Gas Transition Plan - Biogas Research Report

Prepared for Gas Industry Company
Prepared by Wood Beca Limited

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Revision History

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Action	Name	Signed	Date
Prepared by	Emma Rees		17/02/2023
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on behalf of	Wood Beca Limited		

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Appendix A –Feedstock Descriptions

Appendix B – Technology Descriptions

Appendix C –Case Studies

Executive Summary

The Gas Industry Co. (GIC) are developing the Gas Transition Plan (GTP) along with the Ministry of Business, Innovation and Employment (MBIE). The GTP will give direction to the decarbonization of New Zealand's gas sector. The GTP is split into two pillars: Pillar One – Transition pathways for the fossil gas sector, and Pillar Two: The role of renewable gases. Wood Beca Ltd has been commissioned to complete research on biogas and renewable LPG (rLPG) production in New Zealand as an input for Pillar Two.

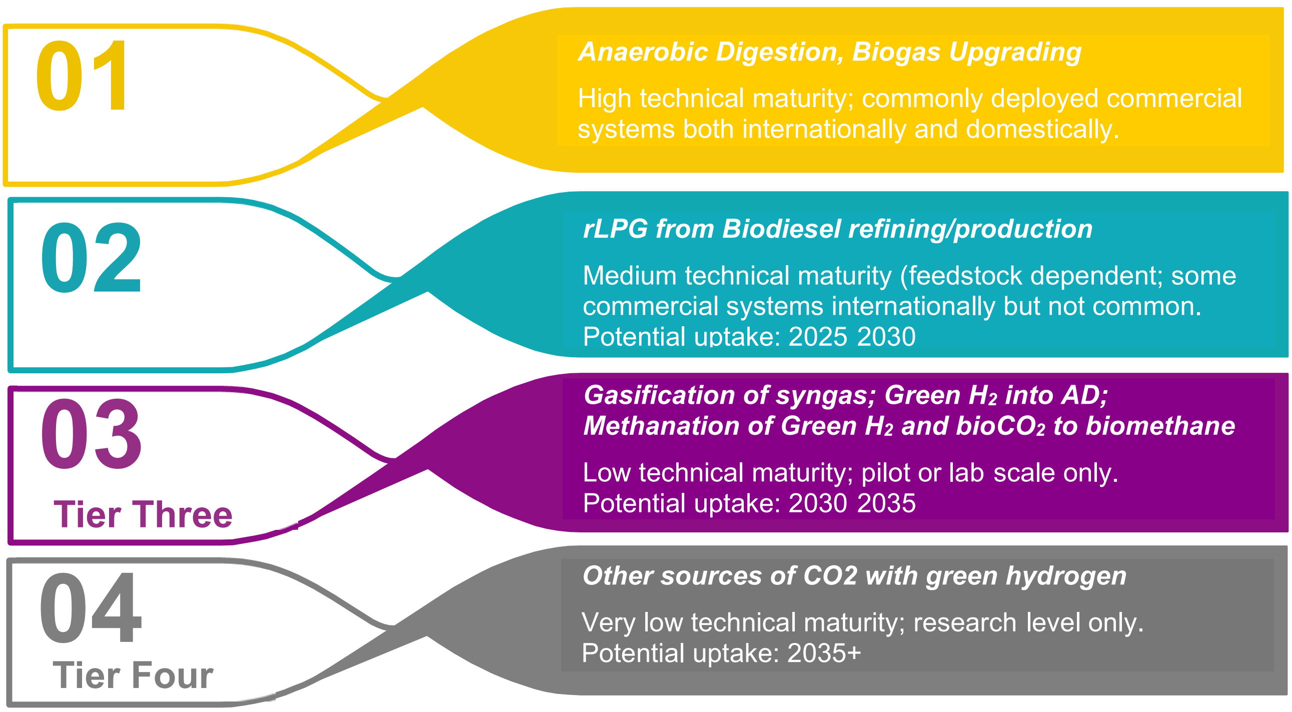
The aim of this report is to demonstrate of the scope of supply potential in the country, and to understand the feasibility and economics of the possible supply opportunities across the emissions reduction budget timeframes.

Context

Natural gas is predominantly used to provide power generation and energy for industry, as well as being used as a feedstock for chemical production (e.g., by Methanex and others). LPG is predominantly used for industrial and residential energy. Currently there is 150 PJ/yr of natural gas and 10 PJ/yr of LPG used in New Zealand. Out to 2050, it is expected that natural gas production and demand in New Zealand will decrease significantly, however, gaseous fuels will still have a key role to play in enabling the transition to green energy sources, and supporting hard-to-abate industries.

Technologies

To determine how renewable gas technologies might be applied in a New Zealand context, a range of both established and developing technologies were investigated in this study. The technologies were divided into several tiers, based on technical maturity and the ability to feasibly implement the technologies in the short to medium term future.



Our analysis demonstrated that anaerobic digestion (AD) and biogas upgrading are the only two technologies likely to make a significant impact on the gas network by 2035.

Biogas Potential

The total biogas **potential** across New Zealand of these material streams is presented below. These figures however may be economically challenging to achieve.

Waste/Residue Feedstocks	
Total Biogas Potential (from organic waste/agricultural residues)	24 PJ/year
Total Syngas Potential (from woody biomass)	63 PJ/year
Total Biodiesel Potential (oils/fats)	4.5 PJ/year

We also investigated possible future sources of biogas energy, including purpose-grown Energy or Utility crops. This could provide vast quantities of bioenergy, but the use of productive land for energy needs to be weighed up carefully.

Energy or Utility Crops	
Total land required to meet NZ natural gas demand (149.5 PJ/year)	21% of NZ productive grassland (1,700,000 ha)

Greenhouse Gas intensity of biogas fuels

Looking at the lifecycle emissions of biogas generated from organic wastes and residues, the emissions released is on average **17 kgCO_2e/GJ**, a **70% reduction** when compared to an equivalent fossil gas (57 kgCO_2e/GJ). The key contributor to the emissions from biomethane is methane that escapes from the generation of biogas and the conversion of biogas to biomethane.

When biogas is derived from a material either going to landfill or other processes that generate large quantities of biogenic methane, capturing and upgrading the gas for use represents a **large net reduction in overall GHG emissions intensity** over the lifecycle of the material. Note this is not included in the value above.
It is anticipated that as biogas upgrading technology continues to improve, methane slip from biogas upgrading will continue to decrease and therefore greenhouse gas emissions will also continue to fall.

Project Economics in New Zealand context

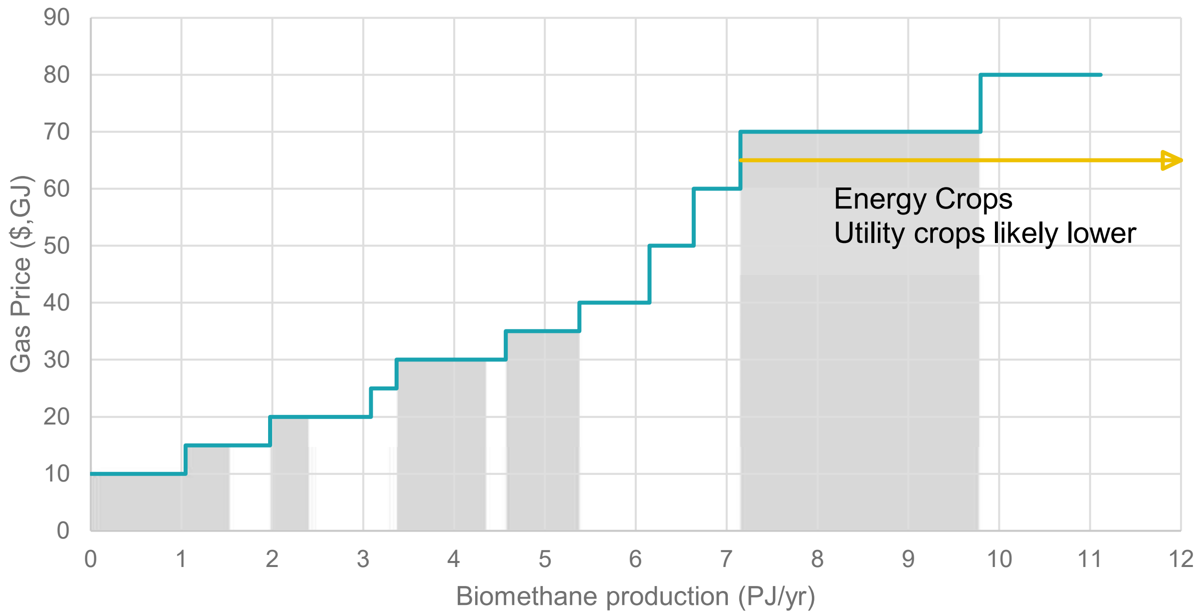
By taking real world examples from overseas biogas installations and building on domestic project examples, we produced a number of case studies that helped to inform the economic biomethane sale price required for different combinations of technology and feedstocks.

Our analysis revealed that biogas from landfills, wastewater treatment plants and foodwaste digesters can be accessed, upgraded, and injected into the natural gas network at relatively low cost. However the majority of the biogas potential identified is economically challenging to access.

Likely uptake of biogas between now and 2035

The total accessible and economic size of this biogas potential is around 7PJ, which is equivalent to nearly all commercial or all residential natural gas use in New Zealand today. Development of these sources of biogas will have large net reductions on NZ's carbon emissions, as these waste streams will divert material from landfill and other high-emitting end locations.

Beyond this, biogas uptake from existing organic wastes will become more expensive. Energy crops are extremely scalable and could provide vast quantities of energy, but will need to be deployed in a way that carefully considers the trade-offs in land use.



Note: grey columns indicated the quantities based on the case studies

Between now and 2035, the key developments to monitor that will have the largest impact on these predictions are:

- Development of domestic biodiesel production; this will unlock alternate processing pathways to rLPG and other renewable biogas fuels beyond AD and biogas upgrading
- Development of domestic green hydrogen production; this can boost the performance of existing AD facilities and support methanation processing pathways for biogas.

Key barriers and opportunities to consider

A transition to biogas supply will require a number of technical and operational changes for the natural gas network. Network balancing is likely to be required and gas storage facilities will play an important role. Review of gas standards should be completed to set reasonable, but not onerous, requirements for biogas upgrading operations.

In terms of uptake speed, some of the most pressing barriers for developers and operators are:

- Feedstock supply security, and security of by-product specifications:
- Seasonal variability in production + demand:
- Access to equipment and technical capability in this rapidly accelerating bioenergy generation market

Analysis of overseas countries that have experienced the most rapid and transformative development of biomethane/other biofuels reveals that the most significant factors in development success are:

- legislated certification schemes that enable the valorisation and trading of renewable gas to support this fuel as a core part of industries decarbonisation strategy, and
- associated support mechanisms for biomethane developments that recognise the multi-sectorial benefits of biofuels including by-product certification

The opportunities for biogas and biomethane to contribute to NZ's low emissions future are significant however there are a number of barriers particularly in the policy space that will need to be resolved for this to be realised.

1 Introduction

1.1 Background

The Gas Industry Co. (GIC) are developing the Gas Transition Plan (GTP) along with the Ministry of Business, Innovation and Employment (MBIE). The GTP will give direction to the decarbonization of New Zealand's gas sector, with the aim of meeting 5-yearly targets out to 2035 in the government's emissions reduction budgets, and with a broader view of decarbonization out to 2050. The GTP is split into two pillars: Pillar One – Transition pathways for the fossil gas sector, and Pillar Two: The role of renewable gases.

Wood Beca Ltd has been commissioned to complete research on biogas and renewable LPG (rLPG) production in New Zealand as an input to Pillar Two.
In addition to traditional biogas/renewable natural gas technologies deployed at scale internationally in countries like Denmark and the US, this scope of work will also consider developing adjacencies to biogas, including rLPG, Di-Methyl Ether (DME) production, and methanation from renewably-sourced CO_2 and hydrogen. Further details on the technical scope of the study are presented in Section 2.

The aim of this report is to demonstrate of the scope of supply potential in the country, and to understand the economics of the possible supply opportunities across the emissions reduction budget timeframes.

This report will cover the following topics to provide clarity on the realistic potential contributions towards New Zealand's emissions targets presented by renewable gas technologies:

- Current and future sources of biogas and other renewable gaseous fuels in New Zealand
- Economics of projects being developed locally and internationally, and how project/energy costs should be translated into a New Zealand context
- Other demands for feedstocks or wider market setting that could compete with or prevent the development of renewable fuel supply systems
- Case studies that can provide tangible examples of success and/or potential of biogas industry in New Zealand
- The relative emissions intensity of biogas sources compared against conventional gases
- Issues or limitations to biogas/low emissions gas blending with natural gas in the transmission system and/or distribution networks
- Required changes the natural gas sector may need to make to respond to emergence of biogas as a replacement for existing conventional natural gas and LPG.

2 Methodology

2.1 Study Development

As discussed in Section 1, the aim of this study is to review existing literature on technologies for producing renewable gases to determine how these might be applied in a New Zealand context. To accomplish this effectively, the technologies are divided into several tiers, based on technical maturity and the ability to feasibly implement the technologies in the various emissions reduction windows. A focus of the research and literature review was on feedstocks available in New Zealand, including available quantities, regional feedstock distribution, and identified barriers to collection and utilization.

Taking into account the technical maturity of the technologies available, the following tiers were developed, and are discussed in this report. Tier One technologies represent technology that can be implemented today, with technical maturity that reflects commercial systems installed in New Zealand or elsewhere in the world. This will be the main focus of this report, with development of price curves and emissions estimates based on case studies. The subsequent tiers are not at a technical maturity yet to define in as much detail, however investigation into the availability, quantity, and utilisation barriers of the feedstocks will be assessed.

This initial tier focus is based on *technical feasibility (with some considerations of scale of feedstock availability, particularly for mature technologies)*, without consideration to the wider policy and market settings, and any wider energy system synergies that would need to be implemented/realized to enable the technologies to be successfully developed. This further commentary is provided as part of the technology analysis (in Sections 5, 6, 7 and 8) and informs our final conclusions on the potential of the listed technologies to contribute towards key emissions budgets.

Table 2-1: Summary of Technical Maturity and Tier Definitions

Timeline/ Emissions Budget Tier	Indicative Technical Maturity and Feedstock Availability	Technology	Study Scope
Tier One: Present (pre-2025)	High; commonly deployed commercial systems	Anaerobic Digestion, Biogas Upgrading	Existing literature will be reviewed and discussed in detail and summarized with estimates of obtainable energy quantities and price curves.
Tier Two: 2025-2030	Medium; some commercial systems but not common	rLPG from biodiesel refining production	Existing literature will be reviewed and summarized with estimates of obtainable energy quantities
Tier Three: 2030-2035	Low; pilot or lab scale technology only	Gasification of syngas then methanation to biomethane or conversion to DME or Fischer-Tropsch to rLPG. Green Hydrogen into AD. Methanation of Green Hydrogen and bioCO_2 to biomethane.	Provide technical commentary only
Tier Four: 2035+	Very low; research-level only	Other sources of CO_2 with green hydrogen	Technologies will be mentioned, however not discussed in detail

Figure 2-1 summarises the processing pathways identified in this study, including identified feedstocks. The tiers of technology are indicated in this figure. Tiers One and Two are indicated in the figure, with the remaining technologies falling into Tier Three. Tier Four is not included on this pathway due to the immaturity of technology and potential feedstocks.

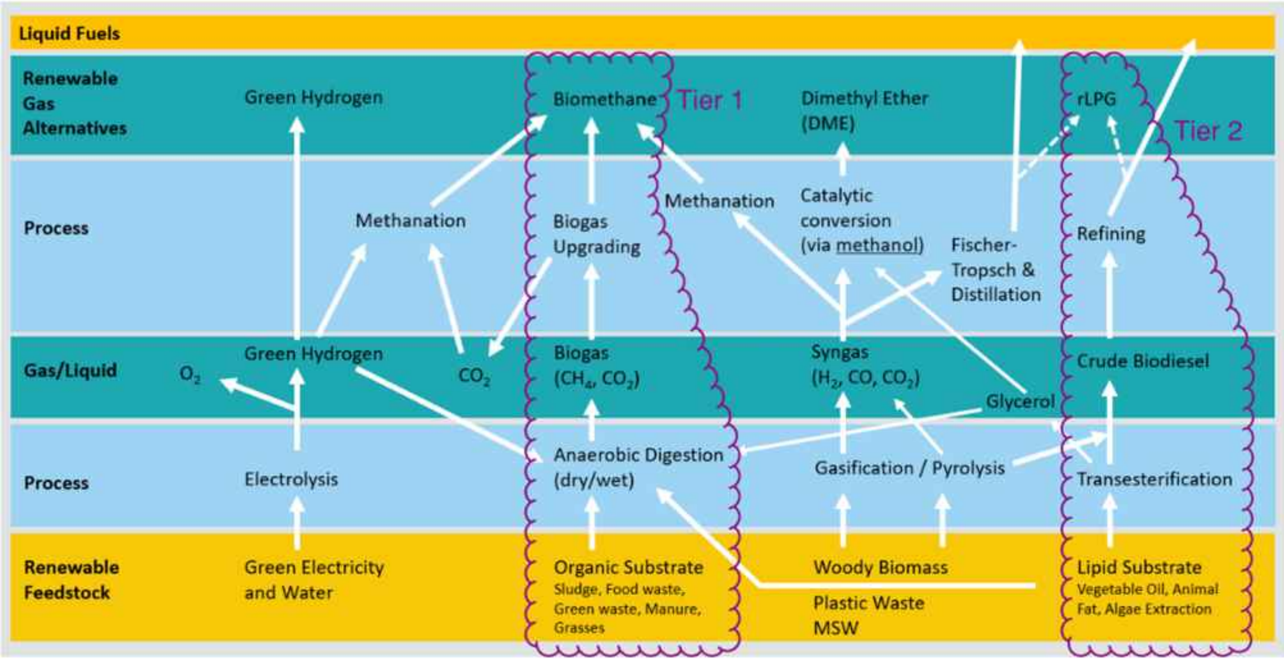


Figure 2-1: Summary of Production Pathways, Including Feedstocks, Processing Technologies, and Products
*Plastic waste and MSW are not renewable feedstocks but can be utilised in Waste-to-Energy applications

The pathway from biogas to syngas (i.e., biogas reforming) has not been considered, as the key driver is to transition the natural gas network, and biogas represents a more valuable intermediate than syngas.

2.2 Feedstocks

A literature review was completed to determine the type of feedstocks that could be utilised for all technologies considered (mature technologies and less developed technologies).
Research was then completed to determine feedstock quantities and, where possible, regional distribution of these based on available literature. An energy potential for the feedstocks was developed based on literature yields for either biogas, syngas, or biodiesel which would act as intermediates for further processing to biomethane, rLPG, or DME.

2.3 Tier One Technologies – Present Technology Deployable pre-2025

Tier One technologies considered mature technologies available at commercial scale and readily available. The only technologies considered at this maturity were anaerobic digestion to produce biogas, and subsequently upgrading this to produce biomethane.

The methodology for Tier One technologies included reviewing available literature from New Zealand and international sources, identification of existing New Zealand biogas examples, discussion of feedstock availability (based on research conducted on total feedstock potential), discussion of by-products from this technology and utilisation of these by-products. Case studies were developed to provide theoretical installations for analysis. These were selected to give a variety of feedstocks, scales, and localities. From the case studies, high-level costs were developed to provide price-stack information, and emissions intensity was also investigated.

2.4 Tier Two Technologies – Emerging Technologies Deployable 2025-2030

Tier Two technologies are less mature than Tier One with some commercial systems, but not commonly deployed. Additionally, consideration of feedstock availability required for these processes was considered in the feedstock research phase.

The methodology for Tier Two technologies included reviewing available literature from New Zealand and international sources with the aim of assessing potential yields, advantages and disadvantages of various processing technologies, and barriers to further technical development and implementation. Assessment of feedstocks and by-products was also included.

Based on feedstock research and yields identified in existing literature, the supply potential was quantified. As with Tier One technologies, case studies were developed to provide a scale of installation based on feedstock availability and gas demand in various regions. Due to the limited information available due to less commercial installations, pricing was not provided for these case studies.

