frontier economics

Assessing emissions from waste to energy

A final report for LMS Energy | 11 May 2021

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1 Introduction

Australia produces approximately 61.5Mt of waste per year, roughly 2.4 tonnes per capita.[1] This total includes approximately 12.6Mt of municipal solid waste (MSW), 21.9Mt of commercial and industrial (C&I) and 27.0Mt construction and demolition (C&D) waste. The total waste produced is a slight increase on previous years.

The management and treatment of waste is an important environmental and economic issue. Poorly managed waste may increase greenhouse gas emissions and negatively impact local water, land and air quality. However, waste also represents an economic opportunity. Certain waste streams may be reused or recycled for a range of productive purposes. Making use of waste streams is the basis for moving towards a circular economy model and more efficiently using primary resources.

One opportunity is the potential for large scale waste to energy (WtE). In Australia, the most common form of WtE is the capture and combustion of 'landfill gas', making up approximately 90% of the waste recovered for energy.[2] Landfill gas (LFG) is a mixture of methane, carbon dioxide, and other gases produced through the anaerobic digestion of organic waste in landfill. The methane may be captured and combusted to produce electricity.

Recently, there has been increased focus on the potential role of alternative WtE approaches in Australia. These include the direct combustion of waste to generate electricity, and high temperature gasification to produce syngas (a fuel made up largely of hydrogen and carbon monoxide) which may be subsequently combusted or refined to produce fuels.

Landfill gas, waste combustion, and waste gasification are substitute approaches to generating energy from waste. Several large-scale thermal WtE (waste combustion and waste gasification) projects have received regulatory approval in recent times. These include:

- The Kwinana WtE facility, a waste combustion plant under development in Kwinana, south of Perth.
- The Recovered Energy Australia gasification project in Laverton North, West of Melbourne

Both projects were supported by life-cycle assessments (LCAs), which estimate the likely greenhouse gas emissions and other environmental impacts over the life of the project. The LCAs were evaluated with reference to a base case in which the waste is diverted to landfill.

The projects are large and will have material consequences for waste management outcomes over coming decades. The Kwinana WtE facility plans to process approximately 400,000 tonnes of MSW per year. This is approximately 26% of the 1,527,363 tonnes of MSW produced annually in Western Australia, and 39% of the 1,023,758 tonnes of MSW which isn't recycled. The Recovered Energy Australian gasification project plans to process approximately 200,000 tonnes of MSW – approximately 7% of total MSW in Victoria and 12% of non-recycled MSW.[3]

[1] Blue Environment, 2020, *National Waste Report 2020* (note that volumes exclude ash)

[2] Blue Environment, 2020, *National Waste Report 2020*

[3] Frontier Economics calculations using data from the National Waste Database 2020.

The analysis undertaken in the LCAs is important, particularly for such large projects. It can estimate the relative environmental costs and benefits of competing WtE approaches, and identify the key factors that drive this. It can identify the scenarios in which one approach has better environmental outcomes and should be preferred. However, it relies on accurate and reasonable assumptions.

This report identifies and discusses some key issues with respect to the environmental evaluation of WtE projects, with a focus on greenhouse gas emissions. It examines how these issues were handled in the Kwinana and Recovered Energy Australia assessments, and outlines some guidance for more appropriate assessment.

1.1 Key issues

An LCA for a large-scale thermal WtE project measures the greenhouse gas emissions (among other outcomes) that would arise from the project relative to an alternative benchmark defined as the base case. The thermal WtE projects provide two services:

- Waste disposal, and
- Electricity generation.

MSW includes organic waste (such as food waste and garden clippings) and 'fossil' (or non-organic) waste such as plastics. The combustion of MSW, particularly the fossil component of MSW, to generate electricity produces greenhouse gas emissions. Emissions from the combustion of the organic component of MSW are not counted in Australia's emissions accounting framework. The level of emissions counted for international accounting depends largely on the composition of the waste: a higher proportion of fossil waste corresponds to higher emissions.

However, the combustion of MSW to generate electricity also avoids some emissions that would otherwise occur. Firstly, it avoids emissions from fugitive LFG (assuming that the alternative disposal of the organic component of waste would be a landfill – fossil waste doesn't produce emissions in landfill). Secondly, it avoids emissions from offset grid electricity generation.

The LCAs for both of the thermal WtE projects considered in this paper, Kwinana and Laverton North, found that the projects led to decreased emissions relative to the base case. This was driven by the two factors above: avoided emissions from organic waste in landfill, and avoided emissions from offset grid production of electricity.

To understand the key drivers of the overall LCAs (and how sensitive this is to changes in assumptions in future) it is important to disaggregate and separately report the emissions streams into the following:

- Direct emissions from the combustion of fossil waste at the thermal WtE facility.
- Avoided landfill emissions from diverting organic waste from landfill.
- Avoided grid emissions from offsetting grid electricity generation.

This allows readers to understand **why** thermal WtE was found to be favourable (in terms of emissions avoided in the LCA results) and to test whether the underlying assumptions are valid and would **persist in the future.**

Based on our analysis, the avoided landfill emissions and avoided grid emissions in the two LCAs are based on backward looking counterfactuals. For avoided landfill emission, the base cases assume landfills with low methane capture rates (and no energy recovery). For avoided grid emissions, the base cases assume electricity generation from high emissions coal. These are not the best practice alternatives to new WtE. They make outcomes in the base case less appealing and therefore the new WtE projects appear more preferable.

There are questions as to whether the current assumptions are appropriate. But there are also questions as to what best practice waste management (and electricity generation) will look like in the future.

In general there should be a case for a more holistic approach to best practice long term waste management strategy rather than looking at projects benchmarked against historical practices which make any improvement look favourable.

Table 1 summarises the key assumptions that may affect emissions estimates from WtE.

Table 1: Key variables affecting outcomes

Greenhouse gas	Key drivers
Direct combustion emissions	Direct combustion emissions depend heavily on the share of organic waste because emissions from the combustion of the organic share of waste are not counted toward emission contributions. A lower share of organic waste (higher share of fossil waste) would result in a higher direct combustion emissions from WtE. Councils are moving towards improved waste separation, with targets on the removal of organics from MSW to be directed towards composting or anaerobic digestion. The National Waste Policy Action Plan has set out a target for halving the amount of organic waste in landfill by 2030.[4] This will increase the fossil component of residual MSW, increasing direct emissions from thermal WtE. **We recommend that LCAs base the waste composition and direct emissions on the National Waste Database, or a similar credible public source. We recommend that sensitivity analysis considers the impact of likely changes to waste composition over time.**

[4] *National Waste Policy Action Plan*, 2019, https://www.environment.gov.au/system/files/resources/5b86c9f8-074e-4d66-ab11-08bbc69da240/files/national-waste-policy-action-plan-2019.pdf

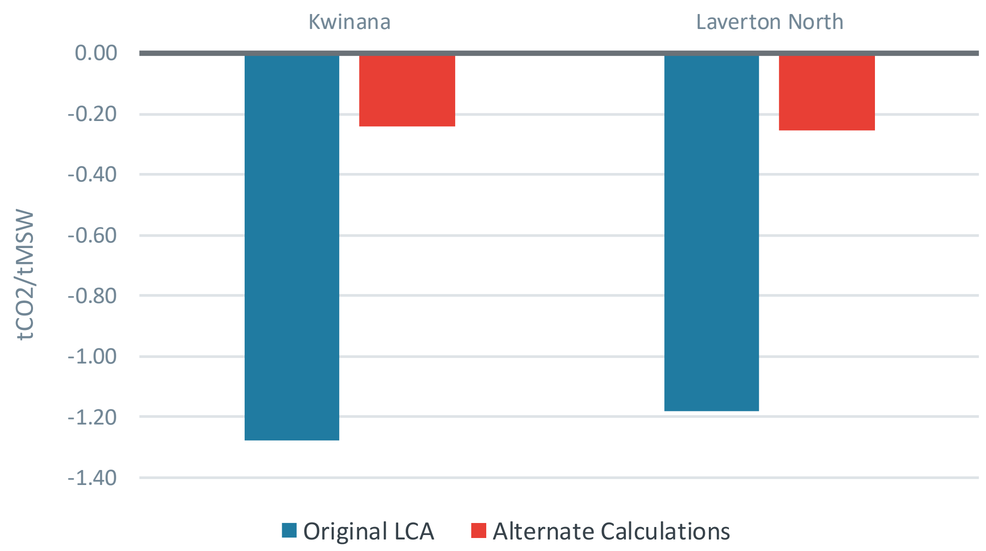
Greenhouse gas	Key drivers
Avoided landfill emissions	Landfill emissions depend on the 'capture rate' of landfill, as well as the organic share of waste. Landfill gas is produced from the breakdown of organic waste in landfill. Some proportion of the LFG is captured and flared or used to generate electricity. The capture rate is the proportion of total LFG generated at the landfill which is captured (and therefore not emitted to the atmosphere). Licensed landfills near metropolitan centres are modern landfills, which are designed and incentivised to capture a higher proportion of LFG. The current baseline used in LCAs reflects a historic national average capture rate, which is materially lower than modern landfills. **We recommend that LCAs adopt a capture rate consistent with the characteristics of a credible, efficient landfill. For WtE projects near metropolitan centres, this is a modern landfill with energy recovery. We recommend a capture rate of 75%, but this could be updated with landfill specific data. We also recommend that the avoided landfill emissions take account of offset electricity from landfill gas electricity generation.**
Avoided electricity emissions	Avoided emissions from offset grid electricity depend on the source of generation in the grid. The avoided emissions in the LCAs assume that the counterfactual is high emissions coal generation. Firstly, it is not clear that new thermal WtE generation will only displace coal generation which has very low marginal cost of operation relative to gas generation. Where thermal WtE is considered partially renewable (in markets with renewable targets) there is an argument that this may be displacing new entrant renewable generation. Secondly, the emissions intensity of grid electricity is falling and will continue to fall over time as coal retires and is replaced by renewables. This means that the thermal WtE benefit from avoided electricity emissions will be falling over time. Thermal WtE produces more electricity per tonne of waste than LFG electricity generation, largely because it derives energy from the fossil share of waste as well as organic. Therefore, lower grid emissions intensity would reduce the avoided electricity benefits of thermal WtE by more than it would reduce the equivalent benefits of LFG electricity generation. **We recommend that avoided grid emissions are calculated using emissions intensity of the generation type most likely to be offset at the margin rather than the highest emissions alternative.**

1.2 Key findings

We make the following key findings:

1. **Both of the LCAs for Kwinana and REA projects and the Laverton North REA overstate the emissions reduction from the new waste to energy projects**

Figure 1: Comparison of net emissions estimated by the LCA and in our study



Source: Frontier Economics calculations

We find that the emissions reduction from the facilities are likely to be about 80% lower than in the LCAs. This is driven by the three key issues outlined above:

- The **direct emissions** in the LCAs appear to be at the low end of the possible range based on the waste composition and literature on thermal WtE emissions. We recommend a higher estimate of direct emissions.
- The **avoided emissions from landfill** are overstated, as the LCAs use a low capture rate (approximately 45%) based on an historical national average. We find a more reasonable estimate for modern landfill to be 75%. Modern landfills are incentivised under the Emissions Reduction Fund (ERF) to capture landfill gas and create Australian Carbon Credit Units (ACCUs). We also find that the avoided landfill emissions should account for offset grid emissions from LFG electricity generation; this is not accounted for in the LCAs.
- The **avoided emissions from grid electricity** generation are based on the highest emitting fuel source in each region – rather than marginal generators. Using estimates of state average marginal emissions reduces avoided grid emissions significantly.

