biogenic carbon (fossil CO_2 emissions only)	0.368	0.195	0.349	0.368
Inputs & offsets				
Process energy use (all fossil CO_2)	0.015	0.015	0.039	0.015
Total offset through energy generation (all fossil CO_2)	-0.085	-0.069	-0.333	-0.085
Total offset through materials recovery (all fossil CO_2)	-0.088	-0.107	-0.099	-0.088

Table 5-13 GHG impacts of CHP incineration (no pre-treatment)

	GHG impact (tCO_2e/t)			
Scenario	Central	Composition Sensitivity	Electricity Sensitivity	Landfill gas sensitivity
Electricity marginal	Renewables & Gas	Renewables & Gas	Gas	Renewables & gas
Recycling target	Missed	Met	Missed	Missed
Electricity marginal intensity	0.10 kgCO2e/kWh	0.10 kgCO2e/kWh	0.40 kgCO2e/kWh	0.10 kgCO2e/kWh
Heat marginal intensity	0.23 kgCO2e/kWh	0.23 kgCO2e/kWh	0.23 kgCO2e/kWh	0.23 kgCO2e/kWh
Total	0.051	-0.096	-0.146	0.051
Direct process emissions				
Excluding biogenic carbon (fossil CO_2 emissions only)	0.368	0.195	0.368	0.368
Inputs & offsets				
Process energy use (all fossil CO_2)	0.015	0.015	0.039	0.015
Total offset through energy generation (all fossil CO_2)	-0.243	-0.199	-0.464	-0.243
Total offset through materials recovery (all fossil CO_2)	-0.088	-0.107	-0.088	-0.088

Table 5-14 GHG impacts of incineration with pre-treatment

	GHG impact (tCO2e/t)			
Scenario	Central	Composition Sensitivity	Electricity Sensitivity	Landfill gas sensitivity
Electricity marginal	Renewables & Gas	Renewables & Gas	Gas	Renewables & gas
Recycling target	Missed	Met	Missed	Missed
Electricity marginal intensity	0.10 kgCO2e/kWh	0.10 kgCO2e/kWh	0.40 kgCO2e/kWh	0.10 kgCO2e/kWh
Heat marginal intensity	0.23 kgCO2e/kWh	0.23 kgCO2e/kWh	0.23 kgCO2e/kWh	0.23 kgCO2e/kWh
Total	-0.304	-0.248	-0.389	-0.304
Direct process emissions				
Excluding biogenic carbon (fossil CO_2 emissions only)	0.107	0.074	0.107	0.107
Inputs & offsets				
Process energy use (all fossil CO_2)	0.014	0.014	0.043	0.014
Total offset through energy generation (all fossil CO_2)	-0.038	-0.036	-0.152	-0.038
Total offset through materials recovery (all fossil CO_2)	-0.387	-0.301	-0.387	-0.387

Table 5-15 GHG impacts of RDF to co-firing scenario

	GHG impact (tCO2e/t)
Scenario	RDF to co-firing
Electricity marginal	N/A
Recycling target	Missed
Electricity marginal intensity	N/A
Heat marginal intensity	Displaces coal
Total	-0.505
Direct process emissions	
Excluding biogenic carbon (fossil CO_2 emissions only)	0.226
Inputs & offsets	
Process energy use (all fossil CO_2)	0.010
Total offset through energy generation (all fossil CO_2)	-0.741
Total offset through materials recovery (all fossil CO_2)	0.000