2.5 Tier Three Technologies – Emerging Technologies Deployable 2030-2035

Tier Three technologies are less mature again and have no commercial scale installations. These have potential to develop for future emissions windows as technology becomes more mature. Feedstocks were considered for these technologies and included in the feedstock research.

The methodology for Tier Three technologies included technical commentary on the theoretical applications of the technologies, discussion of feedstocks and by-products, and some potential barriers to further development. Case studies were also developed for these technologies, with scale of feedstocks in various regions being the key focus. Due to limitations with technical maturity, costs were not provided.

2.6 Tier Four Technologies – Future Technologies Deployable 2035+

Tier Four technologies provide an idea of where technological development may head into the future. These technologies were discussed, but no assessment of feedstock quantities or location of installations has been completed. Only technical commentary was provided.

2.7 Sources of Information

Sources of information were limited to existing literature and relied on similar studies into renewable energy sources. Additionally, feedstock research relied on New Zealand data collection and reporting.

The EECA report *Biogas and Biomethane in NZ – Unlocking New Zealand's Renewable Natural Gas Potential report written* by Beca, Fonterra, & First Gas with support from EECA (Beca, 2021) was a key input for this assessment and is referenced and developed in several places.

A full list of references is included in Section 13.

2.8 Limits of Analysis

- The analysis is limited by available literature and data provided. Estimates of energy potential are limited by literature values for yields and conversion efficiencies of various technologies.
- The energy potential values provided assume all available feedstocks can be processed. The case studies provided in Section 9 provide some more commentary on the feasibility of collection in various scenarios and locations.
- The analysis conducted in this report includes assumptions on feedstock availability, feasibility of collection, and feasibility of implementing the technologies. No consideration has been made to project specific planning constraints, ownership models, land purchasing, and how these factors may materially change with location or between individual installations etc.

- This analysis focuses on the current state of feedstock sources. The distribution of feedstocks is likely to change over time, especially with changing preferences and diets favouring less meat consumption. Land use is also likely to change over time, with different drivers and economies.

3 Context – Current and Forecast Gas Consumption

3.1 Current Natural Gas and LPG Consumption in New Zealand

Context of the current gas network and consumption in New Zealand is important for the future transition to understand the required scale and distribution of current consumers. Natural gas provides energy, as well as being used as a feedstock for chemical production (e.g., by Methanex and others). LPG is utilised for energy and transport. A summary of New Zealand's gas consumption is shown in Table 3-1.

New Zealand has a natural gas reticulation network across the North Island, shown in Figure 3-1. The South Island does not have access to reticulated natural gas, but has small, reticulated LPG networks located in Christchurch, Dunedin, Queenstown, and Wanaka. Bottled LPG is delivered to consumers all throughout New Zealand (Gas Infrastructure Future Working Group, 2021).

Table 3-1: Summary of Natural Gas and LPG Consumption in 2021 (MBIE 1, 2022; MBIE 2, 2022)

Consumer Type	Natural Gas Consumption PJ/year (% of total)	LPG Consumption PJ/year (% of total)
Chemical Sector i.e. Non-energy Use (methane feedstock) and Chemical Industry Consumption	63.8 (43%)	N/A
Electricity Generation	42.9 (29%)	0.0 (0%)
Industrial (excluding Chemical Sector)	26.7 (18%)	3.7 (39%)
Agriculture/Fishing/Forestry	1.3 (1%)	0.1 (1%)
Commercial (and Public Service)	7.7 (5%)	1.8 (19%)
Residential	7.2 (4%)	3.8 (40%)
Domestic Transport	0.0 (0%)	0.1 (1%)
Total	**149.5**	**9.5**

3.2 Forecast Natural Gas and LPG Demand in New Zealand

Possible future natural gas demand is projected in the report *Gas Supply and Demand Projection* (Concept Consulting, 2022). Figure 3-2 taken from this report shows a possible demand projection to 2050.

The report *NZ renewable LPG potential* (Worley, 2021) estimates that in a 70% rLPG substitution scenario the LPG demand will drop to 7.9 PJ in 2035 and 7.3 PJ in 2050.

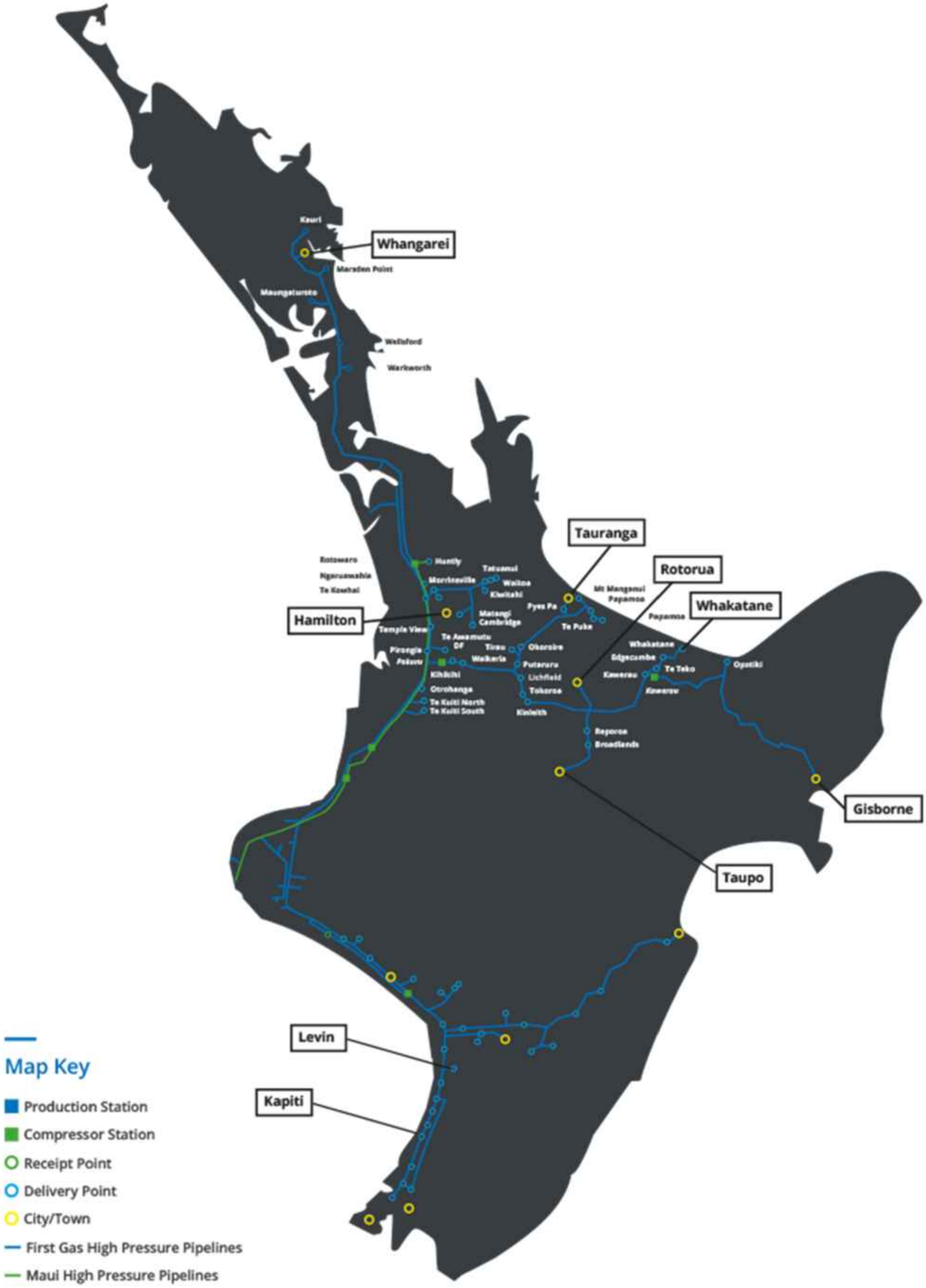


Figure 3-1: Existing Natural Gas Reticulation Network (First Gas, n.d.)

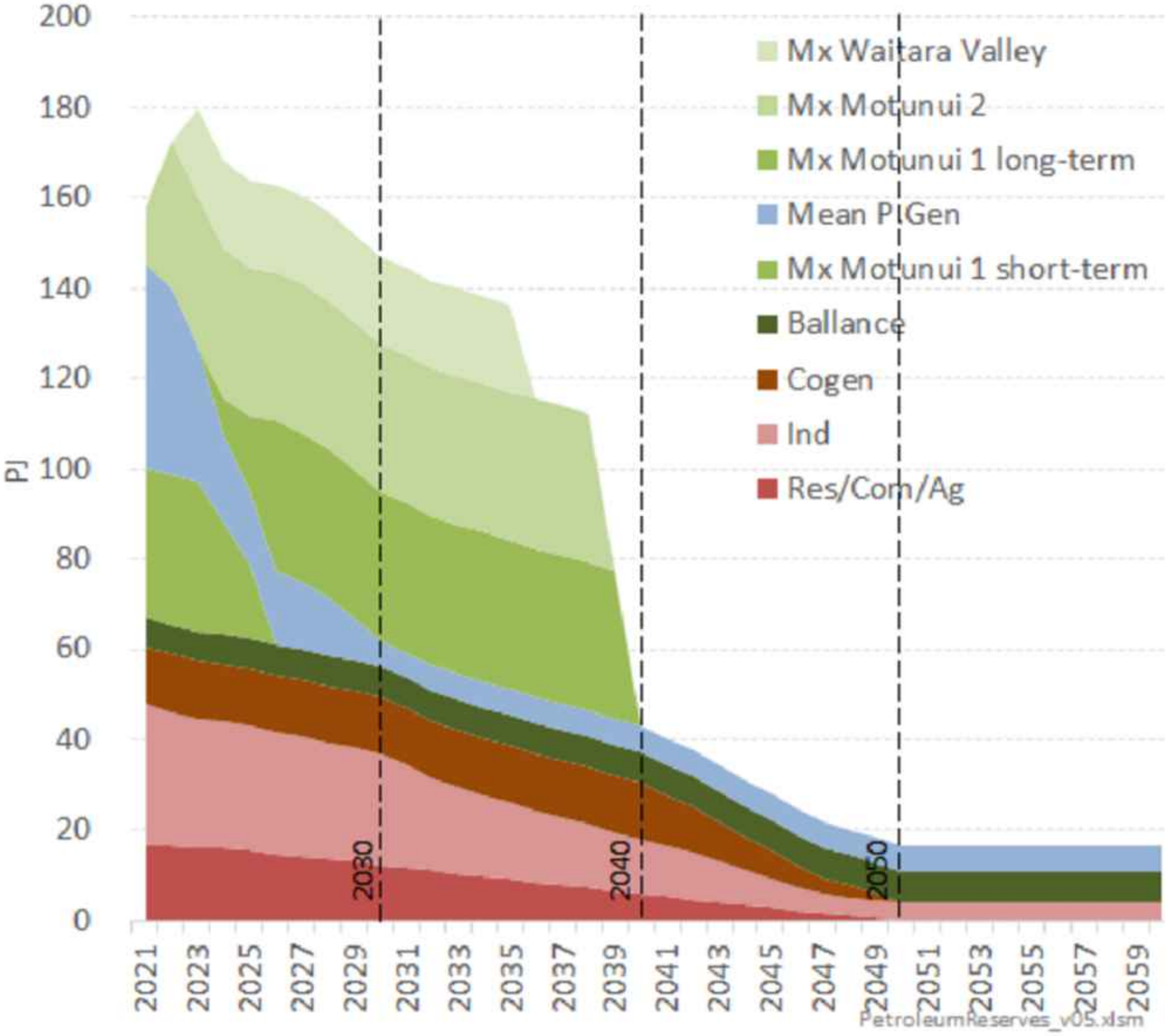


Figure 3-2: Projected natural gas demand (Concept Consulting, 2022)

3.3 Current Biogas Production

An important aspect of this Tier One technology development was to quantify existing biogas resource in New Zealand. This has been included in New Zealand biogas examples, and included in some of the case studies provided. There are current installations in New Zealand treating municipal and industrial wastewater. Current biogas producers are shown in Figure 3-3. In addition to anaerobic wastewater treatment processes, there are a number of landfills with landfill gas capture and in some cases, utilization on site. An estimate of current biogas and landfill gas production is in Table 3-2. Refer to Sections 4.1.1 and 5.2 for further information.

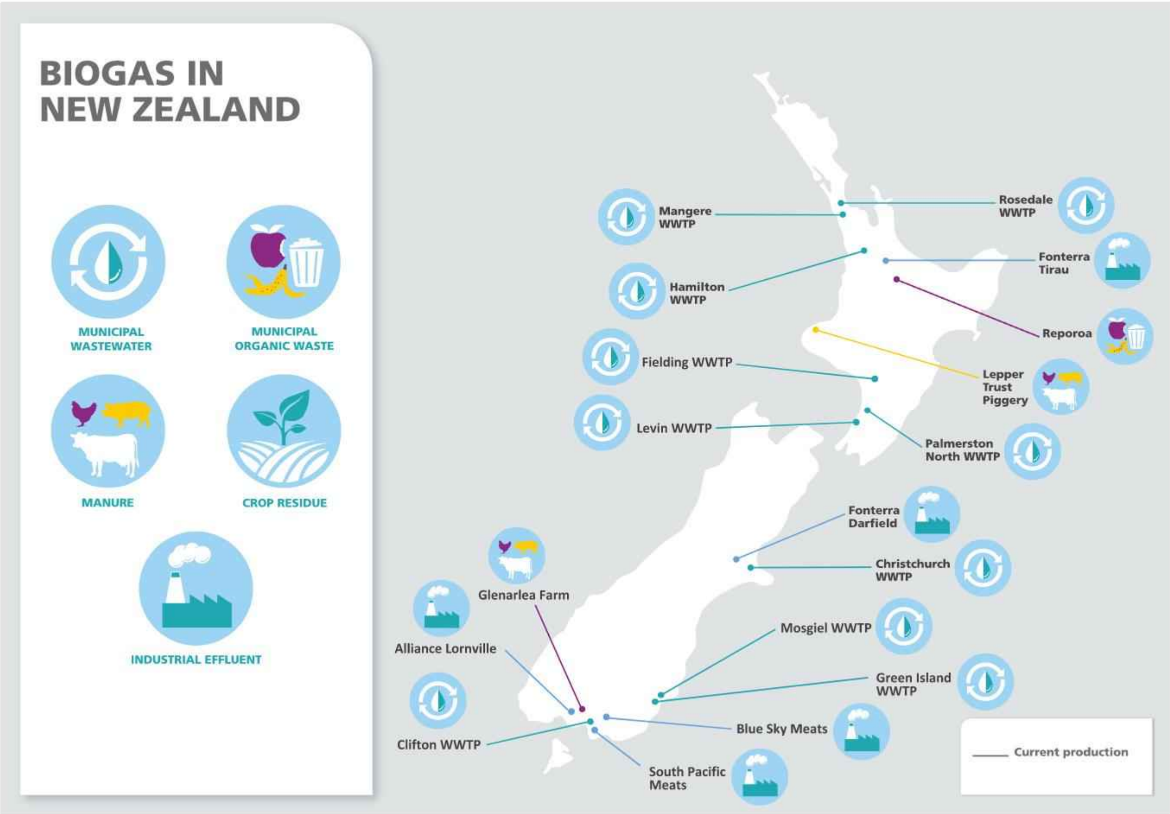


Figure 3-3: Snapshot of Biogas production sites in New Zealand Today (amended from Beca et al., 2021) (excludes landfill gas).

Table 3-2: Current Estimated Biogas and Landfill Gas Production

Source	Estimated Current Generation (PJ/year)
Municipal WWTP Biogas	1.0
Industrial Biogas	0.9
Landfill	3.0
Total	**4.9**
Percentage of NZ Natural Gas Demand	3%

4 Feedstocks

Understanding the available feedstocks for producing renewable gas products is a critical step in determining the feasibility and limitations of various technologies. We have reviewed available quantities of feedstocks in New Zealand to understand maximum achievable gas products, as well as understand the current locality of some of these feedstocks based on available information. Some feedstocks can be utilised by different processes, where others are suitable for a particular technology.
The feedstocks considered can be broken into the following categories:

- Municipal feedstocks, including municipal wastewater, household (post-consumer) food waste, garden/green waste, and municipal solid waste
- Industrial feedstocks, including industrial wastewater and sludges, pre-consumer food waste, and horticultural wastes (e.g. food waste from plantations and fruit/vegetable packing operations)
- Agricultural feedstocks, including grasses, supplementary crops, and animal manure
- Woody biomass, including forestry residues and processing residues
- Oils and fats, including tallow, oil crops, algae, and waste cooking oil.

A summary of the feedstock quantities available and gas product potential is shown in Table 4-1. Further discussion is in subsequent sections. Note, the feedstocks described below are spread across the North and South Islands, with different feedstock mixture availability across the regions.

The maximum energy potential from feedstocks to intermediates identified is 24 PJ/year biogas (excluding conversion of agricultural land to provide feedstocks), 4.5 PJ/year biodiesel, and 63 PJ/year syngas potential. This does not take into account yields from these intermediates to final gaseous products, noting that for biogas to biomethane the yield is close to 100%.

For comparison, as reported in Section 3.1, New Zealand's natural gas consumption is 150 PJ/year with additional 9.5 PJ/year LPG consumption. To meet the forecast natural gas demand of 40PJ/yr., 450,000 ha or 5.6% of New Zealand's productive grassland would be required to grow maize, cereals & grasses to be harvested as a feedstock for energy generation. With a North Island focus, this is 18% of productive grassland in Waikato and Manawatu regions (see Section 4.3.2 for land type definitions). Rather that the dedicated use of land to produce an energy crop, it may be more acceptable to use a utility crop, in combination with agricultural use to provide co-benefits such as soil improvement and reduced nitrogen load. This would require significant cross-sector collaboration.

Table 4-1: Summary of Feedstock Quantities and Product Potential

Feedstock	Feedstock Quantity (t/year)	Product (Biogas, syngas)	Maximum Product Potential (PJ/year)
Feedstocks from Municipal Sector			
Municipal Biosolids	70,000 tDS/year	Both	1.6 PJ/year biogas 0.2 – 0.5 PJ/year syngas
Post-Consumer Food Waste to Landfill	137,000 t/year - household* 273,000 t/year – total post-consumer*	Biogas	0.6 PJ/year biogas – household only 1.2 PJ/year biogas – total post-consumer
Municipal Green Waste	213,000 t/year	Biogas	1.5 PJ/year biogas
Municipal Organics to Composting	100,000 t/year**	Biogas	0.3 PJ/year biogas
Feedstocks from Industrial Sector			
Dairy Wastewater	60,000,000 m³/year	Biogas	1.1-1.9 PJ/year biogas

Feedstock	Feedstock Quantity (t/year)	Product (Biogas, syngas)	Maximum Product Potential (PJ/year)
Meat Wastewater	20,000,000 m^3/year	Biogas	0.7 PJ/year biogas
Pre-Consumer Food Waste	60,500 t/year – total supermarket food waste	Biogas	0.3 PJ/year biogas
Horticulture Wastes	212,600 t (dry weight)/year	Biogas	1.5 PJ/year biogas
Feedstocks from Agricultural Sector			
Grasses / Energy / Utility Crops	5.6% of NZ productive grassland (450,000 ha)	Biogas	Total NZ 2040 natural gas demand (40 PJ/year)
Supplementary Crops	92,000 ha available land area for crop rotation and rehabilitated land	Biogas	8.1 PJ/year biogas
Animal Manure	1,379,000 tDS/year***	Biogas	7.5 PJ/year biogas
Feedstocks from Forestry Sector			
Forestry Residues	2,228,000 t/year	Syngas	23.8 PJ/year syngas
Processing Residues	3,676,000 t/year	Syngas	39.2 PJ/year syngas
Feedstocks from Oils and Fats			
Tallow	160,000 t/year	Biodiesel	4.5 PJ/year biodiesel
Waste Feedstocks			
Total Biogas Potential			23.8 – 24.6 PJ/year
Total Syngas Potential			63.2 – 63.5 PJ/year
Total Biodiesel Potential			4.5 PJ/year
Energy Crops			
Total land required to meet NZ natural gas demand (149.5 PJ/year)			21% of NZ productive grassland (1,700,000 ha)

Note DS = Dry Solids

* Excluding food waste already diverted to composting facilities through source separated organics collection

** Composted organic matter volumes are not fully known – this represents industrially composted organics from Auckland and Christchurch consisting of garden and food wastes.