Our estimates (like the LCAs) are conservatively based on current conditions. They do not take into account likely changes in the waste and electricity sector that will occur over the next ten years.

2. Ongoing changes in the waste and electricity sectors will reduce the environmental benefits of large-scale thermal WtE projects relative to landfills

As outlined in **Table 1**, there are important trends in the waste management and electricity sectors which will materially impact the relative attractiveness of thermal WtE and landfill in the future.

- Increased waste separation, and diversion of organic waste from MSW, will reduce the organic share of residual waste.
- Falling emissions intensity of grid emissions as coal generators retire and are replaced by renewables. This reduces the benefit from avoided grid emissions.

It is important to consider how these changes will impact the relative merits of thermal WtE and LFG electricity generation. We've undertaken some modelling to assess how differences in the waste composition, LFG capture rate, and grid emissions intensity impact the relative emissions of thermal WtE and LFG. The modelling is based on a similar set of assumptions to the Kwinana and REA projects.

All the factors that drive emissions from waste are uncertain. The actual composition of waste is likely to be different from even the best estimates and is likely to change over time. The LFG capture rate may vary between landfills, even with similar observable characteristics. And grid emissions intensity will vary over time and between regions in Australia.

It is therefore very important to conduct robust and detailed sensitivity analyses in an LCA to accurately assess the impact on emissions results. We've undertaken some modelling to assess how differences in the waste composition, LFG capture rate, and grid emissions impact the relative emissions of thermal WtE and LFG. The modelling is based on a similar set of assumptions to the Kwinana and REA projects.

The chart below present the findings of our analysis. **Figure 2** shows the sensitivity of emissions to key input assumptions. The Y-axis shows emissions per tonne of MSW and the X-axis shows the share of organics in the waste stream.

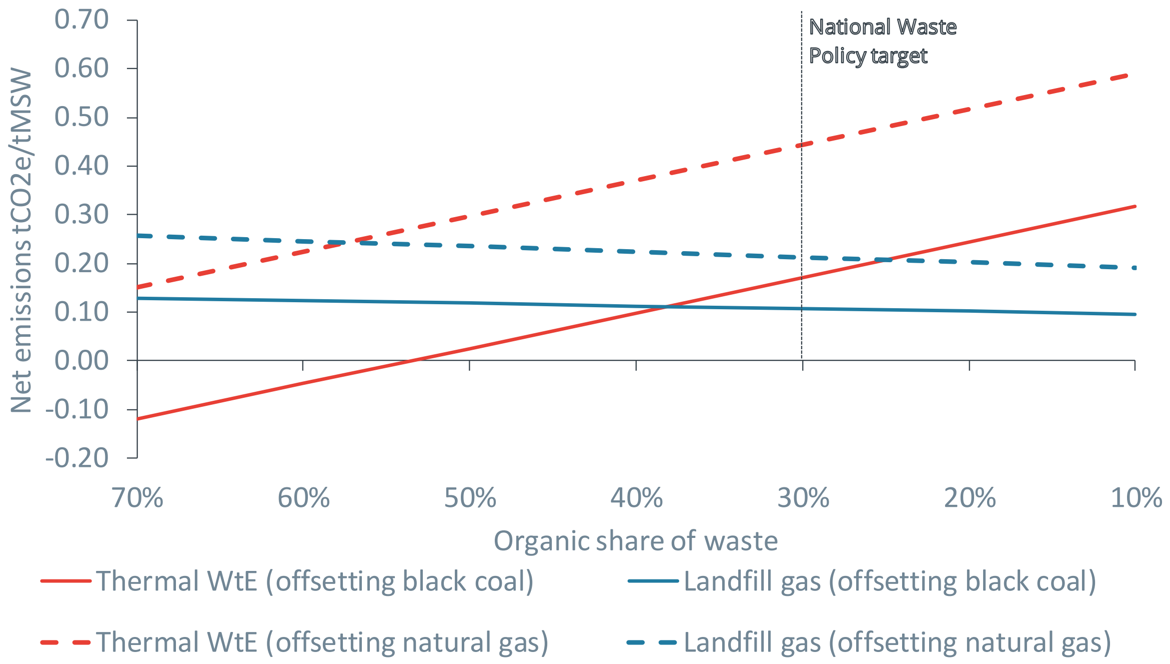
The national average organic share of waste in landfill is 55%, or 70% if paper and cardboard is counted in the organic share.[5] As outlined above, the National Waste Policy Action Plan sets out a strategy to halve the organic share of waste by 2030, which would result in an organic share of approximately 30%. The dotted vertical line represents this target. Policy measures from all levels of government are pushing outcomes from the left to the right of this axis.

- The red lines reflects net emissions from thermal WtE, after accounting for avoided grid electricity emissions. These slope up because a lower share of organic content increases WtE emissions. The blue lines reflect net emissions from LFG electricity generation with an assumed landfill gas capture rate of 75%. Unlike thermal WtE, these slope downwards as decreasing organic shares reduce methane production in landfill, and reduce fugitive emissions.
- The solid lines are calculated on the basis that the thermal WtE or LFG electricity generation offset electricity generated entirely from **black coal** (with emissions intensity of 0.9tCO2e/MWh). The dashed lines are calculated on the basis of offsetting electricity with a

[5] Frontier Economics calculations using data from the National Waste Database 2020.

lower grid emissions intensity of 0.45tCO2e/MWh. This is consistent with either **natural gas** generation or approximately a 50% mix of black coal and renewables (assuming that WtE electricity also discourages new entrant renewables at the margin). We note that Victoria and QLD have 50% renewable targets by 2030, SA is targeting 100% by 2030 and Tasmania is already close to 100% renewable. The dashed lines are a conservative guide to the likely avoided electricity emissions by 2030, which will likely be lower in some regions.

Figure 2: Net emissions from thermal WtE and LFG electricity generation



Source: Frontier Economics analysis

There are several key observations. Firstly, that the direct emissions from combustion WtE increases as the share of organics decreases. Conversely, the avoided landfill emissions decreases along with the share of organics. This reflects the lower overall production of methane with lower organic shares. The national average organic share of waste is about 55%, and heading towards a target of approximately 30% by 2030. With that waste make up, emissions from thermal WtE are likely to exceed landfill, even with unrealistically high avoided emissions.

There are combinations of landfill gas capture rate, emissions intensity, and organic share of waste which are 'tipping points' at which the emissions from thermal WtE exceed landfill. This figure presents a few, but there is a continuum for each set of parameters. For high emissions (black coal) electricity, the tipping point is an organic share of just below 40% - partway to the national target. For lower emissions intensity (natural gas), the tipping point is below 60%, close to the current state of play. If the emissions intensity of electricity was close to zero (offsetting renewables), the tipping would be even higher than 70%. For landfills with high capture rates (around 85%), the tipping points would be reached earlier.

The broad trends in the waste and energy sectors are all moving in a single direction towards states in which thermal WtE produces higher net emissions than landfill. The grid emissions intensity is falling (moving towards the dotted lines and beyond) and the organic share of MSW is falling steadily (towards the right-hand side of the chart). If the state renewable energy targets for

2030 are met, and National Waste Policy Action Plan target for organic share of waste in 2030 is met, thermal WtE emissions will exceed landfill emissions.

Thermal WtE will have higher emissions than landfill in some Australian regions already. This is likely to be the case across the country within ten years, well within the useful life of thermal WtE facilities built today. Beyond this point, the use of thermal WtE would unnecessarily lock in high emissions from the waste sector into the future.

1.3 This report

The remainder of this report is set out as follows:

- Section 2 sets out a critical assessment of the comparison of landfill and waste to energy emissions set out in the life-cycle assessment for the Kwinana waste to energy project
- Section 3 sets out a critical assessment of the comparison of landfill and gasification emissions set out in the Works Approval Application for the Recovered Energy Australia gasification facility in Laverton North
- Section 4 provides a practical framework for future comparisons between landfill gas and thermal waste to energy projects.

2 Case study 1: Kwinana waste to energy

The Kwinana waste to energy (WtE) project is a waste combustion facility under development in Kwinana, South of Perth. The Kwinana WtE facility will use moving grate technology to combust waste, producing steam which is used to generate electricity. It plans to process approximately 400,000 tonnes of waste per year, made up of municipal solid waste (MSW), commercial and industrial (C&I), and construction and demolition (C&D) streams. This waste is estimated to produce approximately 276GWh of electricity for the Western Australian grid per annum.

The source of the waste is a number of towns around South Perth, near the Kwinana WtE facility. These towns include Armadale, Gosnells, Mandurah, Murray, Serpentine Jarrahdale, South Perth, Canning and the City of Kwinana.

2.1 Overview

The Kwinana WtE project was supported by the Australian Renewable Energy Agency (ARENA), which contributed $23 million to the project. The ARENA support appears to be based on a Life-Cycle Assessment (LCA) of the project. The LCA was produced by Ramboll in December 2018 and published on the ARENA website.[6] It includes a critical review undertaken by Andeers Daamgard of the Technical University of Denmark.

The purpose of the commercialisation LCA undertaken by Ramboll is described by ARENA as including:

- To obtain a benchmark on fossil energy used, energy return on energy invested, and greenhouse gas performance[7]

The LCA considers the environmental impact of the Kwinana WtE across a range of measures. An important consideration as outlined by ARENA is the greenhouse gas emissions. The functional unit for the LCA is the production of 1MWh of electricity, supplied to the Western Australian grid.