*** Manure includes 10% of dairy cow manure (them allowing for capture from milking sheds), pig and poultry manure from predominantly non-pasture farming practices.

See Appendix A for review in more detail each of the potential feedstocks.

5 Tier One - Presently Available Technologies and Feedstocks (Pre-2025)

5.1 Anaerobic Digestion (AD)

5.1.1 Description

Anaerobic digestion utilises bacteria in an oxygen-free environment to break down organic matter, producing a gaseous mixture commonly referred to as biogas, predominantly made up of methane and carbon dioxide. Sulfur compounds in the feedstock will also be reduced in the digestion process, which leads to the generation a hydrogen sulfide, some of which are released into the biogas. This needs to be removed prior to utilisation.

Anaerobic digestion of municipal wastewater solids using conventional fully mixed flow through solids digesters is an established practice in New Zealand's WWTPs, as shown in Section 4.1.1. These digesters are typically used for sludge minimisation and stabilization.

Anaerobic wastewater treatment of industrial wastewater is a mature technology. In New Zealand this is typically done in anaerobic lagoons to pre-treat high strength raw wastewater from industrial facilities such as meat processing plants. The biogas produced can be captured by covering the lagoons, however, not all anaerobic lagoon systems in New Zealand currently capture the biogas produced. Alternatively, a more high-rate 'contact' process can be utilised where the anaerobic biomass is retained in the fully mixed anaerobic reactor by a separation process. Fonterra's Darfield plant uses this form of AD. For industrial wastewater that is low in fat and particulates (i.e. high soluble organic content, such as wastewater form beverage, food oil, or sugar factories) an even higher rate of AD typically referred to as UASB (Up-flow Anaerobic Sludge Blanket) and EGSB (Expanded Granular Sludge Bed) can be used. However, there are no current plants of this type in New Zealand and given the niche nature of application they are not discussed further. Recent development of the anaerobic membrane bioreactor is also not discussed here.

Anaerobic digestion of source separated organic wastes, while mature overseas, is not yet common in New Zealand. The first purpose-built organic waste digestion facility (by Ecogas) has recently opened and is moving into production in Reporoa, in the central North Island.

AD technologies for organic waste processing can be categorized based on the following features:

Table 5-1: Anaerobic Digestion Categories

Parameter	Options
Number of Stages	• Single-Stage • Two-Stage
Feed DrySolids (DS) Content	• "Wet"/Low-solids process (<15 to 20 percent DS) • "Dry"/High-solids process (>15 to 20 percent DS)
Operating Temperature	• Mesophilic (approximately 34 to 37° C) • Thermophilic (approximately 55 to 60° C)
Mixing/Agitation	• Gas injection • Internal mechanical components (agitator) • Repumping/Recirculation
Reactor/Digester Type	• Vertical positioning • Horizontal positioning
Process Flow	• Continuous (fully mixed or plug flow) • Discontinuous (batch)

Refer to Appendix B for technical information on AD technologies, including descriptions of technology types, pre-treatment methods, and international examples of organic AD facilities.

5.2 Landfill Gas Capture

Landfill gas (LFG) typically has lower methane content than biogas produced through engineered AD systems. This is due to the better control of process variables in engineered AD systems, and ability to divert contaminated feedstock that can impact biogas production.

Currently landfill gas capture is the largest source of biogas in New Zealand (around 3 PJ/year) (Beca et al., 2021). A summary of the landfills in New Zealand and current gas capture status is shown in Table 5-2.

Table 5-2: Landfills with and without Landfill Gas Recovery (LFGR) (amended from MfE 3, 2022, which last updated this table in 2013)

Name	Operator	LFGR
AB Lime Ltd (Winton)	AB Lime Ltd	Yes
Ahipara Landfill	Far North District Council (Pukepoto)	No
Bonny Glen (Rangitikei District)	Midwest disposal Ltd	No
Broadlands Road Landfill	Taupo District Council	No
Burma Road Landfill	Whakatane District Council	Closed
Butlers Landfill	Westland District Council	No
Central Hawke's Bay District Landfill	Central Hawke's Bay District Council	No
Claris Landfill (Great Barrier Island)	Auckland City Council	No
Colson Road Regional Landfill	New Plymouth District Council	Closed
Eketahuna Landfill	Tararua District Council	No
Eves Valley Landfill	Tasman District Council	No
Fairfield Landfill (Dunedin)	Transpacific Industries Group (NZ) Ltd	Closed
Franz Josef Refuse Station	Westland District Council	No
Green Island Landfill	Dunedin City Council	Yes
Haast Refuse Station	Westland District Council	No
Hampton Downs Landfill	EnviroWaste Services Ltd	Yes
Innovative waste Kaikoura	Innovative Waste Kaikoura Ltd	No
Karamea Refuse Tip	Buller District Council	No
Kate Valley (Amberley)	Canterbury Waste Services Ltd	Yes
Levin Landfill	Horowhenua District Council	Yes
Malborough Regional Council (Bluegums)	Marlborough District Council	Yes
McLean's Pit Landfill	Grey District Council	No
Mount Cooee Landfill	Clutha District Council	No
Oamaru Landfill	Waitaki District Council	Closed
Omarunui Landfill	Hastings District Council	Yes
Palmerston Landfill	Waitaki District Council	Yes
Patearoa Landfill	Central Otago District Council	Closed
Pongaroa Landfill	Tararua District Council	Closed
Redruth Landfill	Timaru District Council	Yes
Redvale Landfill	Transpacific waste management	Yes
Rotorua District Sanitary Landfill	Rotorua District Council	Closed
Ruapehu District Landfill	Ruapehu District Council	No
Russell Landfill	Far North District Council (Transfield Services Ltd)	Closed
Silverstream Landfill	Hutt City Council	Yes
Southern Landfill	Wellington City Council	Yes
Spicer Landfill	Porirua City Council	Yes

Name	Operator	LFGR
Tarras Landfill	Central Otago District Council	Closed
Tirohia Landfill (Paeroa)	HG Leach & Co. Ltd	Yes
Tokoroa Landfill	South Waikato District Council	No
Victoria Flats Landfill (Queenstown/Cromwell)	Scope resources Ltd	Yes
Waiapu Landfill	Gisborne District Council	No
Waikouaiti Landfill	Dunedin City Council	Closed
Waiouru Landfill	New Zealand Defence Force, Waiouru, owned by the NZ Defence Force and operated by Transfield Services Ltd	Unknown
Wairoa Landfill	Wairoa District Council	No
Waitomo District Landfill	Waitomo District Council	No
Whitford Landfill - Waste Disposal Services	Transpacific waste management	Yes
York Valley Landfill	Nelson City Council	Yes

New Zealand has 17 landfills capturing landfill gas, with some facilities flaring and others utilising landfill gas with CHP plants. In NZ 90% of municipal solid waste ends up in landfill with some form of gas capture, where it is left to decompose in sealed landfill cells, and as a result biogas is produced. The biogas produced from landfills is produced in an uncontrolled process environment over many years. Generally, the quality of the gas generated is much lower than the quality of gas produced in a purpose-built anaerobic digestion plant. However, this is a function of how well the landfill 'cap' has been designed in conjunction with the ability of the landfill gas collection system to remove the LFG as fast as it arrives at the surface. It is also influenced by seasonal rainfall, especially when an earthen style cap has been employed without a geomembrane due to water penetration.

Many of the landfills fitted with gas capture technology do not generate energy or electricity from the captured gas. Instead, this gas is flared to destroy methane and other harmful gases and reduce the overall GHG emission potential of the gas. According to recent estimates, 68% of methane generated at landfills with gas capture technology installed is successfully captured with the remainder escaping to atmosphere (Ministry for the Environment, 2019).

Landfill gas production volumes will decrease over time, as existing capped landfills release the available gas volumes, and as the volumes of organic wastes are diverted from landfills in favour of AD processing and general waste minimization trends. The Ministry for the Environment has released a proposed national waste strategy targeting 30% reduction in CH_4 emissions from waste by 2030 and a low-carbon circular economy by 2050. Therefore, landfill gas can provide biogas production in the first tier of gas transition from currently available resources, but should not be considered further into the future as reliance on landfill gas is contradictory to the preferred move towards biogas from AD.

5.3 Biogas Upgrading to Biomethane

5.3.1 Description

Biomethane is generated from the upgrading of biogas, a process which separates the methane in the biogas from the carbon dioxide and any contaminants in the biogas, increasing the menthane content of the gas from 50-60% to over 95%.

Various technologies can be applied to upgrade biogas to biomethane (ADBA, 2020). The three major technologies to remove CO_2 are:

- Adsorption (pressure swing adsorption using zeolites)

- Absorption (water scrubber / physical absorption using organic solvents / chemical absorption using amines)
- Permeation (high pressure membrane separation / low pressure membrane separation)

There are other methods to process impurities from biogas such as cryogenic separation, biological methods and hydrate separation that have yet to be made readily available to the commercial market. These emerging technologies are not outlined in this study but should be considered as part of future biogas production schemes as the technologies evolve and become more commercially viable.

Refer to Appendix B for further details on upgrading technologies.

5.3.2 Equipment Comparison

The individuality of each biogas production scheme will determine the appropriate technology required for upgrading. Where a high methane content is required PSA and chemical scrubbing are ideal technologies. In situations where the raw biogas includes higher concentrations of N_2 and O_2, then the ability for PSA and membrane (to a lesser extent) equipment to remove these, along with separating the CO_2 as a relatively pure co-product, present them as ideal technologies. For cases where the output H_2S requirement is stringent, then most upgrading technologies will be paired with activated carbon filters or iron oxide chemical scrubbers (Sun et al., 2015a).
A comparison of the different biogas upgrading equipment is included in Table 5-3Table 5-3.

Table 5-3: Biogas Upgrading Equipment Comparison

Upgrading Type	Operating Pressure (barg)	Outlet Pressure (barg)	Energy Required (kWh_e/m^3)	Methane Purity (%)	Methane Slip (%)	Pre treatment Required	Cost (Relative CAPEX)
PSA	3 - 10	4 - 5	0.15 – 0.35	96 - 98	<4	Yes	Low/Medium
Water Scrubbing	4 - 10	7 - 10	0.2 – 0.4	96 - 99	<2	Recommended	Low/Medium
Physical Scrubbing	4 - 8	1 - 8	0.2 - 0.3 (scrub) <0.2 (heat)	96-98	2 - 4	Recommended	Medium
Chemical Absorption	1 - 2	4 - 5	0.1 - 0.3 (scrub) 0.5 – 1.0 (heat)	96 - 99	<0.1	Yes	High
Membrane	7 – 20	4 - 10	0.15 – 0.25	96 - 98	<0.6	Recommended	Medium

Biogas upgrading is mature technology. Installations are plentiful around the world, with water scrubbing being a common upgrading method due to lower capital & maintenance costs, however it requires significant volumes of water which can provide difficulty to source depending on plant location. Liquefied CO_2 capture from water scrubbing has not been developed so far, and unlikely to be economical with typical process designs. However, with an increased driver for liquified CO_2 recovery, membrane separation has been developing in maturity, and the number of membrane installations has increased significantly in the last 10 years. This development has improved cost efficiency of these installations, as containerised systems have been developed.

The low methane slip from membrane separation also makes this technology favourable. The methane slip can effectively be reduced to zero if CO_2 is liquified, as any methane in the CO_2 stream will remain gaseous and can be separated and reprocessed.

5.4 Feedstocks

The feedstocks for AD and maximum biomethane potential are shown in Table 5-4Table 5-4. See Section 4 and Appendix A for further details on the feedstocks themselves.

Table 5-4: Summary of AD Feedstock Quantities and Biomethane Potential

Feedstock	Feedstock Quantity (t/year)	Maximum Biomethane Potential (PJ/year)
Feedstocks from Municipal Sector		
Municipal Biosolids	70,000 tDS/year	1.6 PJ/year
Post-Consumer Food Waste	137,000 t/year -household 273,000 t/year – total post-consumer	0.6 PJ/year – household only 1.2 PJ/year – total post-consumer
Municipal Green Waste	213,000 t/year	1.5 PJ/year
Municipal Organics to composting	100,000 t/year	0.3 PJ/year
Landfill Gas	N/A	3.0 PJ/year (existing)
Feedstocks from Industrial Sector		
Dairy Wastewater	60,000,000 m^3/year	1.1-1.9 PJ/year
Meat Wastewater	20,000,000 m^3/year	0.72 PJ/year
Pre-Consumer Food Waste	60,500 t/year – total supermarket food waste	0.26 PJ/year
Horticulture Wastes	212,600 t (dry weight)/year	1.5 PJ/year
Feedstocks from Agricultural Sector (excluding Energy Crops)		
Supplementary Crops	92,000 ha available land area for crop rotation and rehabilitated land	8.1 PJ/year
Animal Manure	1,379,000 tDS/year	7.5 PJ/year
Waste Feedstock Total Potential		**23.8 – 24.6 PJ/year**
Energy / Utility Crops		
Land required to meet NZ forecast 2040 natural gas demand 5.6% of NZ productive grassland (450,000 ha)		40 PJ/year

Note DS = Dry Solids

Competition over limited feedstock availability is a key barrier for the implementation of AD and biogas upgrading on a significant scale. Beca et al. (2021) note the following limitations and conflict of organic wastes. This is discussed further in Section 4.

- **Composting or Other Uses for Organic Waste**, including home composting and commercial composting operations. Increases in home composting would divert food waste from any food waste collection system. However, it is assumed the uptake of home composting is minimal compared to total volume of organic product. Currently, a vast majority of organic waste still goes to landfill and thus composting is not anticipated to significantly conflict with realistic uptake of organic waste as biogas feedstock.
- **Landfill gas capture vs source segregated collection,** as discussed Section 5.2, the increased organic waste being diverted from landfills will reduce the landfill gas production over time. However, biomethane yields are greater from AD facilities compared to landfills, and the existing landfills will continue to produce landfill gas in the near future, hence provide a good gas source early in the transition timeframe.
- **Manure Fertiliser,** while AD has been shown to improve fertilisation properties of manure, its use as a fertiliser via other processes, (e.g., composting), presents a conflict of use. The various value-added manure fertilisers on the market should therefore be kept in mind when considering a realistic uptake of the use of manure as feedstock for biogas and biomethane production. It should be noted that manure acts as a low-cost/no-cost fertiliser for farmers when used on farm. Systems have been considered elsewhere where farmers provide manure in return for the digestate from AD plants to

encourage manure as a feedstock rather than direct use (ABDA, 2020). Additionally, manure presents difficulty in collection. This report has assumed a high portion of pig manure can be easily collected, along with poultry manure due to the farming practices. Dairy manure has been assumed to be collected from the milking shed, however this also presents transport inefficiencies due to the high dilution. Furthermore, farms located in isolated areas increase the difficulty and efficiency of collection due to their remoteness.

- **Anaerobic digestion in the context of the waste management hierarchy,** the production of biogas/biomethane from organic waste products relies on continued creation of waste for collection and processing. While a circular economy can be established with digestate returned to the land as fertiliser. It is expected biogas feedstocks like food waste and industrial wastewater are unlikely to disappear, changing waste management practices around New Zealand could impact the amount of these feedstocks available into the future.

5.5 By-products

Assuming the product of an Anaerobic Digestion plant is Biogas, the following by-products are produced.

5.5.1 Digestate

By weight, digestate offers one of the cheapest sources of nitrogen, phosphorus, and potassium (NPK) nutrients and trace elements available (ADBA, 2020). Unfortunately, wet AD predominantly creates liquid digestate, which is a barrier to its market value. As a liquid, it is inconvenient and more costly to transport, and inconvenient to store. The spreading of liquid digestate also needs to be regulated to minimise ammonia emissions. Dehydrating (aka dewatering) wet digestate overcomes this issue but creates an ammonia rich liquid stream that can be difficult to dispose of. Adding ammonia stripping and conversion to ammonia sulphate overcome this issue but requires significant energy. Utilisation of the gas produced can produce heat to dry the digestate, but this reduces the net biogas produced.

Dry AD is a more novel technology but solves many of the problems of wet digestion. This technology produces compost-grade digestate with a far lower water content. This reduces the cost of spreading, transporting, and is easier to store. Dry AD digestate also does not have the same concerns around ammonia.

Dried digestate can be used as a fertiliser and substrate for seedlings in both agricultural and domestic markets. The end use of the digestate is critical to the successful adoption of AD for large scale biogas/biomethane production. Therefore, the drying of digestate, and effective marketing of the product is a critical barrier to overcome to ensure successful adoption of this technology.

5.5.2 Bio-CO_2

When biogas is upgraded to bio-methane, bio-CO_2 is separated. CO_2 forms a critical component within many other industries and sectors which provide existing markets for CO_2. Meeting the demands for CO_2 with bio-CO_2 separated from biogas provides a further revenue stream. Consideration of producing food-grade or medical grade CO_2 would widen the potential markets (ADBA, 2020).

Common uses of CO_2 include:

- Food and drinks manufacturing: most commonly, CO_2 is required to create carbonated beverages and is used in packaging to extend the life of perishable products.
- Greenhouse agriculture: to promote photosynthesis and thus plant growth, commercial greenhouses often pump in additional CO_2 to elevate its levels. This is often done through combustion of natural gas to produce CO_2 as a flue gas, with little, if any, use for the heat produced.
- Medicine: certain medical practices require inert gases, such as CO_2. As a non-combustible gas, it is typically used to prevent damage to healthy tissue during operations.
- Creation of syngas: biogas can be reformed to syngas (CO and H_2) which can be converted to other products (described in Sections 6 and 7 below).

5.6 GHG Emissions Intensity

The greenhouse gas (GHG) emissions intensity of biomethane depends heavily on the source of the methane, the feedstock and product transportation distances and methods, and the quality of the equipment being used (with higher quality, well maintained equipment having less methane leakage).

Based on assessment of biogas and landfill gas production and upgrading case studies discussed in Section 9, the GHG emissions intensity is summarized in Table 5-5. More specific assumptions are included in Section 9, which includes the emissions associated with transportation of feedstock and digestate, and fugitive emissions from landfills and existing AD facilities.

Key assumptions to note:

- These emissions intensities exclude capital carbon emissions associated with construction of new AD and upgrading plants or additional supporting infrastructure
- The emissions intensity only considers the production and processing of biogas from feedstocks in new AD plants, transmission and distribution of biomethane, and combustion of biomethane
- Methane loss in landfill in not counted in the emissions intensity as it is deemed to be happening anyway
- Not included in the AD emissions intensity assessment the large reduction in overall GHG emissions when biogas is derived from a material either going to landfill or other processes that generate large quantities of biogenic methane.
- CO_2 from biogas, and produced through combustion of biomethane is biogenic (i.e. directly resulting from biologically based materials) hence are not included in the emissions intensity
- Natural gas emissions intensity includes transmission and distribution losses, and combustion of gas

Table 5-5: Summary of GHG Emissions Intensity

Gas	Emissions Intensity ($kgCO_2e/GJ$)
Biomethane from Anaerobic Digestion	19
Biomethane from Landfill Gas	10
Natural Gas	57

The emissions intensity of biomethane produced by AD facilities is higher than that of biomethane from LFG due to slight methane release from the AD plant.

5.7 New Zealand Biogas Examples

A description of some existing and in-development biogas production facilities in New Zealand is provided below. These are also shown in Figure 3-3. This shows some real-life examples of success, difficulties, and potential of the biomethane industry in New Zealand. Cost information is commercially sensitive for these projects, hence is unavailable. However, theoretical case studies have been developed to provide an indication of cost for various projects in Section 9.

5.7.1 Ecogas Organic Waste AD

The Ecogas Reporoa organics processing facility is the first organic waste digestion facility in New Zealand and has only recently completed construction. With municipal connections still in development, the plant is operating at reduced capacity. The facility has the capacity to take 75,000 tonnes per year of organic waste from businesses and kerbside food scrap collections throughout the North Island (Scion, 2020). It can also take food waste from food processing in meat, dairy, and horticulture industries, as well as restaurant waste and cool store rejects (Piddock, 2022). The intent is to separate the biomethane from biogas produced, and use the carbon dioxide at a local glasshouse. The expected total energy output is 0.19PJ/year with approximately 16% of this used as heat at a local glasshouse, 0.1PJ of gas delivered to the grid and the surplus supply used to power the site (Alzbeta Bouskova, 2022).

Majority of screening and separation is to occur at a pre-treatment facility in Auckland. Process water is recycled through the digestate, so the site is self-sufficient for water. The facility contains a large biofilter to manage odour.

5.7.2 Christchurch WTP AD and Landfill

The Christchurch WWTP (CWTP) uses AD of municipal biosolids to generate 0.19 PJ/year of biogas for combined heat and power on-site. The Christchurch landfill gas is utilised for heating at the landfill and is piped to CWTP to provide a portion of the heating requirements for the CWTP biosolids dryer.
Landfill gas is also piped into town to provide heating for Council owned assets and public spaces (including Christchurch City Council offices and the Christchurch Art Gallery).

5.7.3 Dairy Wastewater AD – Fonterra Darfield

The Fonterra Darfield AD site was commissioned in 2020 for the purpose of processing high-strength whey and sludge from dissolved air floatation. The site uses a contact anaerobic digestor and the slurry is recycled back to the digestor via a solid gravity belt. The site produces 13,000m^3/day biogas (0.6PJ). The biogas was intended to be used to preheat the boiler feed, however this has not been implemented and the gas is currently being flared.

5.7.4 Wellington Sludge Minimisation – Moa Point WWTP

Currently, sludge from the WWTP at Moa Point is piped to Carey's Gully sludge dewatering plant at the Southern Landfill. The Wellington City Council is proposing a thermal hydrolysis and anaerobic digestion facility to manage the sludge volumes to landfill. The project is under development and the technology has not yet been decided on. The project is expected to be complete in 2026.

6 Tier Two – Emerging Technologies Deployable 2025 - 2030

6.1 Description

6.1.1 rLPG via Biodiesel Refining

Renewable LPG (rLPG) can be obtained through biodiesel refinement. rLPG is considered an ideal 'drop-in' replacement for conventional LPG as it can be directly integrated into the current supply and distribution pathways without changing the end-use equipment.

Further technical information on biodiesel production is provided in Appendix B.

Following production the biodiesel is purified in a distillation column to extract the lights fraction (LPGs and Naphtha). The conversion of LPG from feedstock through the HEFA pathway is thought to be around 8% but is likely closer to 5% once unwanted by-products are removed. This does not differ significantly from the LPG production from FAME facilities which is estimated to be between 5-10% of the product slate depending on process conditions and feedstock mix.

rLPG is limited by the fact that it is only a gaseous by-product of biodiesel refining which targets liquid fuel. Currently, the majority of rLPG produced is burnt for process heat energy onsite. This is because the mixture is often contaminated and may not meet the required standards for use. The required composition of rLPG for commercial use is set out by NZS 5435:1996 (Table 1). To obtain the desired composition additional processing or optimisation of the production pathway may be required. Additionally, an appropriate percentage at which the lights fraction of biodiesel is sufficient to be worth cleaning and bottling needs to be determined before rLPG can be commercialized.

A limitation of this technology is that the target product is a refined liquid fuel, hence the yield of rLPG from biodiesel is low, see Table 6-1. Therefore, rLPG can be considered the by-product of this pathway.

Table 6-1: Yield of Liquid and Gaseous Fuels from Biodiesel Refining

Feedstock	Pathway	Feedstock Conversion (mass basis)	Product Slate		Lights (LPG) Conversion from Feedstock
			Liquid Fuels (Diesel & Jet)	Lights (LPGs & Naptha)	
Lipids	HEFA	98%	92%	8%	8%

6.1.2 Capacity installed and feedstock potential

New Zealand has limited installed capacity for biodiesel production. Z energy started producing FAME biodiesel in 2018 at Te Kora Hao plant in Wiri, South Auckland, which had an initial capacity of 20million L/year, with potential scale up to 40 million L/year (36,000 t/year). This has an rLPG potential of approximately 2,900 t/year (1.5% of current domestic LPG use) However, in 2020 due to increasing tallow prices resulting from increased international demand, Z Energy has hibernated this plant.

Another producer on a smaller scale is Green Fuels, located in Christchurch, producing 500,000 L/year (450 t/year) of biodiesel from used cooking oil. It is unlikely this small-scale plant would be able to economically process and bottle the light fraction to produce rLPG.

Total New Zealand tallow production is approximately 160,000 t/year, representing 156,000 t/year biodiesel production. Maximising biodiesel production to match available tallow production would require four Z Energy scale plant operating at future capacity, or eight plants operating at current capacity (20 million L/year). This maximum production of biodiesel would provide only 6% of New Zealand LPG demand.

6.2 Feedstock & By-products

Typical feedstocks for biodiesel production include plant-based oils, like canola, sunflower, and palm oils, as well as animal fats and grease. As discussed in Section 4, tallow, a rendered form of beef or mutton fat, has been highlighted as a potential feedstock for biodiesel due to the low volumes of waste vegetable oil, and low production of oil crops. New Zealand produces around 160,000 tonnes of tallow per year with the majority currently exported. As a feedstock for transesterification, tallow can have a high free fatty acid content which can lead to soap formation. The formation of soap is undesirable as it can have adverse effects on downstream processing and lead to reduced yield.

If the feedstock has high free fatty acid content, that is greater than 1-2% like animal fats, biodiesel production through transesterification is unsuitable and additional processing is required. Basic transesterification is also not recommended as some of the catalyst will react to form soap with triglycerides. Pre-processing methods include refining the feedstock prior to transesterification and acid catalysis. Refining the feedstock involves removing free fatty acids by chemical neutralization, where some oil may be lost, or physical deacidification which requires steam and vacuum conditions. In acid catalysis, high ratios of alcohol to free fatty acid and a large amount of catalyst (5-25%) are needed (Dunford, 2016). Tallow is often melted under slow heating and reduced pressure prior to being filtered to remove waxy materials and other suspended matter before undergoing the general biodiesel production process.

By-products of biodiesel production include glycerol, making roughly 10% (w/w) of product stream. Glycerol has high Chemical Oxygen Demand (COD) and is rich in impurities. Anaerobic digestion of glycerol, along with other feedstocks can produce biomethane, effectively as a co-product of biodiesel production. Co-locating biofuel plant with an AD facility would improve feasibility of utilising this by-product.

Key barriers for feedstock utilization include the high export value of tallow. This barrier led to the hibernation of the Z Energy plant, and incentives would be required to ensure tallow remains available for domestic energy production as opposed to favouring an export market.

6.3 Barriers to Implementation

The low yields of rLPG from biodiesel refining mean that the light fraction is often burnt for process energy as opposed to being processed and bottled. This may mean that ideal yields of rLPG from biodiesel production decrease on account of internal plant energy requirements.

Production of rLPG at a scale requires the development of a biodiesel/biofuel industry in New Zealand, as rLPG can only be accessed as a by-product of this process.
To meet New Zealand's current LPG demand of 9.5 PJ/year, 2,450,000 t biodiesel is required to be produced (approximately 75% of New Zealand total diesel consumption in 2021 (MBIE, 2022)). With tallow as target feedstock that represents a 16 times current tallow production. Alternatively, this represents approximately 70 plants of similar scale to the Z Energy Biodiesel plant in Wiri (at full future capacity). Significant growth in the biofuels sector is required to support rLPG production to the scale required to meet New Zealand's current demand.

7 Tier Three Technology – Emerging Technologies Deployable 2030 – 3035

7.1 Description

7.1.1 Syngas Processing

Tier Three technologies include pathway from feedstock gasification to produce syngas. From syngas intermediate, three pathways are considered:

- Syngas to biomethane through methanation
- Syngas to DME via catalytic conversion (via methanol)
- Syngas to rLPG via Fischer Tropsch and distillation.

Description of these technologies is shown in Appendix B.

7.1.2 Biomethane (via Green Hydrogen and CO_2 Methanation)

An additional Tier Three pathway is the production of biomethane through green hydrogen and CO_2.

The methanation process was traditionally developed to convert gasified coal and biomass into synthetic natural gas. More recently it has been used to convert the CO_2 fraction of biogas into biomethane through a reaction with green hydrogen produced via electrolysis. This can occur in a separate methanation plant, but the lower capital option would be considering biological methanation.

'Biological Methanation' is a biological pathway that can occur either in-situ or ex-situ from an existing anaerobic digester and it involves providing favourable conditions for hydrogenotrophs to metabolise injected green hydrogen with the CO_2 already contained within the reactor increasing the CH_4 yield of an existing system. A key challenge is maintaining the pH of the reactor while the CO_2 partial pressure is dropping (therefore favouring the ex-situ biological methanation process).

WWTP sites, with existing digesters are a favourable case study for biological methanation. Installation of renewable electricity generation, such as solar panels or wind turbines on the utility site allowing green electrolysis provided green hydrogen potential.

Limitations on the green hydrogen production include the lack of commercial scale green hydrogen facilities, large electrical consumption, and electrical inefficiency of electrolysis process. However, as production of hydrogen matures, the costs are likely to reduce which would make methanation a more favourable pathway, especially utilizing existing infrastructure in AD facilities.

7.2 Product Yields and Limitations

To determine the yield of DME and methane, it was assumed that the feedstock (syngas) was the output of gasification. The upper-limit conversion values found in literature have been used and reported in Table 7-1. Yields have been calculated assuming a syngas feedstock of dry woody biomass with a nominal heating value of 15 $MJ/kg_{biomass}$.

Table 7-1: Product Conversion Yields from Biomass Gasification

Process	Conversion	Yield
Biomass to Syngas	40%	
Syngas to DME	70%	<5.6MJ/kg $_{biomass}$

Process	Conversion	Yield
Syngas to Methane	95%	$<7.7MJ/kg_{biomass}$

The overall biofuel yields and light fraction percentage will depend heavily on the pathway taken to produce the crude. This will vary due to a wide range of factors. Table 7-2 below provides indicative yields from Fisher-Tropsch compared with alternative technologies. These numbers are based on literature and available vendor data. One of these alternative technologies is advanced plastics recycling processes (chemical recycling) can also produce LPGs as by-products.

The yield of LPGs from FT is similar to that from hydrothermal liquification (HTL), both will likely be under 10%. Advanced (chemical) plastics recycling is a much better source of light hydrocarbons, with a yield of up to 20% of the plastic feedstock. However, this stream would contain contaminants which would prevent it from being used as an LPG substitute, and because the LPG is plastic-derived it cannot be classed as rLPG. Due to the contaminants present, these light hydrocarbons are also usually burnt for process heat and the flue gas can be sent to a thermal oxidizer to destroy any remaining contaminants. At present this is a nascent industry and only a few plants exist globally. The industry is nevertheless slated to grow significantly in the coming decade and may present another source of LPGs and light hydrocarbon gases. This pathway is not a focus in this study as recycling of plastics by definition is not a renewable pathway.

Table 7-2: rLPG Fuel Yields from Various Pathways

Feedstock	Pathway	Feedstock Conversion (mass basis)	Product Slate		Lights (LPG) Conversion from Feedstock
			Liquid Fuels (Diesel & Jet)	Lights (LPGs & Naphtha)	
Biomass	HTL	30%	85%	15%	5%
Biomass	Gasification + FT	23%	80%	20%	5%
Plastics	Adv. Plastic Recycling	80%	75%	25%	20%*

*Will be contaminated. Also not considered rLPG as feedstock is not renewable.

A key barrier that is important to note the energy penalties associated with the transformation of electrical and/or chemical energy. This is illustrated by the methanation reaction where hydrogen is converted to methane. Here there is an overall energy loss to the system, equating to a 17% reduction in the heating value of the fuel. Such a penalty may be acceptable given methane is an easier to handle fuel and can be used in existing natural gas networks and appliances. It does however illustrate one of the challenges facing manufactured 'drop-in' fuels. Energy penalties upwards of 50% are common for Fischer-Tropsch fuels.

Methanation Efficiency for an indicative system:

	Hydrogen			**-->**	**Methane**			***Change***
Reaction	4 $\mathbf{H_2}$	+	CO_2	**-->**	$\mathbf{CH_4}$	+	2 H_2O	
Mass (tonnes/day)	**10**	+	55	**-->**	**20**	+	45	***0%***
Heat Yield (GJ/day)		**1200**		**-->**		**995**		***-17%***

7.3 Feedstock & By-products

Syngas is the reactant to methanation, catalytic conversion and Fisher-Tropsch. Syngas consists of hydrogen (H_2), carbon dioxide (CO_2) and/or carbon monoxide (CO). The upstream processes to produce these feedstocks can vary. Three upstream processes are described below. As discussed in Section 4, from the forestry and processing residues in New Zealand, there is 63.2 -63.5 PJ/year of syngas potential.

1. **Biogenic biogas processes**, producing a mix of methane (CH_4) and carbon dioxide (CO_2). This occurs via anaerobic digestion. The feedstocks into anaerobic digestion include municipal wastewater, food waste, agricultural feedstocks, and manure. These feedstocks are further discussed in Section 5. Post digestion, the biogas may then be reacted with hydrogen to convert the CO_2 into additional methane, increasing biomethane yield. To remain a low carbon-intensity *green* biomethane, the reactant hydrogen is often produced using electrolysis powered by renewable electricity (discussed further in Appendix B). Anaerobic digestion can produce contaminant by-products, notably hydrogen sulphide (H_2S), which is readily removable through scrubbing.
2. **Gasification of organic matter** to produce hydrogen (H_2), carbon dioxide and/or monoxide (CO_2 and/or CO) and contaminant by-products. Gasification occurs at high temperatures (>700^oC) reacting the organic feedstock, commonly woody biomass, without combustion through controlling the supply of oxygen and/or steam to the reaction. Depending on the organic feedstock, gasification can produce a variety of contaminant by-products. These can be difficult and expensive to remove. Syngas clean-up prior to methanation is nevertheless critical and presents one of the major drawbacks of gasification.
3. **Power-to-X via carbon capture and green hydrogen production**, targeting the capture/production of CO_2 and H_2 molecules for further reaction to methane. This has the potential to be a net-zero process where renewable electricity is used to produce hydrogen (via electrolysis) and capture carbon dioxide from the atmosphere (via Direct Air Capture) (a Tier Four technology). Carbon dioxide can alternatively be sourced from existing 'hard-to-abate' processes and 'recycled' to produce lower carbon, but not net-zero, syngas. The process can also be configured to initially use recycled carbon before cutting over to atmospheric carbon as DAC technology improves. Unlike the other processes, there should be no contaminant by-products and this pathway presents an opportunity to convert electrical power into carbon-neutral methane.

Each pathway has specific advantages and disadvantages when used in the Fisher-Tropsch, methanation and catalytic conversion processes.

By-product gaseous hydrocarbons are produced by all common synfuel processes and as the market for 'drop-in' synfuels continues to grow, the quantities of these gaseous hydrocarbons will increase in parallel. Given these gases have traditionally been burnt onsite, further upgrading will likely be required prior to these gases being injected into existing networks.

It is also pertinent to note that due to the relatively high cost of producing synfuels, processes are optimised to maximise the production of the more valuable liquid fuels (diesel and jet). Any gaseous hydrocarbons/LPGs could be supplied to gas networks as a secondary product but would not be a target product. As discussed for rLPG from biodiesel refining in Section 6, the scale of fuel production required to meet the LPG demand with the low yields would be inhibitive.

8 Tier Four Technology – Future Technologies Deployable 2035+

8.1 Description

Tier Four considers production of biomethane via methanation, as described above. However, this technology considers the utilization of CO_2 from other sources outside what is captured from biogas upgrading. Other sources of CO_2 include:

- Carbon capture from atmospheric CO2
- Carbon capture from point sources such as CO_2 in flue gases from combustion

This technology is considered least technically mature, as it considers methanation where green hydrogen production is no longer the limiting step (large scale green hydrogen production is not yet available), and additional CO_2 sources need to be explored. Additionally, atmospheric carbon capture technologies at large scale is also technically immature. Carbon capture from high concentration streams (such as biogas upgrading) has lower technical barriers compared to low concentration separation such as carbon capture from flue gases and from atmosphere.

There are currently 18 direct air capture plants operating worldwide (none in New Zealand), with total capture of 0.01 Mt CO_2/year (IEA, 2022).

9 Case Studies

9.1 Case Studies Summary

We have examined various potential cases and implementation options for production of biomethane, DME, and rLPG across the country. The case studies have been selected based on the distribution of feedstocks, end users of fuels produced, and the scale of potential installations. The case studies are not intended to be exhaustive but illustrate the typical scale of projects that could be implemented for New Zealand's gas transition journey.

The following case studies represent biogas production through AD and upgrading to biomethane. As this technology is more mature, we have reviewed expected capital costs, operational costs, revenue streams, and the impact of plant operation on carbon emissions.

- Landfill gas to biomethane at Kate Valley and Hampton Downs landfills
- Biogas to biomethane using existing anaerobic digesters at different scales, considering Māngere WWTP, and a centralised biogas facility in Southland, covering the Clifton WWTP and several meat works WWTPs
- Food waste and agricultural waste to biomethane using new AD plants in two locations, Wellington, and Taranaki
- Organic and agricultural waste to biomethane through new AD facilities for digestion of green waste, manure and grasses in Waikato and Canterbury
- Large scale agricultural digester using grass crops located in Hawkes Bay.

Additionally, we have considered the scale of installations possible utilising less mature technology listed below. Cost information has not been provided due to the lack of commercial installations, but consideration of feedstock costs has been included.

- Woody biomass gasification and processing to methane via gasification and methanation, located in the central North Island
- Woody biomass gasification and processing to DME via methanol synthesis and further processing, located in the South Island without existing natural gas grid
- Tallow to biodiesel, refined to rLPG, with a new plant located in Dunedin utilising South Island tallow production

A summary of the location of the case studies, the assessed energy potential, and where assessed, the required gas price, are shown in Figure 9-1. South Island case studies have not been priced as the focus of this work is on biogas upgrading and injection into the natural gas grid in the North Island.

For reference, the average 2021 wholesale natural gas price was \$8.46/GJ, with a peak in the Sept 2021 quarter of \$9.10/GJ excluding GST (MBIE 3, 2022).

See Section 9.4 for a tabular summary and conclusions from the case studies. Full details of the case studies are in Appendix C.