Overall, the LCA finds the Kwinana WtE facility results in significant net reduction in greenhouse gas emissions. This is mostly driven by the avoided emissions from landfill and from avoided electricity generation: **Table 2** and **Figure 3** below. In fact, the direct emissions from WtE are estimated to be lower than avoided landfill even without counting any avoided emissions from grid electricity.

Most of this estimated net benefit relies on the assumptions underpinning the counterfactuals of emissions avoided from landfill and electricity generation. In the remainder of this Section, we undertake a review of the assumptions and calculations underpinning the emissions calculations.

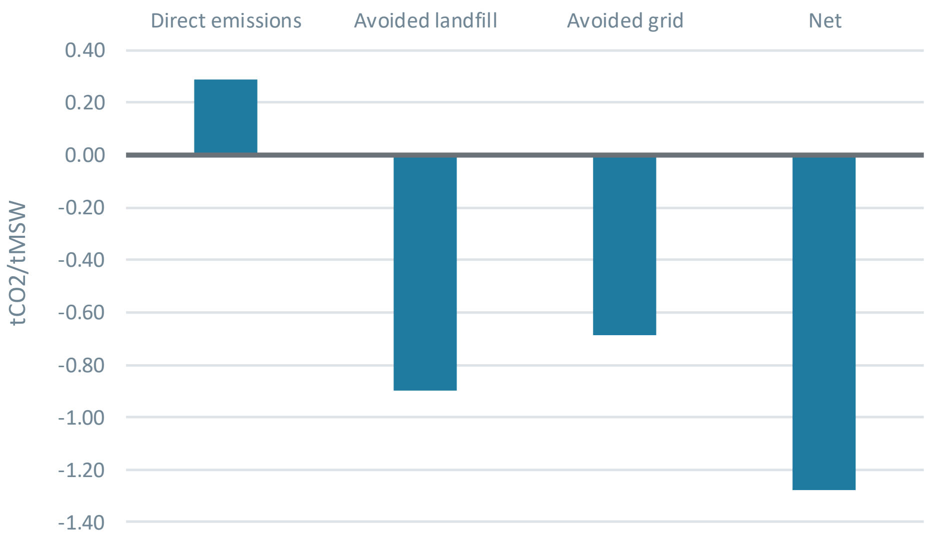
[6] Ramboll, December 2018, *Kwinana waste to energy project: ARENA life cycle assessment*. Online at https://arena.gov.au/assets/2019/01/kwinana-waste-to-energy-project.pdf

[7] ARENA, January 2017, *Life cycle assessment (LCA) of bioenergy products and projects*. Online at https://arena.gov.au/assets/2017/05/AU21285-ARENA-LCA-Guidelines-12-1.pdf

Table 2: Kwinana WtE emissions estimates: LCA

Source	tCO2e/MWh	tCO2e/tMSW
Direct emissions (WtE)	0.42	0.29
Avoided landfill emissions	-1.30	-0.89
Avoided electricity emissions	-0.99	-0.69
Total	**-1.85**	**-1.28**

Figure 3: Kwinana WtE emissions estimates: LCA



Source: Frontier Economics analysis of LCA

2.2 Direct emissions

The Kwinana WtE facility produces direct emissions of several greenhouse gases through the combustion of waste to generate electricity.

Under the National Greenhouse Accounts (NGA), the emissions factors for CO2 emissions from the combustion of organic material is deemed to be 0. That is, CO2 emissions (but not other greenhouse gas emissions) from the combustion of a renewable organic source are zeroed out in the direct emissions calculation. This treatment applies to other bioenergy methods, such as the combustion of captured LFG or biogas.

The LCA estimates direct emissions to be 0.29 tCO2e / t MSW, or 0.417tCO2e/MWh. The estimation is based on several key assumptions:

- Organic share of the waste is 71.2%
- Moisture content of the waste is 36.5% by mass

It is not clear exactly how the emissions were estimated for the LCA. The values in the LCA are taken from the EPC contract. However it appears as though the CO2 emissions factors are based on overall emissions of 1.442tCO2e/MWh. Of this, 1.026 (71.2%) are from the organic component of waste and therefore excluded from counted emissions, and 0.415 (28.8%) are from the non-organic component of waste. There is a small amount of additional emissions of other greenhouse gases.

Implicitly, this seems to assume that the energy density and emissions factors of the organic share of waste is the same as the non-organic share of waste. This is not necessarily true. The energy density of organic and non-organic waste can vary significantly when used for combustion. Differences in these factors can materially impact the project emissions.

The main factor affecting the combustion emissions intensity is the waste mix, specifically the organic versus inorganic share. To assess the reasonableness of the combustion emissions intensity values used in the LCA, we developed independent calculations using a range of publicly available sources.

First, we estimated the emissions from the combustion of waste using the energy density (GJ/tonne) and emissions factors (kg CO2e / GJ) from the NGA.[8] Combining these values with the assumed share of organic waste from the LCA (71.1%) we obtain an estimate of direct emissions of 113.8Mt, which is consistent with the LCA estimate of 115Mt (this included small additions for auxiliary gas). **This implies direct emissions of 0.28tCO2e/tMSW.**

Given the NGA estimates of energy content (12.2GJ/t for organics, and 10.5GJ/t for non-organics) and reported energy generation in the LCA (276GWh), this implies generator efficiency of 21%.[9]

Table 3: Direct greenhouse gas emissions (Frontier Economics calculations on NGA basis)

Greenhouse gas	Emissions factor (kgCO2e/GJ)[1]	Energy GJ/t[1]	MSW kt/year[2]	Energy TJ	GHG MtCO2e
Organic[2]	1.8	12.2	284.4	3,474	6.25
Fossil	88.9	10.5	115.2	1,209	107.5
Total				**4,683**	**113.8**

Source: Frontier Economics analysis using the following: 1. Table 1 National Greenhouse Accounts factors 2018. 2. Organic share is 71.1% in the Kwinana LCA. Total MSW processed is assumed at 400kt per year.

We also considered the Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories. [10] The values for organic and inorganic waste energy content and emissions factors are similar to the Australian NGA. The IPCC values are presented below (**Table 4**).

[8] Australian Government Department of the Environment and Energy, 2018, *National greenhouse accounts factors*. https://www.industry.gov.au/sites/default/files/2020-07/national-greenhouse-accounts-factors-august-2019.pdf

[9] The LCA actually assumes 24% generator efficiency and assumes average energy content of 10.5GJ/t, which provides equivalent electricity output. The combination of these assumptions results in average direct emissions of 0.417tCO2e/MWh in the LCA.

[10] IPCC, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_1_Ch1_Introduction.pdf

Table 4: Direct greenhouse gas emissions (IPCC)

Greenhouse gas	Emissions factor (kgCO2e/GJ)	Energy GJ/t
Organic	91.7[1]	11.6
Fossil	100	10.0

Source: 1. IPCC https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_1_Ch1_Introduction.pdf 2. CO2 from the combustion or decay of short-lived biogenic material removed from where it was grown is reported as zero, which we assume is the difference from the NGA.

Both the NGA factors and IPCC factors align relatively well with the values in the LCA. However, it isn't completely clear how the NGA and IPCC factors were defined and calculated – for example the NGA doesn't describe the assumed composition of the non-organic component, and therefore doesn't allow for differences in composition. It isn't possible to tell whether these are accurate and appropriate assumptions in practice.

To build on our analysis using the NGA benchmark factors, we also attempted to recreate these calculations from first principles based on:

(a) the energy content by MSW waste component developed by the Clean Energy Regulator (CER),[11] in its guideline for determining the renewable and non-renewable components of waste and

(b) the average weighting of MSW from the CER.

On the basis of these calculations, we found that the organic component of MSW has an energy content of approximately 6GJ/t and the non-organic component of MSW has energy content of approximately 25GJ/t. We haven't been able to determine the reason for the difference between this energy density and the energy density used in the NGA factors. It may be because the NGA factors assume an unusual composition of waste – for example with a very high proportion of inert materials and very low proportion of high energy plastics compared to actual MSW.

However, this doesn't necessarily imply that the emissions estimates in the LCA are inaccurate, despite issues in the method and assumptions. The CER guideline doesn't include estimates of emissions intensity for each stream of waste.

We considered a broad range of other studies that examined the emissions from the combustion of waste for energy. These are summarised in **Table 5**. Overall, various other sources report **total** estimated WtE combustion emissions of around 1tCO2e/tMSW, with **the fossil share (the relevant measure) at around 0.4tCO2e/tMSW.** The Kwinana LCA estimate of 0.29tCO2e/tMSW is below the lower bound of these estimates.

[11] Clean Energy Regulator, 2001, *Guideline for Determining the Renewable Components in Waste for Electricity Generation* http://www.cleanenergyregulator.gov.au/DocumentAssets/Documents/guidelines-determining-renewable-components-waste-electricity-generation-0312.pdf

Table 5: Direct greenhouse gas emissions (various)

Greenhouse gas	Fossil (tCO2e/tMSW)
IPCC[12]	0.415
Moora (2017)[13]	0.429
Ritchie and Smith (2009)[14]	0.34 (rising to 0.46 with increased waste diversion reducing organic content)
Productivity Commissions (2006)[15]	0.56
Avfall Sverige (2012)[16]	0.34 - 0.54
Xin (2020)[17]	0.37-0.518

Source: 1. IPCC https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_1_Ch1_Introduction.pdf

The Moora (2017) study calculated the energy content from organic (6.6GJ/t) and fossil (25.5GJ/t) waste using a detailed breakdown of the waste composition. The waste it examined had a wet weight share of 65% organic, 20.6% fossil and 14% inert, which translates to a dry weight share of 52.2% organic, 26.5% fossil, 21% inert. Based on this energy density and organics share, it calculated an emissions rate of 0.429tCO2e/tMSW.

The estimates of emissions are very sensitive to assumptions about local moisture content and the overall waste mix (organic share). Richie and Smith (2009) considers the impact of increased separation and diversion of waste, which will reduce the share of organics in the mixed waste stream (as this will be diverted to composting or similar alternatives) and will increase the relative share of plastics in the mixed waste stream. The net impact of increased separation and diversion is to increase the emissions intensity of waste combustion.