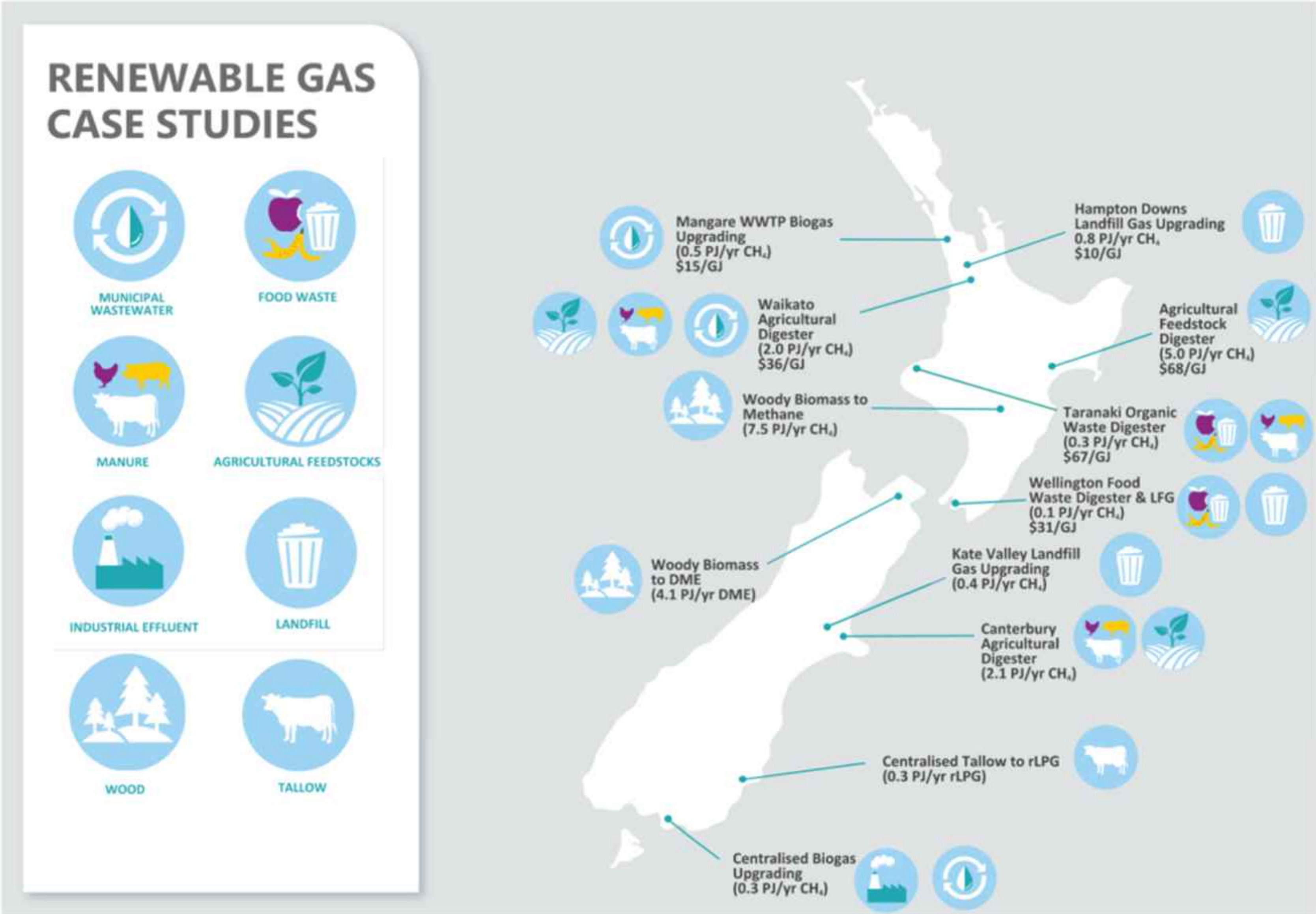


Figure 9-1: Indication of Case Study Locations and Target Fuels

9.2 Emissions Intensity

Significant portion of the emissions results from fugitive emissions from the landfills in case studies which involve utilization of LFG. LFG capture systems only capture 68% of gas produced on average (MfE 3 2022), hence 32% of methane produced leaks to atmosphere. Note, new modern landfills are likely to have higher capture rates than this. Biogas leakage from a high-quality digester is 1%, hence diversion of organic from landfill to AD facilities significantly reduces fugitive emissions and overall emission intensity associated with the biomethane production.

Emissions intensity varies depending on distances travelled – these case studies made specific assumptions around distances travelled to collect feedstocks and return digestate. If this transport could be reduced, or transportation vehicles be swapped for lower emission alternatives, such as electric vehicles or hybrids, these transport emissions would also lower. Additionally, with the introduction of more renewable electricity production as New Zealand moves towards 100% renewable electricity generation, the emissions associated with electricity supply, transmission and distribution will reduce.

On average, considering AD emissions, electricity, transmission and distribution, and combustion of the biomethane (hence excluding any transport or feedstock collection portions), average emissions intensity is 19 kg CO_2e/GJ, compared to 57 kg CO_2e/GJ for fossil natural gas (which excludes production leakage and emissions which can be in the order of 10 kgCO_2e/GJ (MacKay et al., 2021). This excludes landfill fugitive emissions, assuming the biogas production and upgrading would occur in a new plant with minimal gas leakage.

A summary of the emissions associated with the case studies presented is in Table 5-5, with emissions sources break down shown in Table 9-2. These include:

- Emissions from feedstock and digestate transport (where case study appropriate) assuming diesel vehicles
- Fugitive emissions from digesters (where case study appropriate)
- Emissions from electricity consumption, assuming electricity for digester mixing, heating using a heat pump (for AD case studies) and biogas/LFG upgrading
- Emissions from gas transmission and distribution (T&D)
- Emissions from biomethane combustion

Assumptions include:

- Biogas digester is high quality 'gastight' storage & routine IR camera monitoring is conducted
- Extensive leak detection (LDAR) and >50% centrifugal compressors have dry seals (as they will be newly installed to compress for injection in these projects)
- Diesel trucks for transporting feedstock and digestate
- Transport of feedstock from a centralised collection point for residential wastes (not the rubbish trucks going house to house)
- 20 tonne truck transporting feedstock and digestate
- Including transmission and generation emissions for electricity
- Default diesel heavy goods vehicle (HGV) emission factor
- Digester is heated from 15°C to 37°C with heat pump - COP of 2.5 (to maximise gas use)
- Feedstock slurries have heat capacity of water
- All gas produced will be combusted
- CO_2 portion of biogas and CO_2 produced through combustion is biogenic, hence not considered in CO_2 emissions
- No negative emissions for bioCO_2 produced
- Methane release at landfill not included

- Assumed travel distances for feedstock supply and digestate return:
  - Taranaki – 50km feedstock supply radius, 20km digestate return radius
  - Waikato – 100km feedstock supply and digestate return radius
  - Wellington – 50km feedstock supply and digestate return radius
  - Hawkes Bay – 80km feedstock supply and digestate return radius

Specific exclusions from emissions estimates:

- Negative emissions from conversion of agriculture land use to cropping land use
- Reduction in GHG emissions when biogas from AD is derived from a material is going to landfill or other processes that generate large quantities of biogenic methane.
- Negative emissions for bioCO_2 produced
- Methane release at landfill not included
- Food waste collection for residents - i.e. The rubbish trucks
- Incidental emissions, including operator transport to site etc

Table 9-1: Summary of GHG Emissions Intensities for Case Studies and Natural Gas Consumption

Case Study	Emissions (kgCO_2e/GJ)
Hampton Downs Landfill	9
Māngere WWTP	14
Wellington food waste digester + LFG	12
Taranaki Organic Waste Digester	19
Waikato Organic/ Agricultural Digester	20
Hawkes Bay Agricultural Digester	19
Natural Gas	57

Table 9-2: Break-down of Emissions Sources for Case Studies and Natural Gas as Percentage of Total Emissions

Case Study	AD Fugitive Emissions	Transport	Electricity	Transmission & Distrib.	Combustion
Hampton Downs Landfill	N/A	0%	45%	36%	18%
Māngere WWTP	Not counted	0%	65%	23%	12%
Wellington food waste digester + LFG	18%	2%	42%	26%	12%
Taranaki Organic Waste Digester	27%	6%	42%	17%	8%
Waikato Organic/ Agricultural Digester	25%	15%	37%	16%	7%
Hawkes Bay Agricultural Digester	28%	6%	41%	17%	8%
Natural Gas	N/A	0%	0%	6%	94%

9.3 Gas Price

9.3.1 General

Case study costs have been built up based on the unpublished Professional Consulting Engagement (PCE) Project for a Masters of Business Administration (MBA) at the University of Otago called *Increasing the uptake of biogas technology in New Zealand* by Richard Bartlett for Suggested policy measures for the Bioenergy Association of NZ to petition the Government.

The biomethane cost ($/GJ) is made up of several components. This section of the report summarises how these components are built up.

Finally, the biomethane cost as been adjusted to provide an IRR (internal rate of return) of 10% at 13 years, just after the capital has been fully depreciated. No Revenue from a feed-in tariff or renewable gas mandate / certificate premium has been costed in as these can be assumed to be taken off the gas price as give in Table 9-5.

The revenue split for the costed case studies is given in Table 9-3.

Table 9-3: Break-down of Revenue for Case Studies Percentage of Total Revenue

Case Study	Gas Sales	ETS Credits	BioCO_2 Sales	BioFert Sales	Gate Fees
Hampton Downs Landfill	29%	36%	35%		
Māngere WWTP	44%	36%	20%		
Wellington food waste digester + LFG	52%	19%	19%	7%	3%
Taranaki Organic Waste Digester	75%	12%	13%	1%	0.2%
Waikato Organic/ Agricultural Digester	60%	19%	21%		
Hawkes Bay Agricultural Digester	74%	13%	13%		

9.3.2 Price stack

An estimated gas prices stack for converting the feedstocks assessed to biomethane and injecting into the North Island natural gas grid is give in Table 9-4. Gas prices for the first 40% of the feed stocks as estimated using the case studies above. Gas prices for addition proportions of the feedstock are increased to account for factors such as reduced economies of scale, extended collection distances, extend distances to the existing gas network. Further work is required to refine the gas price for these additional proportions. Shaded cells indicated the at the feedstock is considered impractical to obtain. Excluding the Utility Crops, this price stack is presented in graphically in Figure 9-2 where the grey columns indicated the quantities based on the case studies, and hence have a higher level of certainty.

Table 9-4: Price Stack for Biomethane

Feedstock	Max. BioCH_4 Potential (PJ/year)	Available in North Island	Gas Price ($/GJ for)				
			First 40%	40-60%	60-80%	80-90%	Last 10%
Munic. Biosolids	1.6	75%	15	20			
Post-Con. FW	1.8	75%	30	40	50		
Munic. Green Waste	1.8*	75%	70	80			
Landfill Gas	3.0	75%	10	15	20	30	
Dairy Wastewater	1.5	70%	20	25	40		
Meat Wastewater	0.72	50%	10	25	40		
Pre-Con Food Waste	0.26	75%	30	40	50	60	
Horticulture Wastes	1.5	60%	30	40	50	60	
Supp. Crops	8.1	25%	35	45	60		
Animal Manure	7.5	70%	70	80			
Utility Crops*	40**	100%	65	65	65	65	65

*Including Organics currently going to composting
**From 5.6% of NZ productive grassland (450,000 ha)

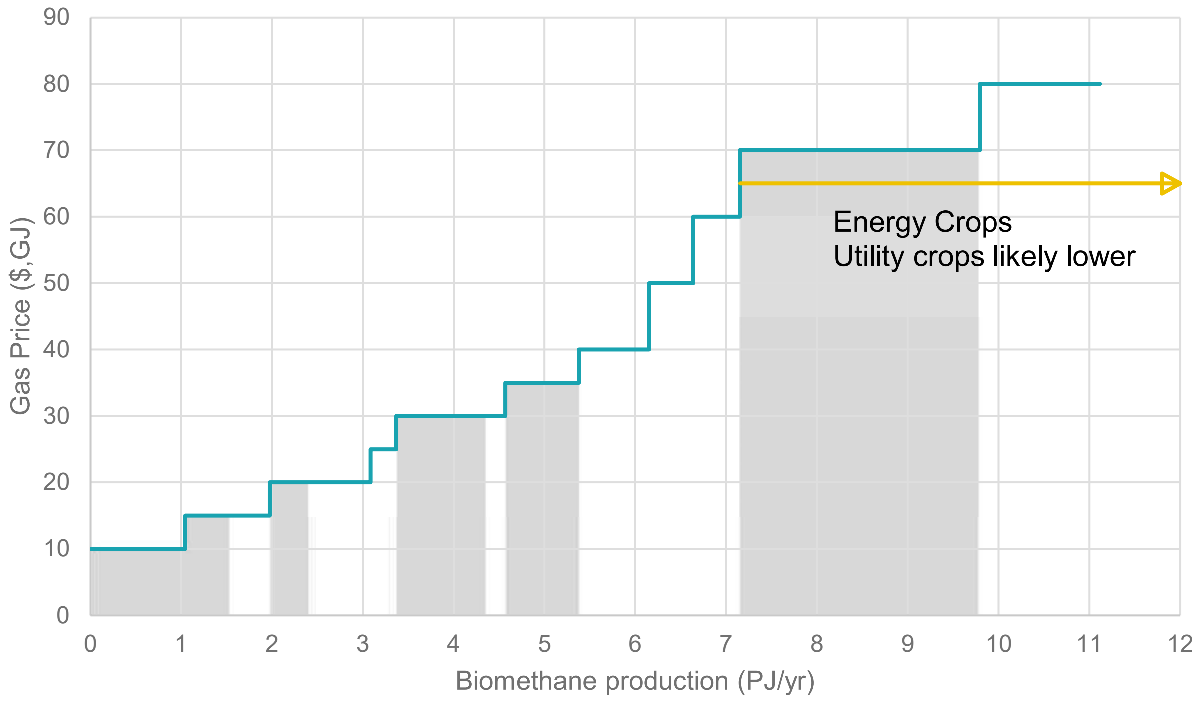


Figure 9-2: Price Stack for Biomethane (grey columns indicated the quantities based on the case studies)

9.3.3 Gate Fees

For case studies processing organic wastes, a fee can be charged to accept this waste. For this study the assumed gate fee was the 'Tailwind' scenario from Bartlett (2021). Which starts at $30/t in year 1, increasing to $50/t in year 2 then increasing $10/t per year every year after that. This is based on MfE's waste disposal Levy (MfE, 2021b)

9.3.4 Emissions Trading Scheme Credits

All case studies were assessed for carbon credits for the following categories:

- Diverting organics away from landfill
- Biomethane replacing NG grid demand
- Biogenic CO_2 replaces fossil derived CO_2
- Digestate replaces natural gas derived Urea

Subtracted from this were the fugitive emissions.

The assumed ETS NZ unit price is given in Figure 9-3. This is based on Climate Change Commissioning Advice to Government (CCC, 2021).

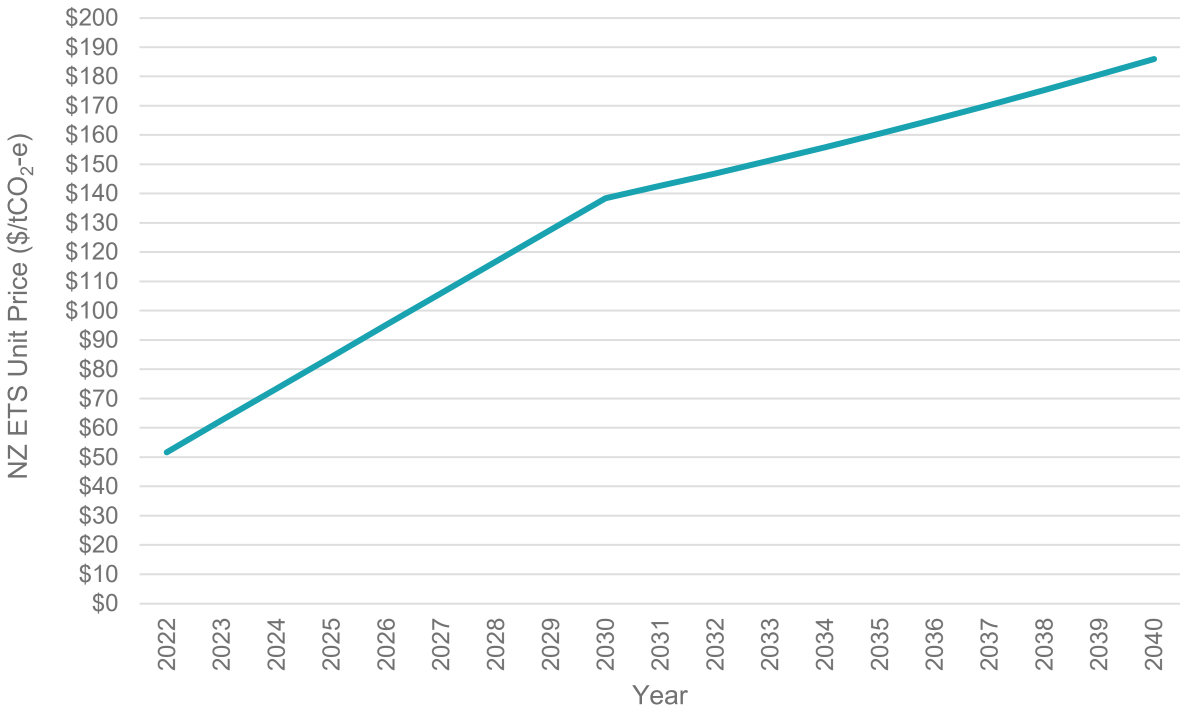


Figure 9-3: Assumed ETS NZ unit price

9.3.5 BioCO_2 sales

The revenue from the sale of food grade CO_2 was assumed at $150/t increasing at 6% p.a. due to supply constraints.

9.3.6 Bio Fertiliser sales

Digestate from digestion of manure and agricultural plant matter was assumed to be returned to the supplier at no cost thus returning the fertiliser value of these feedstock to the supplier, and hence no fee is charged to obtain these feedstocks.
Digestate from digestion of food waste is assumed to return a value as a fertiliser at the following equivalent rates:

- Nitrogen Urea Fertiliser (46-0-0) $1.24/kg
- Triple Super Phosphate (0-19-0) $1.17/kg
- Potassium Chloride (0-0-50) $1.09/kg

9.3.7 Operating Expenses

Operating expenses are built up of the following:

- Electricity costs for
  - Anaerobic digestion operation (excluding heating)
  - Heat pump operation to heat the anaerobic digester
  - Biomethane operation
- Haulage for
  - Feed stock
  - Digestate
- Operator Salary
- Plant maintenance
- Other expenses including
  - Insurance
  - Other Administrative Fees

The assumed Electricity price is $0.148/kWh in 2022 increasing 4.6% p.a.. The haulage cost was assumed to be $4/km for a 20t truck in 2022 increasing 2% p.a..

9.3.8 Depreciation Expenses

Depreciation expenses relate to the account of the capital cost. A 12.5 year straight line depreciation has been assumed.

9.4 Case Study Conclusions

A tabulated summary of the case studies is given in Table 9-5. The case studies showed there is gas potential spread across the country. However, the South Island case studies were not priced as the focus of this work is on biogas upgrading and injection into the natural gas grid in the North Island. If a suitable trading certificate system could be implemented then South Island biomethane plants could off-set a North Island Natural gas use, but large South Island biomethane consumers would also be required. The South Island biomethane case studies involve complex equipment for transportation and use of methane, including compression and decompression facilities. This is user dependent.

Given the cost of woody biomass, forestry residue is likely to only feedstock that represents a cost-effective pathway to produce biomethane (via gasification and methanation) as part of New Zealand's natural gas transition pathway.

Similarly, the opportunity cost of tallow is likely to be cost prohibitive to produce rLPG via biodiesel production and refining.

Given the higher price of LPG (relative to natural gas), use of DME as a renewable substitute may have potential. However, production of DME from gasification of woody biomass is still likely to come with a significant price premium.

A key conclusion from the case studies is that a mixture of feedstocks is required to get gas production of appropriate scale. In the case of a large scale production, such as the Hawkes Bay grass digester, smaller decentralised digesters with decentralised/containerised biogas upgrading and multiple grid injection points may be more feasible, as the transportation costs to cart feedstock to a centralised location is significant. Further economic analysis is required to determine the level of scale where a centralised plant is preferrable over decentralised facilities.

These case studies were developed based on feasible feedstock availability. The scale of these illustrates that a significant number of installations across the country would be required to meet the national gas demand. A key barrier common across the case studies was the feedstock availability, and diversion of the feedstocks from other disposal pathways, or feedstock uses (for non-waste products).

Consideration of digestate marketing is critical for the largescale adoption of AD technology for energy production.