The other impact of increased separation and diversion is to reduce avoided landfill emissions. Overall, it finds that landfill with capture (at 80% collection efficiency) is initially marginally higher emission than combustion WtE on historical waste mixes. As increased separation and diversion reduces the amount of organics in MSW, landfill with efficient capture rates have increasingly

[12] IPCC, *Emissions from Waste Incineration,* https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf

[13] Moora et al, 2017, *Determination of biomass content in combusted municipal waste and associated CO 2 emissions in Estonia* https://www.researchgate.net/publication/320383060_Determination_of_biomass_content_in_combusted_municipal_waste_and_associated_CO_2_emissions_in_Estonia

[14] Ritchie and Smith, 2009, *Comparison of Greenhouse Gas Emissions from Waste-to-Energy Facilities and the Vancouver Landfill*, http://pentz.com/NoIncinerator/greenhouse%20Emmissions.pdf

[15] Productivity Commission, 2006, *Waste Management*, https://www.pc.gov.au/__data/assets/pdf_file/0014/21614/waste.pdf

[16] Avfall Sverige, 2012, *Determination of the Fossil Carbon Content in Combustible Municipal Solid Waste*, https://www.avfallsverige.se/aktuellt/nyhetsarkiv/artikel/determination-of-the-fossil-carbon-content-in-combustible-municipal-solid-waste-in-sweden/

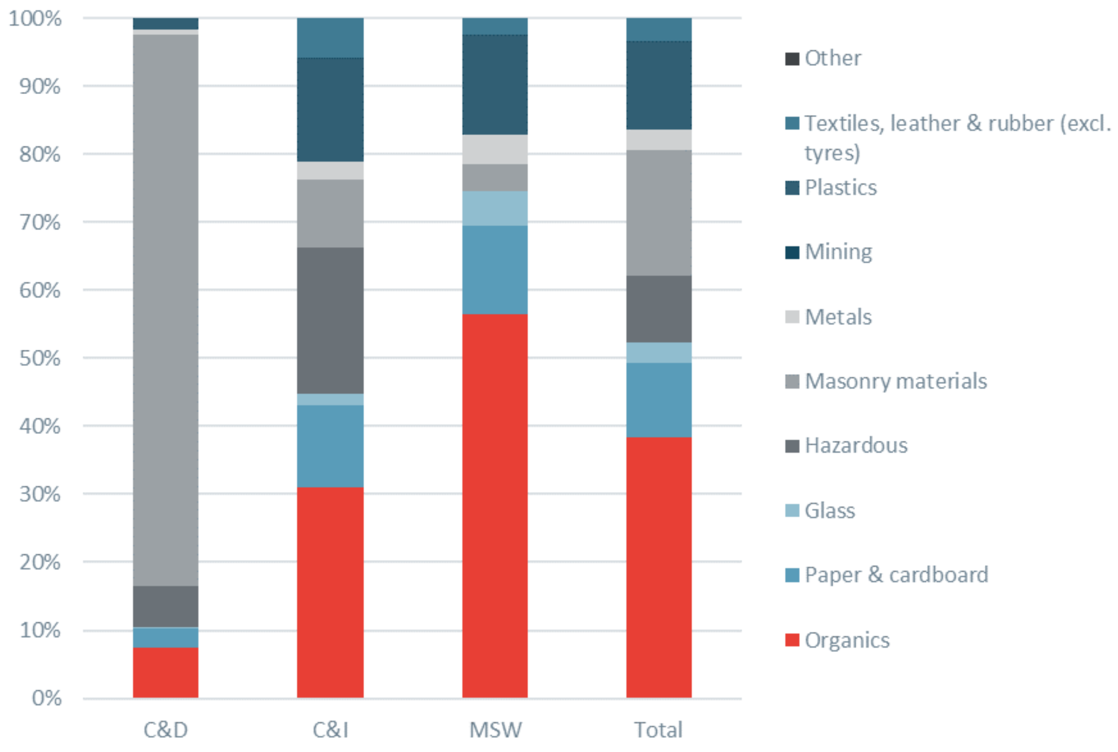
[17] Xin et al, 2020, *An Empirical Study on Greenhouse Gas Emission Calculations Under Different Municipal Solid Waste Management Strategies,* https://www.mdpi.com/2076-3417/10/5/1673

lower emissions. Landfill gas emissions and capture rates are discussed in greater detail in Section 2.3.

This demonstrates that WtE relies on an assumption of a relatively large share of organic content to keep direct emissions relatively low, and that the burning of plastics is actually an extremely high source of emissions. Given that most councils are shifting to increased waste separation (in particular separation of Food Organics and Garden Organics (FOGO) alongside broader policy measures to reduce organic waste, it can be expected that organic content in residual streams will reduce and hence the future emissions from WtE are likely to rise. This is considered in sensitivities below.

The Kwinana LCA assumes 71.1% organic waste and the resulting direct emissions (as applied) of 0.29tCO2e/MSW appears to be an outlier relative to other sources listed above. The National Waste Database 2020 reports that that 57% of MSW that is disposed in landfill in Western Australia is organic, though this rises to 69% if paper and cardboard is also included. This is on a wet weight basis, which is similar to Moora (2017). The National Waste Database values are presented in **Figure 4**.

Figure 4: Waste stream, WA Landfill/disposal 2018-19



Source: National waste database 2020

Overall, it isn't clear how the direct combustion emissions in the LCA have been calculated. The estimate appears to rely on some undocumented, implicit assumptions such as that the energy density and emissions intensity of the organic and fossil shares of the waste stream are identical. The estimated emissions sit below a range of estimates for the combustion of waste relative to a wide range of sources we have considered. Ideally, it would be possible to review the emissions estimate based on the way it was calculated, but that information is not publicly available.

The emissions from waste combustion are uncertain, with studies providing a wide range of estimates. It depends considerably on some assumptions, the most material of which being the proportion of organic waste. In the absence of information setting out how the emissions estimate was derived, we consider **0.42tCO2e/tMSW** would be a reasonable central estimate of the emissions from the Kwinana WtE. However, given the importance of the waste composition, and likelihood of change over the project life, we consider it very important to undertake robust sensitivity analysis on this assumption.

2.3 Avoided landfill emissions

A higher rate of capture to that assumed in the LCA would substantially reduce avoided landfill emissions

The largest part of the emissions reduction from the Kwinana WtE facility presented in the LCA is attributed to avoided landfill emissions. The LCA finds that diverting waste from landfill to combust it avoids approximately **1.3t CO2e/MWh (0.88tCO2e/tMSW)** of greenhouse gas emissions.

Landfill gas emissions are a mixture of methane, carbon dioxide, and other gases produced through the anaerobic breakdown of organic matter in landfill. The amount of LFG produced by landfill depends on a range of factors, including the type of waste – particularly the proportion of organic waste. However, not all LFG is released as an emission. It may be captured and flared (converting methane to carbon dioxide), or captured and burned to produce electricity (again producing carbon dioxide). Under the NGA framework, consistent with the treatment of emissions from combustion of organic waste, carbon dioxide emissions from the combustion of LFG are excluded from emissions calculations.

The LCA assumes a landfill gas 'capture rate' of 46.2%, based on an Australian average for landfill. From the perspective of the LCA, a lower capture rate implies higher avoided emissions from landfill – and vice versa.

Landfill gas collection efficiencies are generally estimated rather than measured, with reference to an expected decay rate of organic material in the landfill waste. Measuring LFG collection efficiency at a particular site is an involved process. It may be necessary to estimate gas collection efficiency a number of times over years to accurately measure lifetime efficiency, as the collection efficiency can vary significantly depending on whether the landfill is open or capped, and various other factors.

There is considerable variation in gas collection efficiencies, due to the way in which landfills are designed, operated and regulated. The type of lining, type of cover, and when gas collection systems are installed are important factors that affect gas collection efficiencies.

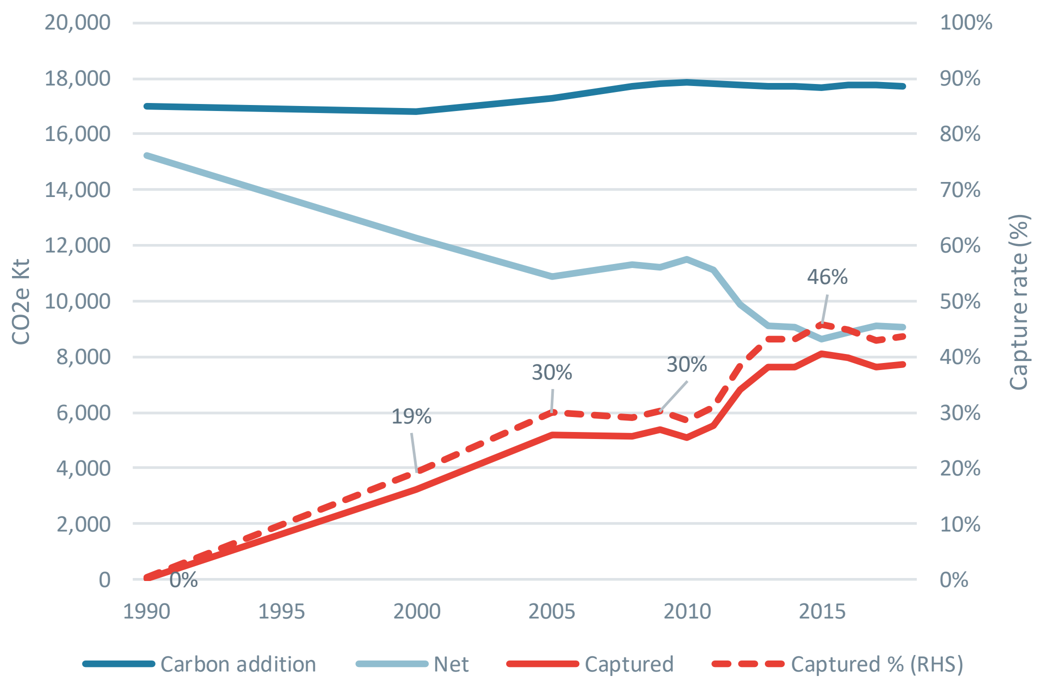
For the purpose of an LCA, the avoided LFG emissions should be based on a reasonable counterfactual of how the waste would otherwise be processed in landfill. As outlined above, it can be an involved process to measure gas capture rates, so in general it may not be possible to base the estimate on the capture rate for a specific landfill. Therefore it is reasonable to use a representative LFG collection efficiency, however this should reasonably reflect the characteristics of an alternative.

Landfill gas is produced over a period of decades, as the organic matter in landfill decomposes. Both the production of methane and capture rate change significantly over the life of the landfill. So a point in time estimate of the capture rate may not accurately reflect the lifetime capture rate. All else equal, the capture rate tends to be lowest while the landfill is open and accepting new waste and increases materially when the landfill is finally closed and capped. So the life-cycle capture rate depends not only on the capture rates while the landfill is open and closed, but also on the duration of each stage and the decay rate of the organic matter. Again, all else being equal a slower decay rate typically allows a higher lifetime capture rate.

In addition to the LFG capture (which may be used for energy production or other purposes), some of the methane emissions from landfill are 'oxidised' at the surface level. The oxidised emissions do not make it into the atmosphere. The National Greenhouse and Energy Reporting waste calculators assume a methane oxidation factor of 10%. The oxidised methane should be taken account of when estimating emissions. There is evidence to suggest that the oxidation rate may be higher than 10%[18] due to site-specific factors, however we consider 10% a reasonable value to adopt in the absence of site-specific information.

The capture rate of 46.2% used for the LCA appears to be based on a low (conservative) estimate based on historical emissions from all landfill in Australia. The average capture efficiency over time, measured by the amount of methane captured relative to total emissions is presented in **Figure 5**).

Figure 5: Australian average waste emissions (captured and net)



Source: NGA-national-inventory-report-2018-volume-2[19]

The Australian average capture rate has trended up from 0% in 1990 to 19% in 2000, 30% in 2010 and 46% in 2015. This would reflect a combination of older landfill (with low/no capture) and

[18] Chanton J et al, 2009, *Methane Oxidation in Landfill Cover Soils, is a 10% Default Value Reasonable?*

SCS Engineers, 2007, *Current MSW industry position and state-of-the-practice on LFG collection efficiency , methane oxidation, and carbon sequestration in landfills*

[19] Department of Industry, Science, Energy, and Resources, *National Inventory Report 2018*, https://www.industry.gov.au/sites/default/files/2020-05/nga-national-inventory-report-2018-volume-2.pdf

newer landfill with capture rates higher than the average. It also reflects an average of large-scale landfills near urban centres (which are more likely to be newer, and have efficient gas capture, and smaller and more remote landfills). This rate should continue to rise as more waste is delivered to newer landfills.

The Australian average is not particularly relevant to Kwinana. The local Millar Road landfill and Henderson landfill both have active gas capture systems with energy recovery. They are large, licensed facilities with an economic incentive to capture gas for energy production. The Millar Road landfill is approximately 10km south of Kwinana, and Henderson is approximately 10km north. We are not aware of publicly available information on specific capture rates for either landfill. However, we consider that the LCA should use a baseline landfill with characteristics similar to these as the relevant counterfactual. Note that the relevant counterfactual depends on the location of the combustion WtE facility. If alternatively Kwinana was in a remote location, and was diverting waste from an old landfill with no gas capture, the counterfactual should reflect that.

It isn't clear how the 46.2% capture rate, and the avoided emissions calculations in the LCA take into account methane oxidation. However, based on our attempt to reconstruct the 46.2% estimate, we think it is likely inclusive of oxidation.

The estimates of LFG capture rates in Australian and international literature vary considerably. **We consider that a range of 60-85% is a reasonable range for the life-cycle efficiency of a modern landfill with gas capture, with methane oxidation additional to this. We consider 75% is a reasonable central estimate if there is no other information available about the landfill. This is based on:**

- Barlez et al (2012)[20] construct detailed estimates of life-cycle capture rates for landfill based on factors including the duration of each stage, type of capture and capping, and decay rate. Depending on the climate, they estimate life-cycle capture rate in the range from 55% to 91%, with a range from 66% to 88% for phased in collection.
- SCS (2007)[21] assess LFG capture efficiencies in the USA for landfills with active gas capture. It considers factors such as the type of cover and type of collection system. It recommends a range of 50-85% (default of 68%) for landfills with daily cover without liner, 85-99% (default of 92%) for landfills with final soil cover but no liner, and 95-99% (default of 97%) for specifically designed landfills with final cover and liners.
- GHD (2010)[22] conduct detailed measurements at the Wollert landfill in Victoria. They estimate a capture rate of 78% to 87%, which we understand can be considered equivalent to a life-cycle capture rate.
- The NGER Determination[23] assumes a maximum capture rate of:
  - a 60% capture rate for landfill with daily soil cover and active gas collection

[20] Barlez, J, Chanton, J and Green, R, 2012, *Controls on landfill gas collection efficiency: Instantaneous and lifetime performance*

[21] SCS Engineers, 2007, *Current MSW industry position and state-of-the-practice on LFG collection efficiency , methane oxidation, and carbon sequestration in landfills*

[22] GHD, 2010, *Report for Wollert Landfill: Flux testing and emissions estimates*

[23] National Greenhouse and Energy Reporting (Measurement) Determination 2008, https://www.legislation.gov.au/Details/F2020C00600

  - a 75% capture rate for a closed or capped landfill (specifically, with an intermediate top cover, a final clay cover less than 1m thick, or a phytocap layer that is at least 1m thick), with active gas collection
  - a 95% capture rate for a capped landfill (specifically, with a final clay cover at least 1m thick, or a geo-membrane cover system) with active gas collection
  - Note that the NGER values are point in time estimates based on contemporary characteristics of the landfill, not lifetime capture rates
- Productivity Commission (2006)[24] assumed capture rate for modern landfill to be 75% based on Australian evidence
- Dastjerdi et al (2019)[25] assume a capture rate of 75% based on guidelines from the United Kingdom
- Ritchie and Smith (2009) find that typical capture efficiencies range from 65% to 90% and estimate an average capture rate of 80% in Vancouver

Consideration should be given to the characteristics of the landfill, and it may be reasonable to apply the higher estimate (approximately 85%) in some cases.

Based on a LFG capture rate of 75% we estimate a more reasonable estimate of avoided landfill emissions is **0.41tCO2e/MSW** (assuming the same organic content). However, this excludes any recognition of the avoided electricity from LFG.

The LCA also failed to account for any avoided emissions from electricity generated by LFG. The modern landfill which is a suitable counterfactual for the avoided emissions would also generate electricity with the captured methane.

We estimate that the avoided electricity emissions from LFG ranges from:

- 0.13tCO2e/tMSW (45% capture rate using the average WA grid emissions intensity of 0.72tCO2e/MWh), to
- 0.34tCO2e/tMSW (85% capture using black coal emissions intensity of 0.99tCO2e/MWh)

Incorporating the avoided electricity emissions reduces the **net** LFG emissions avoided to **0.11-0.19tCO2e/tMSW** using a 75% capture rate.

The variation in LFG emissions by capture rate and avoided grid emissions is presented in **Table 6**.

[24] https://www.pc.gov.au/__data/assets/pdf_file/0014/21614/waste.pdf Page 72 *Based on the available evidence, the Commission considers that for the purposes of estimating the external costs of landfill greenhouse gas emissions, it is reasonable to assume collection efficiencies of up to 75 per cent of landfill gases.*

[25] Dasterjdi, B et al, 2019, *An evaluation of the potential of waste to energy technologies for residual solid waste in New South Wales, Australia*

Table 6: LFG emissions avoided

LFG capture rate	Gross LFG emissions (tCO2e/tMSW)	0.99tCO2e/MWh avoided (black coal)		0.72tCO2e/MWh avoided (WA grid average)	
		LFG electricity avoided (tCO2e/tMSW)	Net LFG (tCO2e/tMSW)	LFG electricity avoided (tCO2e/tMSW)	Net LFG (tCO2e/tMSW)
45%	0.90	0.18	0.72	0.13	0.77
75%	0.41	0.30	0.11	0.22	0.19
85%	0.25	0.34	-0.09	0.25	-0.00

Source: Frontier Economics calculations

2.4 Avoided grid emissions

The ARENA LCA estimated that the 276GWh of electricity generated by the Kwinana WTE facility would offset approximately 274,000 tonnes of emissions from grid production of electricity. This assumed the emissions intensity from avoided electricity of 0.99tCO2e/MWh based on 100% black coal. However, Appendix 2 of the LCA adopted the average WA grid emissions intensity of 0.72tCO2e/MWh.

The WtE facility is assumed to generate approximately 0.69MWh/tMSW so the assumption of 0.99tCO2e/MWh displaced translates to avoided grid emissions of 0.69tCO2e/tMSW (assuming the black coal emissions intensity).

It is reasonable to estimate the avoided emissions using the emissions intensity of the avoided marginal generation. Based on the characteristics of the WA electricity market, we consider that the average emissions intensity is a reasonable estimate of the marginal intensity. At the margin, most new entrant generation in WA will be zero emissions renewables firmed with storage and gas. Overall, we consider it reasonable to apply the WA grid average of 0.72tCO2e/MWh as there is a similar amount of gas and black coal generation with comparable marginal cost, which makes gas as likely to be displaced as black coal. However this value will likely decrease over time as more renewables enters the market.

If we apply the WA grid average emissions intensity of 0.72tCO2e/MWh, the avoided emissions from the Kwinana facility would fall to 0.49tCO2e/tMSW.

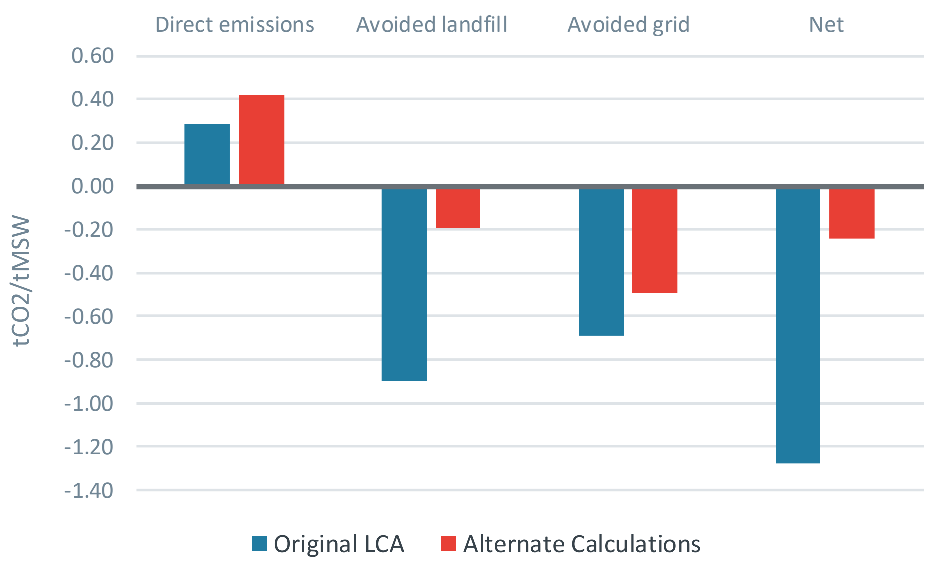
The latter assumption reduces the annual emissions avoided by around 76ktpa. The emissions intensity of the grid (and the emission avoided) is likely to decline further over time as coal retires and the sector transitions to more renewables.