Table 9-5: Case Study Summary

Case Study	Description	Feed Stock	Product Potential (PJ/year)	Bio-methane Cost ($/GJ)	Emissions Intensity (kgCO$_2$e/GJ)
Kate Valley Landfill	• Landfill in North Canterbury with existing landfill gas capture • Installation of landfill gas upgrading plant • Compression of biomethane for transport	• Landfill gas from existing municipal solid waste: 300,000 t/yr. MSW	0.4 PJ/year biomethane	N/A	N/A
Hampton Downs Landfill	• Landfill in North Waikato with existing landfill gas capture • Installation of landfill gas upgrading plant • Injection of biomethane to national grid	• Landfill gas from existing municipal solid waste: 600,000 t/yr. MSW	0.8 PJ/year biomethane	10	9
Māngere WWTP	• Municipal WWTP located in Auckland with existing AD • Installation of biogas upgrading plant • Injection of biomethane to national grid	• Biogas from digestion of municipal wastewater 115 million m^3/yr. wastewater	0.5 PJ/year biomethane	15	14
Combined Southland AD Plants	• Combined biomethane potential from three meat processing plants and Clifton municipal WWTP, all with existing onsite anaerobic wastewater treatment and biogas production • Installation of biogas upgrading plant • Injection of biomethane into a newly established, localised reticulation network	• Biogas from digestion of municipal wastewater and meat processing wastewater	0.3 PJ/year biomethane	N/A	N/A
Wellington Food Waste Digester and LFG	• Installation of new AD facility in Wellington to digest organic waste co-located with Southern Landfill • Upgrading of landfill gas from Southern landfill • Installation of biogas upgrading plant • Compression of biomethane for transport	• Pre-consumer food waste from supermarkets: 4,500 t/yr. • Post-consumer food waste from source separated food waste collection scheme: 11,000 t/yr. • Total food waste: 15,500 t/yr. • Landfill gas: 4,000,000 m^3/yr.	0.1 PJ/year biomethane	31	12

Case Study	Description	Feed Stock	Product Potential (PJ/year)	Bio-methane Cost ($/GJ)	Emissions Intensity ($kgCO_2e/GJ$)
Taranaki Organic Waste Digester	• Installation of new AD facility in Stratford, Taranaki to digest organic waste • Installation of biogas upgrading plant • Injection of biomethane into the grid	• Pre-consumer food waste from supermarkets: 1,400 t/yr. • Post-consumer food waste from source separated food waste collection scheme: 3,300 t/year • Total food waste: 4,700 t/yr. • Dairy manure: 49,000 tDS/yr.	0.3 PJ/year biomethane	67	19
Waikato Organic/ Agricultural Waste Digester	• Installation of new AD facility in central Waikato as a centralised facility to digest organic waste • Installation of biogas upgrading plant • Injection of biomethane into the grid	• Dairy manure: 904,000 t/yr. (226,000 tDS/yr.) • Pig manure: 116,000 t/yr. (329,000 tDS/yr.) • Green waste: 60,000 t/yr. • Grass Crops: 120,000 t/yr.	2.0 PJ/year biomethane	36	20
Canterbury Organic/ Agricultural Waste Digester	• Installation of new AD facility in Canterbury as a centralised facility to digest organic waste • Installation of biogas upgrading plant • Compression of biomethane for transport	• Dairy manure: 616,000 t/yr. (154,000 tDS/yr.) • Pig manure: 449,000 t/yr. (112,000 tDS/year) • Green waste: 63,000 t/yr. • Grain stubble: 125,000 t/yr.	2.1 PJ/year biomethane	N/A	N/A
Hawkes Bay Agricultural Feedstock Digester	• Installation of new AD facility in Hawkes Bay to digest grass/silage • Installation of biogas upgrading plant • Injection of biomethane into the grid	• Crops harvested from 43,000 ha of productive grassland: 1,450,000 t/yr.	5 PJ/year biomethane	68	19
Landing Residues Woody Biomass Gasification and Methanation	• Installation of new gasification and methanation facility in the Central North Island to produce syngas and process to methane via methanation process • Injection of biomethane into the grid	• Woody biomass (landing residues) from harvesting sites: 995,000 m^3/yr. (184,000 dry t/yr.)	1.4 PJ/year biomethane	$0/GJ*	N/A

Case Study	Description	Feed Stock	Product Potential (PJ/year)	Bio-methane Cost ($/GJ)	Emissions Intensity ($kgCO_2e/GJ$)
Landing residues and Pulp Logs Gasification and Methanation	• Installation of new gasification and methanation facility in the Central North Island to produce syngas and process to methane via methanation process • Injection of biomethane into the grid	• Woody biomass (landing residues) from harvesting sites: 995,000 m^3/yr. (184,000 dry t/yr.) • Woodchip: 100,000 dry t/yr. • Pulp: 690,000 dry t/yr. • Total woody biomass: 970,000 dry t/yr.	7.5 PJ/year biomethane	$130/GJ*	N/A
Woody Biomass Gasification and DME production	• Installation of new gasification facility, and DME production plant utilising methanol synthesis pathway in Nelson region • Bottling of DME for LPG market	• Woody biomass (landing residues) from harvesting sites: 255,000 m^3/yr. (47,000 dry t/year) • Pulp: 690,000 dry t/yr. • Total woody biomass: 735,000 dry t/yr.	4.1 PJ/year DME	$177/GJ*	N/A
South Island Tallow to rLPG	• Installation of new biodiesel production and refining facility in the Dunedin area • Bottling of rLPG	• Tallow: 80,000 t/yr.	0.3 PJ/year rLPG	$318/GJ*	N/A

* For less developed technologies, price presented is based on feedstock costs only. Actual cost estimates would need to include plant operating costs and capital costs, but these technologies are not mature enough to quantify these costs at this stage

10 Biogas Supply Potential

Based on the analysis presented in this report, there are a number of conclusions we can draw regarding the future contribution of biogas fuels to New Zealand's overall decarbonisation pathway, and the supply of low emissions energy to enable a transition to green fuels.

Across the tiers of biogas technologies we reviewed as part of this work, there are opportunities with a range of supply potential as well as technical maturity/availability. In this section we will focus on how the mix of technologies available to us is likely to enable access to affordable energy in the short and medium term.

10.1 Energy Availability

From Section 4, with consideration to all of the potential technologies on offer and the wide array of organic feedstocks that could be converted into biogas fuels, there is more than enough material to supply NZ's current and future energy demand if this material was solely directed towards green energy generation. This however needs to be tempered with realistic expectations of how this material is likely to be used, and how these use cases may change over time.

To review this in a way that better reflects the availability of energy and its likely use cases, we need to review the different sources of bioenergy in several sub-categories.

10.1.1 Organic Wastes – 9PJ Total

The most readily-accessible materials that can be used for biogas generation are biological waste materials. Consisting of Food Waste, Green Waste, Wastewater and Horticultural wastes, this category of feedstock material performs the best in our case studies since there are commonly existing collections available and the material incurs a cost to dispose.

The technology that is required to produce grid-ready bioenergy from these sources is commonly available, with NZ's first organic waste biomethane injection facility planned for operation in 2024.

Our estimates suggest that around 70% of this energy potential would be able to be feasibly accessed and utilised for biomethane generation and grid injection, but the remainder is unlikely to be accessed and treated in a way that would allow for energy use within the gas network.

Generation of this material is well-distributed across the North Island (barring some significant point sources of generation around large industrial facilities) and generally falls in close proximity to gas users. The organic wastes generated are also produced fairly consistently throughout the year. With this in mind, the energy products accessed should be able to be fed into lower-pressure distribution networks and with minimal buffering required to align gas use vs gas supply especially in colder months.

10.1.2 Agricultural Residues – 15PJ Total

Biogas generation from agricultural residues is similar to Organic Wastes in that the technology required to utilise this material for energy generation is robust and well advanced. However, the key difference that affects both material accessibility and likely uptake is that this material is often left uncollected on-farm, either because the material provides some residual benefit to the farmland or because collection is difficult to perform effectively.

Our estimates suggest that much of this material (especially supplementary crops) would be difficult to access in a way that would provide energy to the natural gas network, or there would be prohibitive costs to perform this effectively. Around 40% (the majority of this being manure streams) could still be collected and processed given favourable energy prices (discussed in the next section).

Agricultural residue generation/collection will fluctuate in volume throughout the year as agricultural seasons change/milking seasons pass. This can be managed with material treatment in some cases i.e.

silage storage, or exploration of codigestion opportunities may also enable use of seasonal crops in existing digesters. However, codigestion opportunities will need to be considered carefully in the context of waste criteria (discussed later).

10.1.3 Forestry Residues – 63PJ

The other remaining category of existing feedstocks that could be used to generate biogas energy is residues from forestry operations, and conversion into syngas products. The potential energy generation from this feedstock is extremely large; much larger than the forecast natural gas demand in NZ by 2040 presented in Section 3, but there are a number of issues to be considered when analysing how this material will contribute to biogas production.

Firstly, the technology for generation of drop-in fuel production from these sources i.e. biomass gasification and reforming would be new to New Zealand and while developed internationally would take time to be implemented and approved for use locally.
Secondly, there is strong competition for the use of biomass residues to offset primarily coal use in the form of wood pellets/wood chip in the leadup to the ban on coal boilers by 2037. Direct use of biomass as a heating fuel is the highest energy yield application of residual biomass material and direct biomass use would also be the cheapest use of this energy content, given the minimal processing required.

10.1.4 Purpose-grown Crops – up to 150PJ/year

Looking beyond currently available organic waste sources for biogas production, the most significant potential source of biogas supply comes from future purpose-grown energy cropping opportunities. Looking at the availability of biogas from organic waste streams, by the time ~7PJ of biomethane becomes available it becomes cost-comparable for additional biogas generation to come from purpose-grown energy cropping activities and processing.

The technology required to make this energy available is readily deployable, and this solution is inherently very scalable. However, it will require the dedication of productive grasslands to energy production which has inherent conflicts with our existing agricultural operations and harvest seasonality will need to be managed in a similar way to agricultural residues (explained above).

Alternatively, it may be more acceptable to use energy crops as a utility crop, in combination with agricultural use to provide co-benefits such as soil improvement and reduced nitrogen load. This would require significant cross-sector collaboration.

10.1.5 Other Feedstocks/Technologies

Looking at some of our other Tier Two/Three and Four technologies, a common observation is that while rLPG and biomethane could be produced from existing organic material streams the biogas outputs are generally not the primary product of the process. Instead, they are by-products of biodiesel, SAF or other energy products. It is not possible under the remit of this study to interpret how biogas products may become available as markets for liquid or solid biofuels/other bioproducts develop domestically, but this should be considered going forward as the development of parallel domestic bioenergy initiatives gain more certainty.

10.2 Timing of Availability

10.2.1 Emissions Budget 1 – Now to 2025

Between now and 2025, NZ’s first biomethane to grid exporting plant developed by Ecogas in Reporoa will become fully operational and make its first sales of low emissions gaseous fuel to the grid. This first cab off the ranks will be an extremely significant milestone for biogas supply developers and provide domestic proof of concept for similar plan developments in the future.

Beyond Ecogas' plant, the only other potential sources of biomethane to the grid that could be realised are developments accessing existing biogas sources and providing upgrading services only. This could consist of landfill gas or WWTP biogas upgrading and export projects, similar to how these projects have historically manifested overseas. There are no currently-announced projects of this nature in New Zealand, which means these projects are unlikely to be fully operational and be providing biomethane to the grid by 2025.

10.2.2 Emissions Budget 2 – 2025 to 2030

Between 2025 and 2030, we are likely to see the most significant development of Tier 1 biogas technologies, utilising accessible waste streams. This will be driven by organic waste diversion from landfill target from councils, and targets for landfill gas capture providing scale and investment into alternative organics processing capacity and improved landfill gas harvesting and utilisation.

Increases in the ETS price will also provide the driver for councils to consider WWTP biomethane capture and export to address both their Scope 1 processing emissions and generate additional revenue for their assets.

The total accessible biomethane resource to grid is likely to be in the order of 3-4PJ.

10.2.3 Emissions Budget 3 – 2030 to 2035

Beyond 2030 is when we could start to see more advanced biofuel reforming technology developed and operational in New Zealand, including biomass to syngas reforming leading to DME, rLPG or non-AD biomethane production. This would be supported by domestic production of other fuels like biodiesel or SAF.

Development of Tier 1 biogas technologies would continue again, driven by increases in the supply of natural gas. Post-2030, most councils will need to have committed to landfill alternatives for their organic waste streams and these would likely be supported by commercial/industrial organic waste streams as well. Depending on the prices reached by natural gas and any other support received from government level, energy or utility cropping may start to appear in locations adjacent to the natural gas network.

10.2.4 Beyond 2035

The continued development of green hydrogen production and technical advancement of direct-air capture CO_2 could open up additional technical pathways for natural gas generation after 2035. More likely is that green hydrogen will be used to supplement biomethane generation in existing AD facilities (bio-methanation) or it will be utilised in point-source CO_2 generation locations i.e. geothermal power plants, major industrial boiler systems to generate additional biomethane that is compatible with existing infrastructure and appliances.

10.3 Energy Pricing

As demonstrated in the pricing curve in Section 9, our case studies and analysis show that there are variable price points for biogas development between 0 and 7PJ of biogas supply, at which utilisation of existing organic waste streams and development of purpose-grown energy crop reaching price parity at around $65/GJ supply.

Between 1 and 7PJ of total supply per year, our analysis demonstrates that for each additional $10/GJ increase in biomethane sale price another petajoule of biogas energy is able to be supplied to the market. Beyond $65/GJ, the marginal cost of energy supply flattens considerably as the major opportunity becomes energy cropping which does not experience the same level of feedstock supply constraint as available organic wastes.

The prices demonstrated in our analysis are significantly higher that current natural gas prices and future anticipated natural gas prices assuming that the ETS price follows the same trajectory modelled by the

Climate Change Commission in their advice to government. Based on these prices, it is unlikely that biomethane would be able to be manufactured and supplied to energy users without the following:

- Alternatives to biogas supply being cost-prohibitive based on upfront capital i.e. the alternative being a swap-over to biomass heating or electric heating with significant upfront capital requirements for new boilers or energy supply infrastructure;
- A renewable gas certification scheme or direct government support for development and sale of renewable gases that provide a price premium for low emissions gas products.

Market research is required to determine what acceptable premium commercial/industrial or residential operators would be willing to pay to procure low-emissions gas fuel, either to meet their own emissions reductions targets or avoid asset replacement.

10.4 Key Future Opportunities/Risks

For successful development of biogas production facilities, achieving scale is an important way to ensure that the additional cost of grid connection and gas upgrading does not affect the financial benefits of the project. Co-location of facilities is an excellent way to make the most out of existing assets, either by multiple AD or biogas plants sharing an upgrading plant (i.e. food waste digestion next to landfill), or enabling multiple organic material streams to be utilised in the same facility (i.e. centralised digestion hubs for agricultural residues).

Much of our analysis has focused on the application of biogas technology in the North Island, given the presence of the natural gas network and location of majority of gas users. This is not to say that there will not be biogas available for use in the South Island supported by co-location of generators and users or for use as a transport fuel.

Compressing or liquefying biomethane for transport to North Island from South Island increases the overall fuel supply cost, and GHG emissions for transport, plus significant additional investment required for import and export facilities. For this reason, we have focused this assessment on NI-specific opportunities.

Beyond the 7PJ/year of biomethane able to be accessed from food/garden wastes, agricultural residues and crops present the largest tangible opportunity to improve and increase supply of biogas to gas users in New Zealand. Our analysis has discussed some of the factors that limit the viable portion of agricultural materials able to be accessed for bioenergy generation, but notably these are all reflective of current agricultural practices in New Zealand. The Ministry for the Environment's recent publication "He Waka Eke Noa" has outlined that there are significant changes expected in primary industries around New Zealand to enable a transition to net zero emissions. Among these recommendations are a number of objectives that will support the collection and use of residues and energy crops with high dry solids content in order to minimise feedstock collection costs, boost biomethane yields & optimise economic viability of large scale biomethane production. This will be essential in order to scale up a low emissions gaseous fuel industry that services more than 15-20% of existing natural gas demand.

11 Required Changes to Natural Gas Sector

11.1 Technical Limitations on Natural Gas Network

Utilising currently-available biogas upgrading technology, there are no technical barriers that would prevent the use of biomethane able to be produced from available residues entering existing natural gas assets. This being said, NZS5442:2208 (Specification for Reticulated Natural Gas) sets out requirements for upper oxygen content that does impose higher capital and operating costs for NZ developers of biogas upgrading facilities in comparison with other international specifications. A review of this standard and potential modification to oxygen limits, balancing the competing drivers for minimising corrosion and maintaining Wobbe Index, should be undertaken as it will have tangible impacts on the cost of bringing biomethane to market.

The key technical limitations or issues that will need to be considered to enable success of a biogas supply network relate to the operation of the grid in a distributed generator/distributed user model instead of a model where all of the gas input comes from gas fields located in Taranaki.

A distributed generation/use model would mean less gas movement between regions, with more gas production staying in the region it originated. For the majority of distribution networks in New Zealand, gas flow from local distribution networks does not commonly go in the reverse direction, but the majority of urban biogas installations would likely tap into medium pressure networks rather than high pressure networks. To help the system balance and facilitate flows between distribution networks, reverse compression stations would be required as gas moved from medium pressure to high pressure pipelines. This is a significant operational departure from the current gas network and would need to be considered carefully.

Gas storage facilities like Ahuroa could play an important role in flattening national supply and demand of biogas at lower annual gas volumes, and allowing the network respond to seasonal variations in both gas production (across agricultural seasons) and gas use (summer vs. winter).

11.2 Policy and Legislative Barriers

Analysis of overseas countries that have experienced the most rapid and transformative development of biomethane/other biofuels reveals that the most significant factor in development success are:

- legislated certification schemes, and
- associated support mechanisms for biomethane developments that recognise the multi-sectorial benefits of biofuels

Certification schemes that enable the valorisation and trading of renewable gas attributes are a fundamental requirement for current gas users that wish to switch over to biogas as part of their transition to low-emissions fuels. In line with international carbon accounting standards, without a mechanism for associated GHG emissions to be coupled with energy being supplied in a centralised grid, there is no way for companies that purchase biogas as users from producers to prove that their fuel is biological in origin, and no way to mandate that fossil gas users need to use an emissions factor that better represents the source of their energy pre-transmission/distribution system.

Voluntary schemes are useful in setting out the structure of accreditation systems and socialising the concept of tradeable energy credits but based on international guidance do not satisfy the requirements for additionality of science-based support mechanisms and should not be banked on by gas users looking to demonstrate alignment with zero-carbon trajectories.

Beyond energy, it is important that support mechanisms for biogas developments recognise the cross-sectoral benefits provided by biogas technologies, including:

- low carbon energy generation;
- development of circular organic material cycles;
- alignment with bioeconomy and circular economy principles;
- generation of low-emissions fertiliser products to support agriculture;
- generation of green CO_2 to support medical and food & beverage manufacturers;
- contributing towards waste emissions reductions.

To direct appropriate development of co-digestion organic waste processing opportunities and provide confidence in utilisation of biogas by-products, adoption of standards similar to the UK's PAS 110 allows for biosolids to be graded and certified based on their source and chemical compositions, which then allows them to be sold as an organic fertiliser supplement. In the absence of support for similar standards in New Zealand, it will be extremely difficult to differentiate this bio-digestate from biowaste and other biosolids as per existing legislative classifications, and therefore market and sell this valuable by-product from anaerobic digestion. It is necessary to provide market participants with guidance around when organic waste materials can be considered suitable for processing and re-application to land vs. requiring special treatment/disposal, backed by clear and well-tested standards backed by international experience.

To expand on a point from Section 10, guidance from the Ministry for the Environment on the role of bioenergy technologies as part of New Zealand's transition to a circular economy/robust bioeconomy is still largely in development as per the recommendations from the recent Emissions Reduction Plan. This generates some uncertainty for local authorities to manage until these final strategies are published in 2024 which will delay commitment to landfill alternatives for organic materials. The target of a 30% reduction by 2030 should be kept as a minimum, but more firm guidance on the role of AD, gasification and other "waste-to-energy" technologies for organic wastes would help firm up investor/develop confidence in these technologies and promote early adoption.

11.3 Wider Sector Opportunities

With future biogas capacity able to scale up well beyond the projected natural gas use in 2040 by the use of dedicated energy cropping and digestion, thought could be given to the possibility of using biomethane and storage in existing assets like the Ahuora gas storage facility to provide dry year resilience to the electricity system, in addition to supply residual direct gas users. As discussed in Section 10, there are a number of factors pertaining to dedicated energy cropping/biogas generation that will need to be resolved prior to development. However, the inherent scalability of these cropping operations and existing infrastructure that support long term gas storage do provide some unique advantages.

11.4 Other Barriers to Implementation

Beyond general technical and policy barriers, barriers to implementation include procurement and planning constraints, geographic barriers, and feedstock challenges.