2.5 Overall findings: Kwinana

We find that the LCA applies assumptions that reflect the upper bound of possible benefits from WtE from both direct emissions and avoided emissions.

If we apply our alternative suggested assumptions then the net benefits from avoided emissions are as reflected in **Figure 6** and **Table 7**. This is based on the conclusions and discussion above, including adopting 75% capture rate for LFG and using the WA average grid emissions intensity for avoided electricity emissions.

Figure 6: Kwinana WtE emissions estimates: alternate calculations



Source: Frontier Economics calculations

Table 7: Kwinana WtE emissions estimates: alternate calculations

Source	Original (tCO2e/tMSW)	Revised (tCO2e/tMSW)
Direct emissions (WtE)	0.29	0.42
Avoided landfill emissions	-0.89	-0.22
Avoided electricity emissions	-0.69	-0.49
Total	**-1.28**	**-0.29**

This still reflects a net benefit, however:

- The direct emissions from WtE are higher than the avoided emissions from LFG with capture.

- The bulk of the emissions benefit is avoided electricity emissions.
- This benefit will decline over time as
  (a) the electricity sector transitions to mostly renewables, which should reduce the average emissions intensity of the sector. This will directly reduce avoided emissions from electricity; and
  (b) if there is increased waste separation with FOGO diverted to compost or anaerobic digestion (AD), this will have the combined effect of (i) raising direct emissions from WtE and (ii) reducing emissions avoided from LFG.

These potential changes will affect facilities even after they are built: a static comparison at the time of investment does not "lock in" the estimated emissions avoided for the life of the asset,

The materiality of these changes is considered in Section 4.

The LCA should consider a range of sensitivities that assess the sensitivity of the result to changes in:

- The landfill gas capture efficiency rate
- The composition of waste over time, particularly the organic proportion, and
- The emissions intensity of grid electricity

3 Case study 2: Recovered Energy Australia gasification (Laverton North)

The Recovered Energy Australia (REA) project is a proposed gasification WtE facility in Laverton North, West of Melbourne. It proposes to use thermal gasification to process residual MSW into syngas – a fuel consisting mostly of hydrogen and carbon monoxide. At high temperatures, waste molecules breakdown to form the syngas, as well as residual slag. The syngas may be further processed as an energy fuel or, as in the case of the REA project, directly combusted to produce electricity.

The REA project plans to process approximately 200,000 tonnes of residual MSW per annum. This would be used to produce approximately 15MW of electricity for export to the Victorian grid. It estimates it would produce approximately 137 GWh of electricity per year, with 16.8 GWh required for operation of the plant and office, and 121GWh exported to the grid.

3.1 Overview

The REA project submitted a final Works Approval Application (WAA) to the Victorian Environment Protection Agency (EPA) in June 2019. The application was approved by the EPA in January 2020.[26]

Section 8 of the REA WAA to the EPA is titled 'Energy Use and GHG Emissions'.[27] This section sets out the estimated impact of the project on net emissions. The analysis set out in Section 8 appears to be based on analysis by MRA consulting, which is attached as Appendix 14: Modelling of GHG Emissions.[28]

Overall, the WAA finds that the REA facility results in a significant net reduction in greenhouse gas emissions. This is mostly due to avoided emissions from landfill and electricity (**Table 8** and **Figure 3**) with very similar overall outcomes to the Kwinana WtE LCA.

[26] Engage Victoria: Recovered Energy Australia. https://engage.vic.gov.au/epa-works-approvals/recovered-energy-australia

[27] Recovered Energy Australia, June 2019, *Works Approval Application: 8: Energy use and emissions,* https://s3.ap-southeast-2.amazonaws.com/hdp.au.prod.app.vic-engage.files/8915/6454/8700/10_Section_8_Energy_Use_and_GHG_Emissions.pdf

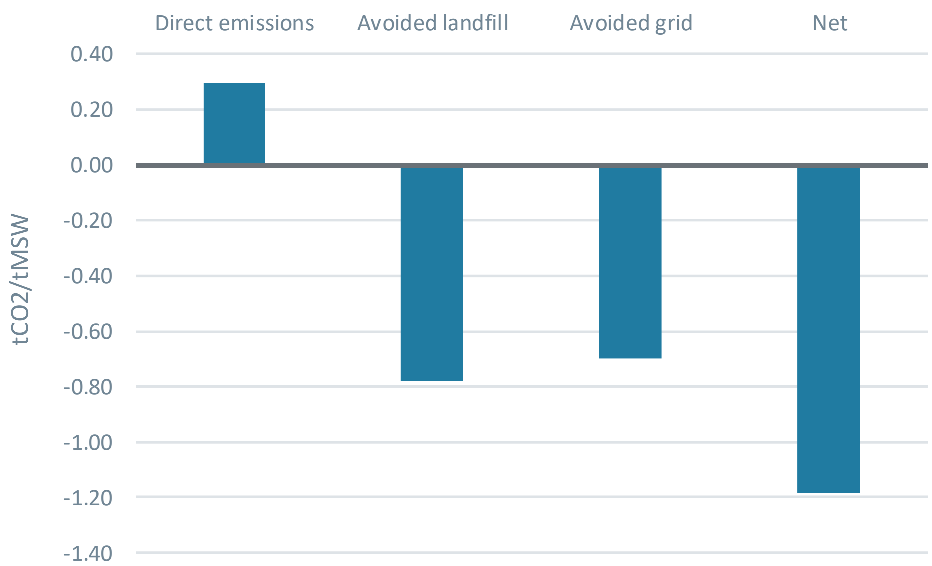
[28] Recovered Energy Australia, June 2019, *Appendix 14: Modelling of GHG Emissions*. https://s3.ap-southeast-2.amazonaws.com/hdp.au.prod.app.vic-engage.files/1715/6454/8701/Appendix_14_Modelling_of_GHG_Emissions.pdf

Table 8: REA facility emissions, LCA

Source	tCO2e/MWh	tCO2e/tMSW
Direct emissions (WtE)	0.49	0.30
Avoided landfill emissions	-1.29	-0.78
Avoided electricity emissions	-1.16	-0.70
Total	**-1.96**	**-1.18**

This is summarised in **Figure 3** below.

Figure 7: REA facility emissions, LCA



Source: Frontier Economics analysis of WAA

A Victoria Parliamentary inquiry into waste management[29] considered the REA proposal and noted that these assumptions depended on the historical waste mix and the assumed displacement of brown coal electricity:

> *"However, it is unclear how the above findings may vary where food and organics have been removed from municipal waste and the calorific value of the residual differs significantly. The removal of these materials from going to landfill is discussed in detail in Chapter 3. Ensuring that food and organics are eliminated*

[29] Parliament of Victoria Environment and Planning Committee, 2019, *Inquiry into recycling and waste management final report*, https://www.parliament.vic.gov.au/file_uploads/LCEPC_59-02_Inquiry_into_recycling_and_waste_management__6hNrvBj7.pdf page 171

from landfill through diversion to composting or anaerobic digestion will significantly decrease the greenhouse gasses emitted from landfill. Further, comparisons by energy generation source relate only to energy generated from fossil fuels. Lee Bell stated at a public hearing that when compared to renewable energy, such as solar or wind power, incinerators produce far higher greenhouse gas emissions".

3.2 Direct emissions

The REA facility produces emissions of greenhouse gases through the thermal treatment of waste to produce syngas. The LCA assumptions (and direct emissions outcomes) are very similar overall to Kwinana. It uses several key assumptions:

- The organic share of the waste is 70% in total, including paper and cardboard
- The energy density of the organic and non-organic waste streams is in line with the NGA factors, that is:
  - 12.2 GJ/kg for organic waste
  - 10.5 GJ/kg for non-organic waste

Based on these assumptions, it estimates the direct emissions to be 0.30 tCO2e/tMSW.

The main factor affecting the combustion emissions intensity is the waste mix, specifically the organic versus inorganic share.

We replicated the calculations for the direct emissions and obtained a consistent estimate.

Given the NGA energy content and reported energy generation (121GWh net), this implies generator efficiency of 21%.

The combination of these assumptions results in average direct emissions of 0.49tCO2e/MWh.

Table 9: Direct greenhouse gas emissions (NGA basis)

Greenhouse gas	Emissions factor (kgCO2e/GJ)[1]	Energy GJ/t[1]	MSW kt/year[2]	Energy TJ	GHG MtCO2e
Organic[2]	1.8	12.2	140	1,708	3
Fossil	88.9	10.5	60	630	56
Total				**2.338**	**59**

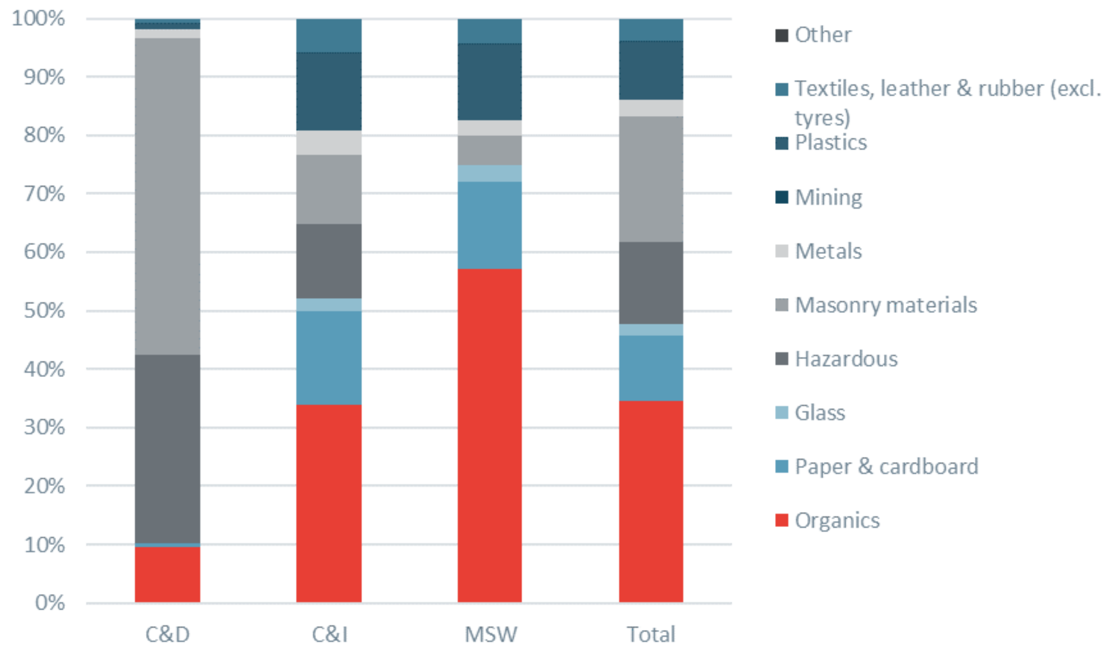
Source: 1. Tale 1 National Greenhouse Accounts factors 2018. 2. Organic share is 70% in the REA LCA. Total MSW processed is assumed at 200kt per year.

Again, we attempted to recreate these calculations from first principles based on (a) the Nolan (2001) energy content by waste material and (b) the average weighting of waste material (MSW) from the CER. The detailed calculation implies that Organic waste has an energy content of **6GJ/t** and Non-Organic was has an energy content of **25GJ/t.**

As with Kwinana, the REA LCA assumes 70% organic waste and the resulting direct emissions (as applied) of 0.29tCO2e/MSW appears to be an outlier relative to other sources listed above.

The National Waste Database 2020 reports that that 57% of VIC MSW that is disposed in landfill is organic, though this rises to 72% if paper and cardboard is also included (**Figure 8**). This is on a wet weight basis, which is similar to Moora (2017).

Figure 8: Waste stream, Vic Landfill/disposal 2018-19



Source: National waste database 2020

As outlined above, the underlying assumptions are very similar to the Kwinana case study. Based on the same set of studies, we consider that the direct emissions estimate of 0.29tCO2e/tMSW sits below a reasonable range. We consider that direct emissions of 0.42tCO2e/tMSW would be more reasonable as a central estimate.

Again, it is evident that there is wide variation in emissions that depends on moisture and the waste mix (organic content). It seems likely that there will be increased waste separation in future which is likely to reduce the organic share in MSW and this is likely to raise the direct emissions from combustion. This is acknowledged in the REA LCA executive summary (p22).

Given the importance of the waste composition for direct emissions, and the considerable uncertainty in any estimate, we consider it very important to undertake a robust sensitivity analysis on these assumptions. We present some sensitivity analysis in Section 4.

3.3 Avoided landfill emissions

As with Kwinana, a higher assumed rate of landfill gas capture would substantially reduce avoided landfill emissions

The largest part of the emissions reduction in the REA LCA is avoided landfill emissions. **The LCA finds that diverting waste from landfill to combust it avoids 1.29t CO2e/MWh**

(0.78tCO2e/tMSW). This is based on an assumed LFG 'capture rate' of 45%. This appears to be a low (conservative) estimate based on lagged historical emissions from landfill.

The avoided emissions calculation in the LCA is based on the formula:

$A = B \times (1-D) + C \times D$

Where:

- A is the emissions factor used in the LCA
- B is the emissions factor in the absence of any gas capture (1.298tCO2e/tMSW)
- C is the emissions factor with 100% capture (0.143 tCO2e/tMSW)
- D is the assumed capture rate (45%)

We think this formula has been applied incorrectly. Firstly, it is not clear how the emissions factor could be 0.143tCO2e/tMSW if 100% of the gases are captured. It seems like this value should be 0 (it is not clear what the emissions are made of if not LFG). Secondly, it doesn't appear that oxidation factors have been accurately applied to non-captured emissions. It should be possible to calculate emissions directly using the assumed capture rate, and oxidation factor applied to any emissions not captured.

For the purpose of an LCA, the avoided LFG emissions should be based on a reasonable counterfactual of how the waste would otherwise be processed in landfill. As outlined above, it can be an involved process to measure gas capture rates, so in general it may not be possible to base the estimate on the capture rate for a specific landfill. Therefore it is reasonable to use a representative LFG collection efficiency, however this should reasonably reflect the characteristics of an alternative.

In addition to the reasons and sources cited for Kwinana, Randell Environmental Consulting and Sustainability Victoria (2019)[30] cites AGEIS to report average Victorian landfill capture at 61% in 2014, which is considerably higher than the current Australian average. This suggests that Victoria is more progressed ***on average*** than other states towards a greater share of waste going to modern landfill with higher capture rates. However, the capture rate at new ***marginal*** landfill is still likely around 75%.

Randell/SV (2019) also reports average emissions intensity from **Victorian licensed landfill at 0.4tCO2e/t waste. This would suggest a capture rate of around 80%.** However, it is not clear if this applies to MSW or all waste streams: on average all waste streams have lower organic content so this may be contributing to the lower average emissions as opposed to higher capture rates.

Based on the factors outlined in Section 2.3 for Kwinana, and the Victorian specific factors outlined above we estimate a reasonable capture rate for a modern landfill accepting new waste to be 75%, with 10% oxidation.

We estimated emissions for the Laverton North REA in two ways:

[30] Randell and SV, *Greenhouse gases from the waste sector and opportunities for reduction (2019)*, https://www.sustainability.vic.gov.au/-/media/SV/Publications/About-us/What-we-do/Strategy-and-planning/SWRRIP-2019/Greenhouse-gases-from-the-waste-sector-and-opportunities-for-reduction.pdf

- Firstly, using the values in the LCA but updating for the 75% capture rate, updating the treatment of oxidation, and assuming emissions are 0 if the capture rate is 100%. Based on this, we estimated LFG emissions to be is 0.32tCO2e/MSW
- Secondly, adopting the same values as in the Kwinana case study, 0.41tCO2e/MSW

We consider the second estimate provides a reasonable value for avoided landfill emissions.

However, this excludes any recognition of the avoided electricity from LFG, which is omitted in the LCA. We estimate that the avoided electricity emissions from LFG ranges from:

- 0.16tCO2e/tMSW (45% capture rate using emissions intensity of 0.9tCO2e/MWh – which is similar to NSW black coal or Victorian average emissions intensity), to
- 0.31tCO2e/tMSW (85% capture the same emissions intensity of 0.9tCO2e/MWh)

Incorporating the avoided electricity emissions reduces the **net** LFG emissions avoided to **0.14tCO2e/tMSW** using a 75% capture rate.

Table 10: LFG emissions avoided

LFG capture rate	Gross LFG emissions (tCO2e/tMSW)	0.9tCO2e/MWh avoided (NSW black coal)	
		LFG electricity avoided (tCO2e/tMSW)	Net LFG (tCO2e/tMSW)
45%	0.90	0.16	0.74
75%	0.41	0.27	0.14
85%	0.25	0.31	-0.06

Source: Frontier Economics calculations

3.4 Avoided grid emissions

The LCA estimated that the 121GWh of electricity generated by the REA facility would offset approximately 140,000 tonnes of emissions from grid production of electricity. This assumed the emissions intensity from avoided electricity of 1.17tCO2e/MWh based on 100% brown coal. **Under this assumption, the avoided grid emissions in the LCA are 0.7tCO2e/tMSW.**

Although Victorian generation is mostly brown coal, this assumption is very optimistic given that there is a rising share of renewable output, with a 50% renewable target by 2030. Victoria is also connected to other states and because brown coal is much lower cost than NSW black coal any increase in LFG electricity production output is more likely to displace NSW black coal before it displaces Victorian brown coal. The VIC average emissions intensity is 0.9tCO2e/MWh while the NEM average is 0.72.[31] These are more appropriate than applying the Victorian brown coal

[31] AEMO, https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/market-operations/settlements-and-payments/settlements/carbon-dioxide-equivalent-intensity-index

emissions intensity. In future, the average electricity emission intensity will continue falling as Victoria (and the NEM) transitions to renewables. Even though existing renewables may continue to operate, electricity generated by WtE (or LFG) is likely to displace new entrant renewable investment from occurring.

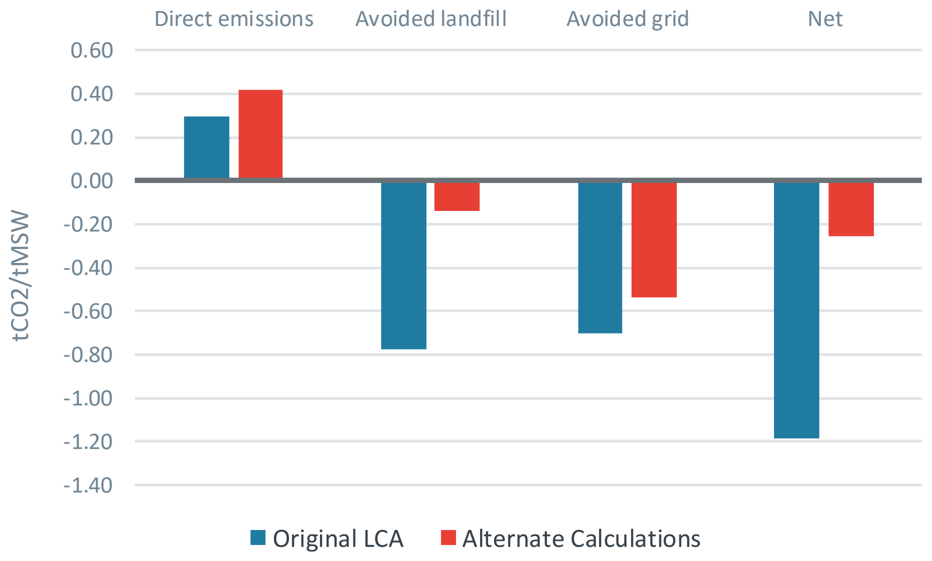
If an emissions intensity of 0.9tCO2e/MWh is conservatively adopted the estimate of avoided grid emissions from the REA project falls to 0.54tCO2e/tMSW.

3.5 Overall findings: REA

We find that the LCA applies assumptions that reflect the upper bound of possible benefits from WtE from both direct emissions and avoided emissions.

If we apply our alternative suggested assumptions then the net benefits from avoided emissions are as reflected in **Figure 6** and **Table 7**. This is based on the discussion above, including 75% capture rate for LFG and using the Victorian average grid emissions intensity for avoided electricity emissions.

Figure 9: REA WtE emissions estimates: alternate calculations



Source: Frontier Economics

Table 11: REA WtE emissions estimates: alternate calculations

Source	Original (tCO2e/tMSW)	Revised (tCO2e/tMSW)
Direct emissions (WtE)	0.30	0.42
Avoided landfill emissions	-0.78	-0.13
Avoided electricity emissions	-0.70	-0.54
Total	**-1.18**	**-0.25**

This still reflects a net benefit, however much like Kwinana:

- The direct emissions from WtE are higher than the avoided emissions from LFG with capture
- The bulk of the emissions benefit is avoided electricity emissions
- This benefit is likely to decline over time as
  - (a) the electricity sector transitions to mostly renewables, which should reduce the average emissions intensity of the sector. This will directly reduce avoided emissions from electricity; and
  - (b) if there is increased waste separation with FOGO diverted to compost or AD, this will have the combined effect of (i) raising direct emissions from WtE and (ii) reducing emissions avoided from LFG.