As AD and biogas upgrading are technically mature, and available at commercial scale world-wide, the development of technology is not considered a barrier for implementation. However, as these systems are designed and built overseas, availability of supply to New Zealand and timeframes for procurement are dependent on overseas market pressures, and subject to the demand for similar equipment in other countries with their own ambitious biogas uptake targets. Installation of large-scale plants also requires planning and consenting which would introduce a barrier, especially regarding rapid uptake.

A key barrier is to implementation is the location of existing gas infrastructure and distribution of biomethane production potential. The natural gas grid is North Island specific, hence most of the natural gas users are also located in the North Island. However, total biomethane potential is not limited to the

North Island, and to maximise biomethane potential, AD plants would also be required in the South Island where existing reticulation of natural gas does not exist.

If gas is produced without proximity to the existing grid, it could be compressed or liquified for transport for injection to the grid at another location. However, this increases processing costs, associated emissions (for transport), and required extensive equipment at export and import locations to pressurise and de-pressurise the gas. Utilisation of gas locally by creating new reticulation and new gas users (converting users of other fuels, such as solid fuel boilers) in the South Island could be utilised, however this does not meet the aim of transitioning the existing natural gas network and consumers to renewable gases. The short-term focus therefore may need to be on installations in proximity to existing gas infrastructure, with wider transitions occurring at later timeframes.

The key barrier to implementation of AD is related to feedstock availability. This had both economic and public perception aspects. Further discussion of barriers for each specific feedstock is included in Section 4 and Section 10. A summary of key barriers include:

- **Diversion of crops or land availability for food production towards energy production.** Economic barriers include lost revenue to farmers for reduced yield of agricultural products. This may require economic incentives from government initiatives to overcome. Consideration of reduced production on national GDP, is required, especially for large-scale transition of land use. Additional barriers include public perception of diverting resources from food production. Consideration of maximising energy yields with minimum disruption to food supply is required. Public education is an important factor.
- **Diversion of resources which are otherwise utilised.** This includes gas already utilised on site for heat and electricity generation, and utilisation of manure on farms in agricultural settings, and utilisation of agricultural residues through farming practices (e.g. burning stubble for pest control, integrating organic matter back to soils etc). Consideration of digestate reuse pathways on farms in return for supply of organic waste feedstocks can create a circular economy for these resources. Utilisation of gas produced locally will require economic incentives to divert these resources from use onsite as this would change the energy balance, requiring import of energy to these sites and processes in many cases which incurs cost.
- **Collection of feedstocks.** For municipal feedstocks, such as food waste, this requires public education programmes to maximise uptake and minimise contaminants introduced to the feedstock. For agricultural feedstocks, an additional barrier for manure collection is the highly pastural farming practices in New Zealand. Manure from dairy milking shed can be collected, but to do so the manure is significantly diluted. This increases transport costs and emissions based on volumes transported. Locality of feedstocks for collection may limit the amount that can be feasibly collected.
- **Seasonal Variability in Industrial Biogas production.** Biogas production from meat processing sites has seasonal variability, with more production during peak processing, and negligible production during plant shutdowns, compared to more consistent production from municipal sources. This will mean there is variable gas availability across the season. If gas supply can align with gas demand (e.g. providing gas to meat works) this barrier is avoided.
- **Seasonal availability of agricultural feedstocks** is also a barrier, however storage of feedstock for consistent feedstock availability could be implemented – such as creating silage from grass during harvest season to supplement during other periods of the year where feedstock availability is reduced.
- **Operational complexity of containerised plants.** Operational and technical complexity, as well as the introduction of new process risks (flammable materials etc.) may inhibit installations on sites that do not specialise in wastewater treatment of biogas, or handling of explosive/flammable materials – this is overcome by an operational model where a company owns and operates the upgrading plant which is located at the processing plants.

12 Conclusions

This analysis reviewed existing literature to provide answers regarding a number of key questions around the use of biogas fuels moving towards a zero-carbon economy, and what role biogas may play in the future of the natural gas network.

Current and future sources of biogas and other renewable gaseous fuels in New Zealand

Today, New Zealand produces and captures around 4.9PJ worth of biogas in landfills, wastewater treatment plants, and industrial processes. Currently, a portion of this gas is flared as there is no productive application for it at its source, and the rest is used to generate low-grade heat and power.

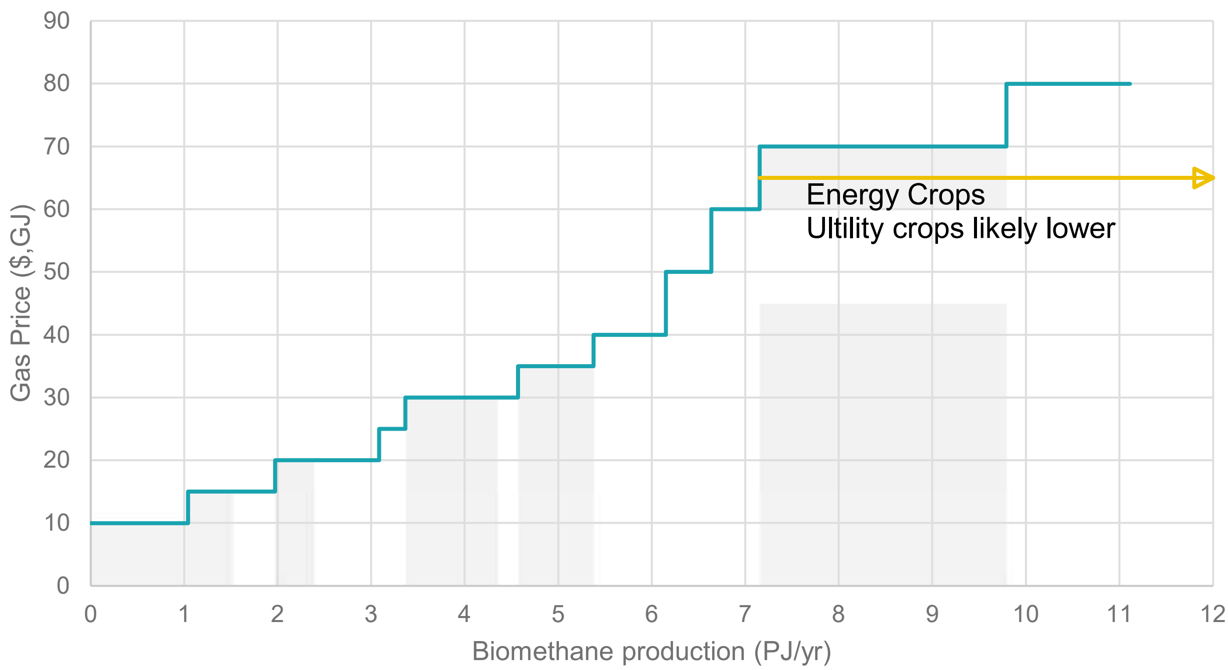
In this review of renewable gas technology and feedstock materials, a range of pathways towards low emissions fuels were reviewed. In Sections 4 through 7, available organic feedstock materials were matched with the best available processing pathway to produce biogas outputs.
Our report identified the following energy potentials exist within New Zealand, using existing technology:

- **Up to 24 PJ of biogas** from organic wastes and agricultural residues
- **Up to 63 PJ of syngas** from forestry residues, that could be converted into biogas or rLPG
- **Up to 4.5 PJ of biodiesel** from tallow
- **In excess of 40 PJ of biogas** from future energy or utility crops

However, there are significant challenges in accessing this energy, discussed more below.

Project Economics in a New Zealand Context

We analysed a range of potential renewable gas installations across New Zealand, using data from international examples applied in a New Zealand context (see Section 9 for more details on these case studies). This gave us the following estimates of achievable biomethane production costs, and how much biomethane would be available at different price points considering current domestic market settings:



Our analysis revealed that while some amounts of biogas from landfills, wastewater treatment plants and foodwaste digesters can be accessed, upgraded, and injected into the natural gas network at relatively low cost, the majority of the biogas potential identified is economically challenging to access given current market settings and geographical locations of key organic material sources (especially in the South Island).

The key competing demand for these feedstocks is the established practice of burning the biogas in combined heat and power (CHP) engines.

Competing Demand for Feedstocks and Other Market Barriers to Address

Organic wastes and agricultural residues are the simplest feedstocks to access for bioenergy production in the short term, although the feasible energy generation potential of these organic streams only represents around 7PJ of biogas. The key competing demand for these feedstocks is alternative waste management technologies, like composting, or no current demands exist because organic residues are viewed as being too hard to collect.

Forestry residues that could be converted into DME or biomethane via syngas will become increasingly hard to access as demand for solid biofuels increases. Forestry residues are a key enabler for the transition away from coal for heat and power generation, and it is likely that this incumbent demand will develop faster and deliver better results than using biomass for biogas generation.

Tallow and other bio-oil/fat waste is not likely to be a major contributor towards gaseous biofuel; it is much more likely to be used for the production of biodiesel (with rLPG being a small by-product stream).

Purpose-grown energy crops, which could enable the production of much higher quantities of biogas above available waste/residue streams, will compete with other agricultural operations for productive grassland, especially meat and dairy production. This is a significant challenge for the uptake of energy cropping, although the recent He Waka Eke Noa has recommended that to reach net zero portions of productive agricultural lands will need to be transitioned away from these industries. Alternatively, it may be more acceptable to use energy crops as a utility crop, in combination with agricultural use to provide co-benefits such as soil improvement and reduced nitrogen load. This would require significant cross-sector collaboration.

Emissions Intensity of Biogas Fuels Compared to Incumbent Fossil Gases

Analysing the process of biomethane production distribution and use for organic materials across a range of sources, the emissions released from the production, transportation and use of biomethane is on average **17 $kgCO_2e/GJ$**, a **70% reduction** when compared to an equivalent fossil gas (57 $kgCO_2e/GJ$ including use and transmission). The key contributor to the emissions from biomethane is methane that escapes from the generation of biogas and the conversion of biogas to biomethane.

For biomethane and other biofuels produced from waste streams to landfill and other process where the waste degrades naturally to produce biogenic methane, utilisation of this organic waste to produce renewable fuels represents a significant net emissions reduction i.e. the net emissions impact compared to business as usual is **negative**. Whole of lifecycle fuel emissions will vary on a case to case basis and should be considered holistically.

Barriers to bringing biogas to the natural gas network today

For many potential producers of biogas, reaching scale to support biomethane upgrading will be a key challenge. Communities or partners collaborating on either a central bioenergy plant, or separate bioenergy plants with a common upgrading/injection point will help enable more operators to come to market.

In terms of uptake speed, some of the most pressing barriers for developers and operators are:

- Feedstock supply security, and security of by-product specifications: securing consistent quantity and quality of feedstock is vital to the success of a bioenergy production plant.
- Seasonal variability in production + demand: this can be managed by processing organic materials for storage (i.e. silage generation from grass), or by utilising existing gas storage assets to smooth out peaks in production and demand.

- Access to equipment and technical capability: as many countries internationally are rapidly accelerating their bioenergy generation capacity to achieve energy security and meet emissions targets, New Zealand developers will need to compete with international supply challenges to complete their own projects. Additionally, technical capability will need to be developed and accessed domestically to support implementation of distributed bioenergy generation.

Analysis of overseas countries that have experienced the most rapid and transformative development of biomethane/other biofuels reveals that:

- legislated certification schemes, and
- associated support mechanisms for biomethane developments that recognise the multi-sectorial benefits of biofuels

are the most significant factor in development success. These programmes provide confidence to investors and signal that investment in these technologies is sustainable/supported by regulators.

Beyond energy, it is important that support mechanisms for biogas developments recognise the cross-sectoral benefits provided by biogas technologies, including:

- low carbon energy generation;
- development of circular organic material cycles;
- alignment with bioeconomy and circular economy principles;
- generation of low-emissions fertiliser products to support agriculture;
- generation of green CO_2 to support medical and food & beverage manufacturers;
- contributing towards waste emissions reductions.

How Transmission/Distribution Networks will have to change to accommodate biogas

Moving towards a natural gas network where a significant portion of the gas comes from distributed biogas plants requires careful redesign of way users, generators and retailers interact.

A distributed generation/use model would mean less gas movement between regions, with more gas production staying in the region it originated. For the majority of distribution networks in New Zealand, gas flow from local distribution networks does not commonly go in the reverse direction, but the majority of urban biogas installations would likely tap into medium pressure networks rather than high pressure networks.

Gas storage facilities like Ahuroa could play an important role in flattening national supply and demand of biogas at lower annual gas volumes, and allowing the network respond to seasonal variations in both gas production (across agricultural seasons) and gas use (summer vs. winter).

A review of Standard NZS5442:2208 (Specification for Reticulated Natural Gas) and potential modification to oxygen limits, balancing the competing drivers for minimising corrosion and maintaining Wobbe Index, should be undertaken as it will have tangible impacts on the cost of bringing biomethane to market. This will ensure the gas network and regulators are fit for purpose to handle biogas production and transmission in line with examples set by other countries with more developed biogas supply networks.

The opportunities for biogas and biomethane to contribute to NZ's low emissions future are significant however there are a number of principally policy barriers that will need to be resolved for this to be realised.

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A

Appendix A Feedstock Descriptions

Feedstocks from Municipal Sector

Municipal Wastewater

The majority of New Zealand is serviced by centralised wastewater treatment plants (WWTPs), with the remaining portion on local systems including septic tanks. Based on WaterNZ data, the total amount of wastewater treated annually is approximately 450 million m³/year (WaterNZ, 2022). A survey conducted in 2019 of 23 WWTPs, each with a connected population of over 25,000 people, identified production of 300,000 wet tonnes (~54,000 tDS/year) biosolids per year (Tinholt, 2020). Most of the smaller WWTPs are pond-based systems and only dispose of solids infrequently, through pond desludging. A further assessment of plants with population >10,000 population equivalence (PE) estimated total biosolids 70,000 tDS/year (dry solids), with 48,000 tDS/year from main urban centers, seefigure below. (Offer, 2019).

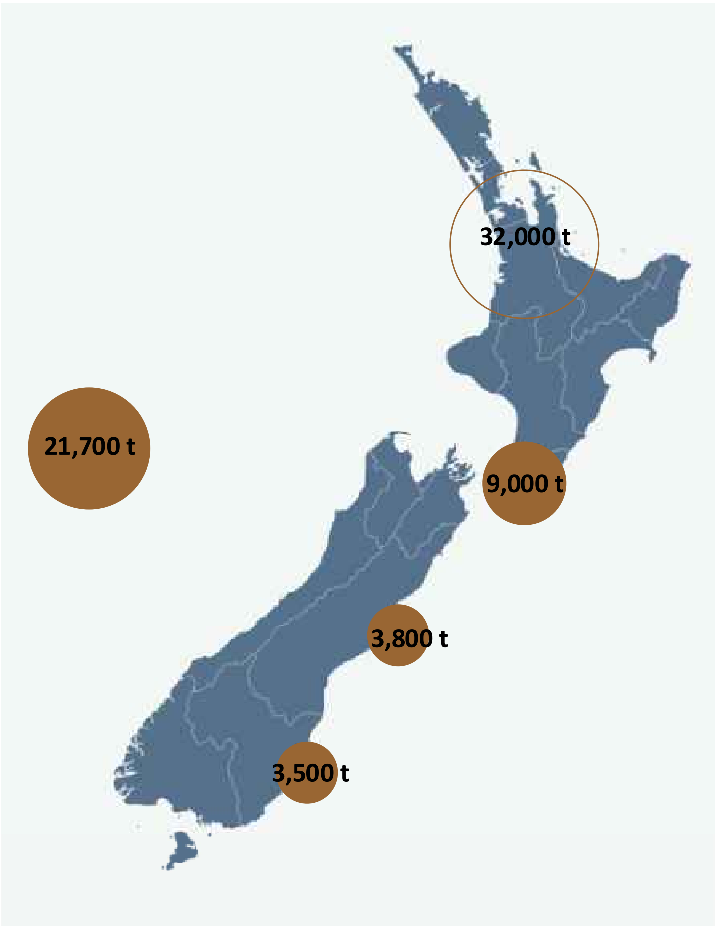


Figure 13-1: Distribution of Dry Biosolids from Municipal WWTPs (Offer, 2019)

Anaerobic digestion of municipal wastewater solids is an established practice in New Zealand's larger WWTPs where biogas is currently used for combined heat and power on-site or flared. A summary of the existing WWTPs in New Zealand with anaerobic digestion in place is shown in the following table.

Inventory of Municipal WWTPs in New Zealand Currently Practicing Anaerobic Digestion of Municipal Biosolids with Biogas Capture Amended to Include Total Potential (Internal Sources; Calibre, 2018; Beca, GHD & Boffa Miskell, 2020)

Council, Name	Proportion of NZ Population (2017)	Biogas Production (estimate) (PJ/year)
Christchurch City Council, Bromley	8.0%	0.2
Watercare, Rosedale WWTP (North Shore)	4.4%	0.1

Council, Name	Proportion of NZ Population (2017)	Biogas Production (estimate) (PJ/year)
Watercare, Māngere WWTP (Island Road)	26.9%	0.5
Hamilton City Council, Pukete WWTP	3.2%	0.1
DCC, Green Island	0.5%	0.2
DCC, Mosgiel	0.2%	
Horowhenua District Council, Levin WWTP	0.4%	
Invercargill City Council, Clifton WWTP	1.8%	
Palmerston North City Council, Totara Road WWTP	1.8%	
South Waikato District Council, Tokoroa WWTP	0.3%	
Taupo District Council, Taupo	0.5%	
Tauranga City Council, Chapel Street WWTP	1.7%	
Whangarei District Council, Whangarei WWTP	1.2%	
Manawatu District Council, Fielding WWTP	0.3%	
Total Existing Municipal AD	**53%**	**1.0**
Potential Additional AD *	32%	0.6
Total Municipal AD Potential**	**85%**	**1.6**

* Based on total population municipal wastewater excluding portion using pond systems (15% of population), excluding portion already utilizing AD (Beca, GHD, & Boffa Miskell, 2020)
** Scaled from population and existing biogas production

It should be noted that the theoretical maximum production of biogas is presented. It may not be economical for small WWTPs, especially in remote locations, to anaerobically digest their sludge for biogas production.

Sludge and digested biosolids can also provide syngas through gasification or pyrolysis, which can be used as a feedstock for production of rLPG through other processes discussed later in this report. The syngas yields for gasification and pyrolysis provided by Chang et al. (2022) are shown in the following table. Heating rates of sludge in pyrolysis shift the product composition. Slow heating rates favour char production, moderate heating rates favour liquid phase tar production, and high heating rates favour syngas production.

Both pyrolysis and gasification require the sludge to be dried, which has an energy demand. The syngas produced is typically consumed in the process for heating requirements. For pyrolysis, all required energy must be sourced externally as no combustion takes place. Note all gas volumes noted in this report are given in normalized at 0°C and 1 atm unless noted otherwise.

Table 13-1: Syngas Yields from Pyrolysis and Gasification of Sewage Sludge (Chang et al., 2022)

Technology	Syngas Yield	Syngas Composition (vol % - dry and no N_2)	Syngas LHV	Syngas Potential (PJ/year)
Pyrolysis (no oxygen, 400-800 °C)	0.21 kg/kg sludge TS (raw sludge) 0.14 kg/kg sludge TS (digested sludge)	21% CO 31% CO_2 24% H_2 12% CH_4	16.1 MJ/m³	0.2 PJ/year

Technology	Syngas Yield	Syngas Composition (vol % - dry and no N_2)	Syngas LHV	Syngas Potential (PJ/year)
		7% C_2-C_x		
Gasification (limited oxygen, 650-950 °C)	0.53 kg/kg sludge TS No strong correlation to VS content	19% CO 31% CO_2 35% H_2 9% CH_4 4% C_2-C_x	5.8 – 13.1 MJ/m³ (average 9.2 MJ/m³)	0.5 PJ/year

A key barrier to utilization of municipal wastewater AD is production of biosolids. The contaminants and public perception influence reuse options. Beneficial reuse of biosolids would be preferred, though there are limited appropriate uses for this as biosolid application to land used for food production is not readily accepted. Utilisation of biosolids on forestry land or similar should be considered for widespread biosolids disposal. The biosolids reuse regulations are due for review, with nutrient recovery a key topic. WWTP sludges are specifically excluded from digestate reuse for food production in the UK (PAS110, section 3.68) (BSI, 2014).