The materiality of these changes is considered in Section 5.

Much like Kwinana, we consider the avoided emissions are likely lower than in the LCA, and very sensitive to underlying assumptions in the waste composition, LFG capture rate, and grid emissions. These are all likely to continue to change in the future, particularly the avoided grid emissions and waste composition, so it is important to undertake a robust sensitivity analysis to all of these factors.

4 Framework for considering emissions from waste to energy

This section sets out some considerations for developing robust and accurate assessments of greenhouse gas emissions for WtE projects. It is broadly structured in two parts:

1. Selecting appropriate values for key parameters
2. Assessing the robustness of estimates to differences in uncertain parameters through sensitivity analysis.

4.1 Selecting appropriate parameter values

There are several key parameters that are used in the LCA to estimate emissions from a waste to energy project.

For the calculation of direct emissions, the most material parameter is the composition of waste, particularly the organic and non-organic split. The composition of waste should be based on the most accurate available estimate, and presented at the most granular level. The National Waste Report provides a detailed breakdown of waste streams by state. This credible, publicly available data is a reasonable starting point. A proponent of an LCA may have more accurate data, for example that relates to a particular region. This may be used, but should be clearly sourced, transparently presented, and the data generation process described.

For the calculation of avoided landfill emissions, both the Kwinana and REA LCAs adopted capture rates based on historic performance of average landfills. **This is not appropriate.** The avoided emissions should be calculated with reference to a best-practice, credible alternative. For a waste to energy facility near a major metropolitan centre, this is almost certainly a modern landfill with gas capture and energy recovery. In remote areas, it may be a landfill with no gas capture. The location and context matters.

Ideally, the gas capture rate would be estimated with reference to a particular landfill. However, this is unlikely to be practical in most cases. Therefore it is reasonable to base the capture rate on some benchmark. For a modern landfill, we consider that a 75% life-cycle capture rate plus oxidation is a reasonable benchmark. However, this may be higher in some cases, up to 85%. The LFG emissions should be calculated using the NGER solid waste calculator[32] with the methane capture directly inputted based on the assumed capture rate.

In the Kwinana and REA LCAs, the avoided grid emissions were based on the highest emissions alternative – black coal in WA and brown coal in VIC. **These are inaccurate assumptions**, which increase the avoided grid emissions. Overall, it is more reasonable to apply an estimate of the marginal emissions intensity, which may be an average of several fuels. It is unlikely to be entirely made up of the highest emissions intensity alternative. It may be reasonable to use alternative assumptions in some cases but these should be clearly justified.

[32] Clean Energy Regulator, *Calculators*, http://www.cleanenergyregulator.gov.au/NGER/Forms-and-resources/Calculators

It is important to consider how all of the factors above may change over time. There are obvious trends in waste management and electricity generation which are underway and will continue to impact the relative merits of WtE projects even after the investment occurs. Accounting for these changes over time is important for accurately assessing WtE projects, due to long asset lives and long-term waste contracts.

The organic proportion of residual waste is likely to decrease over time with increased separation of waste, particularly diversion of FOGO in separate bins. The introduction of dedicated FOGO bins in many council areas around Australia, together with related policy measures including education campaigns, will lead to significant reduction in the organic proportion of residual waste. The National Waste Policy Action Plan sets out a strategy to halve the organic share of waste by 2030.[33] Overall, this would increase the direct emissions from combustion of residual waste, and reduce the fugitive emissions from residual waste in landfill.

Electricity generation is transitioning to a higher share of renewable electricity. This will reduce the average and marginal emissions intensity of grid electricity. The net emissions from thermal WtE is particularly sensitive to grid emissions intensity, as it produces more electricity per tonne of waste than thermal WtE. As grid emissions fall, the relative emissions from thermal WtE will rise.

4.2 Undertaking robust sensitivity analysis

All the factors that drive emissions from waste are uncertain. The actual composition of waste is likely to be different from even the best estimates and is likely to change over time. The LFG capture rate may vary between landfills, even with similar observable characteristics. And grid emissions intensity will vary over time and between regions in Australia.

It is therefore very important to conduct robust and detailed sensitivity analyses in an LCA to accurately assess the impact on emissions results. We've undertaken some modelling to assess how differences in the waste composition, LFG capture rate, and grid emissions impact the relative emissions of thermal WtE and LFG. The modelling is based on a similar set of assumptions to the Kwinana and REA projects.

The chart below present the findings of our analysis. **Figure 10** shows the sensitivity of emissions to key input assumptions. The Y-axis shows emissions per tonne of MSW and the X-axis shows the share of organics in the waste stream.

The national average organic share of waste in landfill is 55%, or 70% if paper and cardboard is counted in the organic share.[34] As outlined above, the National Waste Policy Action Plan sets out a strategy to halve the organic share of waste by 2030, which would result in an organic share of approximately 30%. The dotted vertical line represents this target. Policy measures from all levels of government are pushing outcomes from the left to the right of this axis.

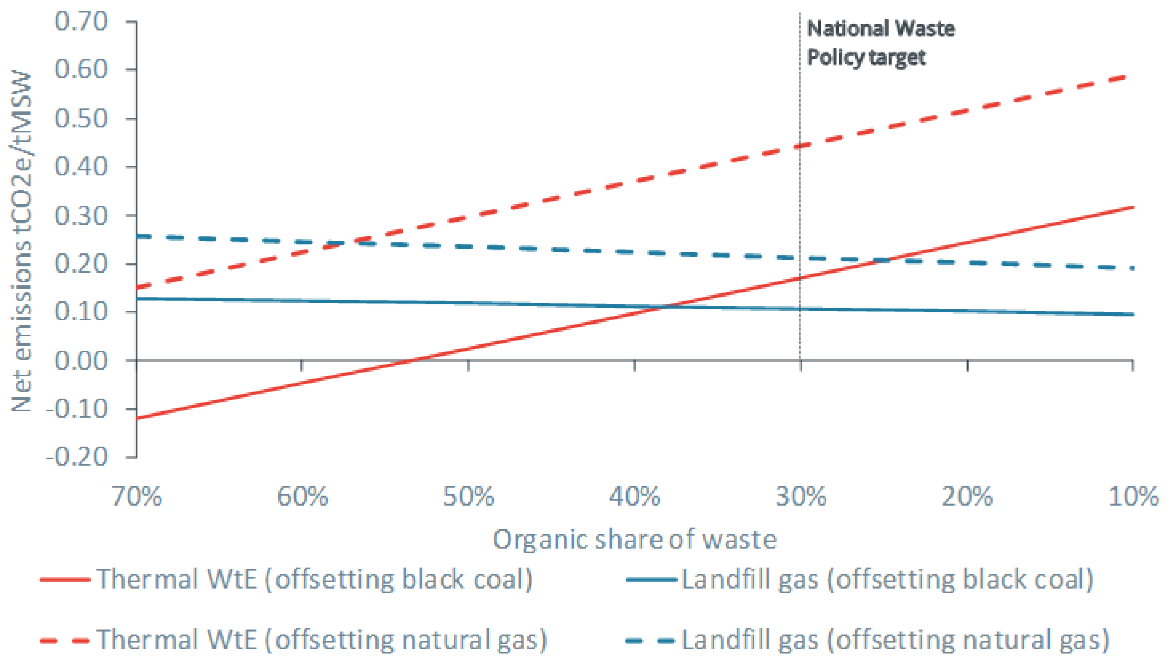
[33] *National Waste Policy Action Plan*, 2019, https://www.environment.gov.au/system/files/resources/5b86c9f8-074e-4d66-ab11-08bbc69da240/files/national-waste-policy-action-plan-2019.pdf

[34] Frontier Economics calculations using data from the National Waste Database 2020.

The red lines reflects net emissions from thermal WtE, after accounting for avoided grid electricity emissions. These slope up because a lower share of organic content increases WtE emissions. The blue lines reflect net emissions from LFG electricity generation with an assumed landfill gas capture rate of 75%. Unlike thermal WtE, these slope downwards as decreasing organic shares reduce methane production in landfill, and reduce fugitive emissions.

The solid lines are calculated on the basis that the thermal WtE or LFG electricity generation offset electricity generated entirely from **black coal** (with emissions intensity of 0.9tCO2e/MWh). The dashed lines are calculated on the basis of offsetting electricity with a lower grid emissions intensity of 0.45tCO2e/MWh. This is consistent with either **natural gas** generation or approximately a 50% mix of black coal and renewables (assuming that WtE electricity also discourages new entrant renewables at the margin). We note that Victoria and QLD have 50% renewable targets by 2030, SA is targeting 100% by 2030 and Tasmania is already close to 100% renewable. The dashed lines are a conservative guide to the likely avoided electricity emissions by 2030, which will likely be lower in some regions.

Figure 10: Net emissions from thermal WtE and LFG electricity generation



Source: Frontier Economics calculations

There are several key observations. Firstly, that the direct emissions from combustion WtE increases as the share of organics decreases. Conversely, the avoided landfill emissions decreases along with the share of organics. This reflects the lower overall production of methane with lower organic shares. The national average organic share of waste is about 55%, and heading towards a target of approximately 30% by 2030. With that waste make up, emissions from thermal WtE are likely to exceed landfill, even with unrealistically high avoided emissions.

There are combinations of landfill gas capture rate, emissions intensity, and organic share of waste which are 'tipping points' at which the emissions from thermal WtE exceed landfill. This figure presents a few, but there is a continuum for each set of parameters. For high emissions (black coal) electricity, the tipping point is an organic share of just below 40% - partway to the national target. For lower emissions intensity (natural gas), the tipping point is below 60%, close to the current state of play. If the emissions intensity of electricity was close to zero (offsetting renewables), the tipping would be even higher than 70%. For landfills with high capture rates (around 85%), the tipping points would be reached earlier.

The broad trends in the waste and energy sectors are all moving in a single direction towards states in which thermal WtE produces higher net emissions than landfill. The grid emissions intensity is falling (moving towards the dotted lines and beyond) and the organic share of MSW is falling steadily (towards the right-hand side of the chart). If the state renewable energy targets for 2030 are met, and National Waste Policy Action Plan target for organic share of waste in 2030 is met, thermal WtE emissions will exceed landfill emissions.

Thermal WtE will have higher emissions than landfill in some Australian regions already. This is likely to be the case across the country within ten years, well within the useful life of thermal WtE facilities built today. Beyond this point, the use of thermal WtE would unnecessarily lock in high emissions from the waste sector into the future.

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