Post-Consumer Food Waste

Food waste represents 9% of total MSW sent to landfill. The food waste sent to landfill in 2020 was 334 kt/year (MFE, 2021a). This comprises of food waste from households, retail and other post-consumer sources, and pre-consumer sources (like supermarkets). Pre-consumer sources (estimated 18% of food sent to landfill), which will be discussed in Section 4.2.4 separately as the collection systems and barriers differ from post-consumer food waste.

New Zealand households waste an estimated 29 kg/person/year or 149 kt/year of food waste. A portion of food waste generated already is diverted from landfill (thus not included in the 334 kt/year reported above) via source separated collection, such as Christchurch's composting scheme (~10,000 t/year). More councils are introducing kerbside food waste collection recently, including but not limited to New Plymouth, Tauranga and Hamilton. Auckland's food waste is also now collected for digestion at Reporoa. The amount of food waste diverted from landfill is expected to increase in line with MfE's proposed strategy for a 30% reduction in CH_4 emissions from waste by 2030.

Food waste sent to landfill is converted to landfill gas (i.e. biogas), and many landfills capture this with some utilising it in combined heat and power (CHP) engines. Diversion of food waste from landfill will reduce landfill gas production. Landfill gas is discussed in Section 5.2.

The Ministry for the Environment (MfE) are working on updates to the New Zealand waste legislation and strategy. This is currently open for consultation, but currently includes the proposal for all urban populations to have kerbside food scraps collection (MfE 2, 2022). Based on this, there has been an increase in the number of councils around the country introducing kerbside food waste collection schemes.

Source separation of post-consumer (e.g. household and retail) food waste has advantages of less contamination, easier processing, and increased food waste diverted from landfill compared to separation of food waste from combined MSW. Even source separated food wastes still contain a level of non-organic materials, such as packaging, and public education programmes are critical in these systems as these programmes depend on residents to accomplish much of the separation. Alongside public education, another important defense against contamination are the waste collection drivers and teams. If they are well resourced and not time-poor, they will have the time to conduct a quick visual inspection of the top of bins prior to loading. The incidence of contaminated feedstock is thereby reduced. Contamination could also be obscured from view in the bins, withholding collection services from addresses or whole streets is considered when the contamination is intentional or reoccurring.

If all the household food waste produced (including that already diverted) is anaerobically digested, this represents 0.6 PJ/year of biogas potential. If the total post-consumer food waste sent to landfill (excluding diverted food waste) is considered, this represents 1.2 PJ/year. This 1.2 PJ/year represents organic waste that is not otherwise utilised for a beneficial reuse pathway.

The solid product (digestate) provides a high-quality fertiliser product which could be marketed for horticultural and agricultural use. There remains the need for contraries removal and disinfection. There are no regulations or guidelines for digestate from food waste in New Zealand currently. The current composting guidelines provide some guidance on the level of treatment that would be required for such a product. However New Zealand's first food waste digestion project in Reporoa is currently establishing a digestate market by adopting UK voluntary standard PAS110. .

The Ecogas anaerobic digestion facility at Reporoa can take 75,000 tonnes organic waste from businesses and kerbside food scrap collections throughout the North Island (Scion, 2020). The plant can take food waste from kerbside collections, food processing in meat, dairy and horticulture industries, as well as restaurant waste and cool store rejects (Piddock, 2022). This plant is the first organic waste digestion facility in New Zealand.

Municipal Solid Waste (MSW)

a. Renewable Gas Production

New Zealand sent approximately 3,540 kt of waste to landfill in 2021 (MFE,2021). Of this, 15% (530 kt) was organic waste (including green (5.7%) and food waste (9.0%)).

Some urban centers, including Christchurch have long-standing source segregated organic waste (food waste and/or green waste bins) programmes with a move towards more council kerbside organics collections and organics recovery facilities (MFE, 2022). The composition of MSW in Christchurch, that has an organic waste collection service, as recorded by Christchurch City Council (CCC) in 2018 had 9.7% compostable green waste and 0.05% food waste (CCC, 2022). This shows the food waste source separation is effective in reducing food waste disposed to landfill, with less effective for green waste. This remains as a recoverable resource. Source separated municipal waste (SSMW) provides an opportunity for utilisation of post-consumer food waste and green/garden wastes, discussed in Sections 4.1.2 and 4.1.4 respectively.

Combined municipal waste has a biological component which, in many cases, may not be feasible for recovery of the readily biodegradable portion at the landfill or transfer stations. However, in larger centres, screening of MSW prior to landfill can separate the organic portion to be utilised as a feedstock for anaerobic digestion. Both physical and chemical contaminants can have a negative impact on the reuse opportunities of the solid by-product (digestate), and their removal forms a large part of the expense for utilisation of the solids following digestion.

Any remaining organic not able to be separated prior to landfilling provides a feedstock for landfill gas production. It is important to note the separation and diversion of organics from landfill will reduce the landfill gas production over time. To reduce overestimation of gas potential through double-counting the contribution of organic portion of MSW, landfill gas has not been included in this analysis. Separation and controlled anaerobic digestion of this organic waste produces higher-quality gas with a greater methane content and less inerts which affect calorific values, compared to landfill gas.

b. Waste-to-Energy

Additionally, municipal waste has a big energy component that is not readily biodegradable but provides feedstock for pyrolysis or gasification plants which would produce a gas source. MSW gasification yield varies significantly based on process conditions and feedstock composition. Research conducted provided a large variety in results. Yield from various sources is summarised in the table below. Further investigation into product composition and yield for various process conditions and feedstock composition is required to confirm the feasibility of utilising this feedstock.

Syngas Yield from Gasification of MSW

Source	Yield	LHV
Gu et al. (2020)	0.3 m³/kg	10.98 kJ/L
Saleh et al. (2020)	2.53-2.57 m³/kg (single-stage and multi-stage respectively)	3.7 – 4.1 kJ/kg
Zhao et al. (2021)	Typically 1.2 – 2.2 m³/kg for single stage 0.7 m³/kg for 2 stage	-

Advanced plastic recycling produces an off-gas in the light fraction range of LPG. Hence, separated plastic waste also provides a feedstock with potential to produce LPG. 8.3% of MSW sent to landfill in 2020 was plastic, representing 308,000 t/year of plastic not currently being recycled (MFE, 2021). Amount of plastics already being recycled or collected for recycling are not readily available.

Garden and Green Waste

Green waste represents 5.7% of total MSW sent to landfill. The green waste sent to landfill in 2020 was 213 kt/year (MFE,2021), representing 1.5 PJ/year biogas potential if all green waste was anaerobically digested. As with food waste, a source separation of household green waste will provide higher-quality feedstock, with less contamination compared to green waste extracted from combined MSW.

Overall, the solids produced are a valuable by-product with various market opportunities. Though it should be noted there are potential issues with herbicides in the feedstocks, and deactivation of seeds in the solids is required prior to reuse of the digestate. This may require drying or further processing of the digestate to achieve this. A blended feedstock of food and garden waste could provide a valuable by-product in the digested solids, which could have a market for sale in suburban settings.

Utilisation of this feedstock for digestion competes with the existing composting facilities, though the volumes presented may not capture this (as the values provided represent the portion sent to landfill). Diversion of green waste and food waste from composting facilities would require marketing input. If these feedstocks are kept separate, and not co-digested with municipal wastewater, the resultant digestate could replace the existing composting market as a valuable soil enhancer and compost product.

Total volumes of food and green waste diverted to existing composting facilities are not fully known. This represents a feedstock that is not accounted in the MSW portions reported as it is already diverted from landfill. There are 12 commercial composting facilities in New Zealand (Nature Pac, 2020). One provider with two facilities, Living Earth, receives approximately 50,000 t/year of food and garden waste from source separation in Christchurch, and a further 50,000 t/year in Auckland (Living Earth, 2022).

Diversion of organic wastes from composting to other processes, such as anaerobic digestion, allows energy generation, and the digestate solids still provide a valuable soil enhancer. This can be used directly, or then returned to the composting facility for further processing. This is a barrier for co-digestion of municipal biosolids with organics as it inhibits the end use of the post-digestion solids stream.

Feedstocks from Industrial Sector

General

The industrial sector provides good opportunity for anaerobic digestion of wastewater produced due to the higher strength waste produced. This is especially applicable for producers of large volumes of wastewater

with high biological loadings, such as meat processing plants, dairy processing factories, pulp and paper sites, distilleries, and breweries. Currently most wastewater treatment is aerobic, and the few treatment plants using hydraulic or pond anaerobic treatment systems do not all have gas capture systems for biogas reuse, with biogas often being flared (Beca et al., 2021). Only 8 industrial WWTPs flare or utilise captured biogas, leaving a significant untapped resource, estimated in the Beca Biogas report as 2.4 to 3.2 PJ/year (Beca et al., 2021).
Pulp and paper wastewater has a lower COD concentration and subsequently low biogas yield potential, hence has not been considered further. Furthermore, the pre-treatment of pulp and paper wastewater may be required due to nutrient deficiency, lignocellulosic material and sulfur containing substances which can result in slower degradation (Beca et al., 2021).

Beca noted that additional by-products from industrial processes, such as trade waste, spent grain and yeast from distilleries and breweries, grease from grease traps, and paunch grass from slaughterhouses, are unlikely to have quantities that warrant specific AD plants, but can provide increased feedstock to other AD plants to boost biogas production (Beca et al., 2021). This biogas potential has not been quantified in this report. Industrial wastewater from smaller industrial sites is often sent to municipal WWTPs, hence has been included in the feedstocks in Section 4.1.1.

Dairy Wastewater

Beca et al. (2021) and Worley (2021) outline the biogas potential from industrial wastewater. These reports both estimate approximately 60,000,000 m^3/year of wastewater (from Fonterra only), providing a biogas potential of 1.1 – 1.9 PJ/year (Beca et al., 2021). Fonterra currently operates anaerobic digestion at its Darfield plant but has recently decommissioned its anaerobic pond at its Tirau plant. During operation (assumed 46 weeks/yr allowing for annual plant shutdown and seasonal operation) Darfield currently produces 13,000 m^3/d biogas which equates to 0.05 PJ/year, and flares this as the driver for digestion is waste minimisation and management.

Meat Processing Wastewater

Meat processing plants produce approximately 20,000,000 m^3/year of wastewater (Beca et al., 2021; Worley, 2021). Beca report the COD of raw wastewater from meat processing plants is estimated to be 3600 g/m^3, hence could yield 0.7 PJ/year biogas if all wastewater was anaerobically digested.
Meat processing plants are distributed across the country, as shown in the map on the following page (Beef + Lamb New Zealand, 2019).

Figure 13-2: Meat Processing Plants in New Zealand (Beef + Lamb New Zealand, 2019)

Pre-Consumer Food Waste

Pre-consumer food waste considers food wasted prior to it having reached consumers, within control of the foodservice operator. The focus feedstock discussed here is food wasted from supermarkets, though there may be other streams of pre-consumer food waste from other suppliers. Non-supermarket food waste sent to landfill will be considered in Section 4.1.2 above. Any diversion of this food waste (e.g., to community groups or animal feed) represents an additional resource that has not been quantified here. The Waste Minimisation Institute of New Zealand (WasteMINZ) reported on supermarket food waste, based on an audit completed by Goodman-Smith (2017) (WasteMINZ, 2018). The study found food was donated to food rescue (various community groups for human consumption), sent for stock food (especially to piggeries). A total of 60,500 tonnes of food waste and diversion per annum (approximately 160 tonnes per store per annum, or 13 kg/person/year). A summary of current destinations of food waste is shown in the table below.

The Mean Distribution (%) of Retail Food Waste and Diverted Product to Each Destination (Goodman-Smith, 2017).

Destination	Mean Distribution (%)
Animal feed	37%
Landfill	25%
Food Donation	18%
Protein Reprocessing	12%
Compost	8%

Therefore, the landfill portion (15,100 t/year) would be accounted in the total municipal waste volumes reported, but the animal feed etc represents another resource, though a barrier to this would be displacing this stock food. The public acceptance of utilising the portion of this feedstock which currently being donated for human consumption for energy production may be a barrier. A solution to this barrier would be to continue to satisfy food donations, while diverting the balance to composting and AD. The biogas potential if the landfill portion, total excluding portion donated for human consumption, and the total food wasted and diverted was anaerobically digested is shown in the table below. This distribution is likely to change over time as diets and preferences change to more plant-based diets (resulting in less demand for animal fodder as meat consumption reduces).

The existing diversion schemes for supermarket food waste implies systems for collecting food waste would not be difficult to implement. Waste minimisation drivers in supermarkets such as Countdown's "odd-bunch" produce, and reduced bakery over supply are showing to reduce food waste from supermarkets. It is expected the food waste would reduce over time as waste minimisation practices are improved. However, there will always remain a portion of food that must be wasted, though the amount of this is uncertain.

Pre-consumer food waste would require processing to remove packaging and other contaminants prior to anaerobic digestion. The resultant solids stream would provide a high-quality soil enhancer.

Biogas Potential from Pre-consumer Food Waste Volumes Reported in Goodman-Smith (2017)

Feedstock Description	Feedstock Quantity (t/year) (% of total)	Biogas Potential (PJ/year)
Landfill portion of food waste produced	15,100 (25%)	0.06
Total produced excluding portion donated for human consumption	49,600 (82%)	0.2
Total food waste produced	60,500 (100%)	0.3

Horticultural Wastes

Horticultural wastes consider residues from food harvesting, packaging and processing operations. These residues (including green waste such as tree cuttings, damaged produce etc) are often used for stock feed or composted. Hall and Gifford (2007) reported 113,000 tonnes (dry weight) of fruit and vegetable residues per year were produced from various fruit and vegetable crops. Of this, 58% was in the North Island and 42% in the South Island. Of the total fruit and vegetable residues in 2007, Hawkes Bay had 28%, Gisborne had 12%, Central North Island had 11%, Canterbury had 18%, and Nelson/Marlborough had 16%. The distribution is likely to have shifted slightly since 2007 based on the increase and decrease in various fruit and vegetable production, but it is important to note significant feedstock resources distributed around the country.

The current production has been adjusting this for the increase in production of the various fruits and vegetables since 2007, summarised in the table below. An estimated 212,600 tonnes of horticultural residues was produced in 2021, having a biogas potential of 1.5 PJ/year assuming all feedstock is anaerobically digested.
A comparison between exported values ($/year) has been made to scale total production. The 2007 export value was adjusted for inflation to provide an approximate comparison for export amounts. Comparison has been made on total fruit and vegetable exports, as data on individual fruits and vegetables provided in Hall & Gifford (2007) was not available for 2021.

Scaled Production of Horticultural Wastes for Total Fruits and Vegetables (Hall & Gifford, 2007; HortResearch, 2007; 2021)

Parameter	Units	2007	2007 (inflation adjusted)	2021
Total Horticultural Export	NZ$ million	$2679.4	$3554.2	$6684.7
Horticultural residues - current	t (dry weight)/yr	113,060		212,600

Feedstocks from Agricultural Sector

Agricultural Residues

The focus in previous studies (Beca et al., 2021; Worley, 2021; Calibre, 2018) regarding agricultural feedstocks has been predominantly crop remnants left in the field following harvesting (e.g. grain stubble, and crop wastes) and animal manure. The reasoning behind this, cited in the Beca report (Beca et al, 2021) was the low likelihood of energy cropping, i.e. planting crops for energy production, to come into effect in New Zealand. Reasons for this include public perception of diverting food products for energy, and conversion of productive food-producing land to other crops. Crop remnants represent a feed stock and providing some biogas potential (reported 1.4 to 2.9 PJ/year if 30 to 60% of crop residue in Canterbury is anaerobically digested (Beca et al., 2021).

Significantly greater crop utilization for feedstock is required to approach New Zealand's current gas demand. There are additional supplementary crops that fit within existing agricultural processes, and utilisation of land that is not currently utilised for food production, which is discussed below.

Grasses

Grasslands is a significant carbon sink as well as a feedstock for renewable energy generation. Grasslands have additional benefits of long persistency of high dry matter yield, intercropping potential with legumes and subsequent reduction in fertiliser application rates, protection of soil from erosion, and groundwater formation (Ecotricity, 2022).

New Zealand has 19 million ha of exotic grassland, of which 8.3 million ha is high producing grassland, 1.75 million ha is low producing grassland, and 0.15 million ha is depleted grassland (StatsNZ 1, 2021). This is a considerable resource if grass is to be cut and fed into an anaerobic digester. Ecotricity produced a report on the potential of grass-fed digesters to provide a green source of gas in the UK (Ecotricity, 2022). Ecotricity's research partners estimate their grass mill systems can yield around 160 GJ/ha/year, harvesting species rich herbal leys (mixture of diverse plant species). However, the yield from grasses that could be grown in New Zealand is lower at approximately 90 GJ/ha/year (Thomas, Wallace & Beare, 2014).

High producing grassland is defined by Land Air Water Aotearoa (LAWA) as grassland of "good pastoral quality and vigour reflecting relatively high soil fertility and intensive grazing management" typically used for animal grazing, with the majority spread across the country with 15% in Canterbury, 14% in Manawatu – Whanganui, 10% in Otago, 10% in Southland, and 15% in Waikato. Re-purposing this land for growth of grasses for energy production would compete with existing food production hence has not been considered further.

Low producing grassland is defined by LAWA as “grassland of poor pastural quality reflecting lower soil fertility and extensive grazing management or non-agricultural use”. The lower productivity of this land suggests it could be utilised as a resource for grass growth for digestion, however, there is uncertainty around the feasibility of grass growth in these areas without intensive intervention (e.g. irrigation, or major soil improvements). There is a total of 1.75 million ha across the country, with significant portions in Canterbury and Otago, with 0.62 million ha (35%) in each region (StatsNZ 1, 2021).
Depleted grassland is defined by LAWA as “areas, of mainly former short tussock grassland in the drier eastern South Island, degraded by over-grazing, fire, rabbits and weed invasion … bare ground is more prominent.” It is uncertain if this land could be rehabilitated to provide a grass feedstock. However, if grass growth were feasible, this represents a good potential feedstock with 0.15 million ha across the country, 14% (0.2 million ha) in Canterbury (StatsNZ 1, 2021).

Readily improvable grasslands have likely already been converted to improve yields, hence no longer included in “depleted grasslands” land coverage. This can be seen by the influx of irrigation on the Canterbury plains. Remaining depleted grassland is likely to be in hill country or steep areas, making growth, harvest and collection difficult. Therefore, a portion of highly productive or low producing grassland should be targeted for grass crop growth for digestion. Conversion to silage would provide more stable feedstock compared to freshly harvested grass due to seasonal variations in growth. Dry matter yield is in the order of 19 tDM/ha/year for dairy farming pasture types (Thomas, Wallace & Beare, 2014).

Based on this yield, 21% of the nation’s highly productive grassland would be required for digestion. However, as the natural gas grid is located in the North Island, a North Island focus would be more appropriate. 70% of the highly productive grassland in Waikato and Manawatu regions would be required for digestion. This creates obvious barriers to uptake and would not be a short transition. Extensive government support would be required, with economic incentives for farmers to divert grassland from grazing. Additionally, impacts on national GDP would need to be considered, as this widespread change would significantly impact national yields of dairy product and meat product exports, which make up a significant portion of the New Zealand’s total exports and GDP.

A key barrier for this feedstock is the displacement of feed for stock or potential grazing land.
A significant change in the driver for grass growth, from animal feed to energy crops, would be required. This would require government incentives to make this economic for farmers. However, additional to the economic barrier is the public perception of diverting resources from food production to energy production. Based on average operating profit for dairy farmland, the cost of the grass is $33/GJ. This is a feedstock only cost, and the processing costs would also need to be considered to determine a $/GJ value for biogas production.

Supplementary Crops

Supplementary crops, or crops planted for the primary purpose of improving soil properties or resting land between productive crop harvests, represent a feedstock for anaerobic digestion (e.g. legumes planted for soil enhancement). These crops which form part of normal farming practice but are not intended for sale and consumption, but rather would be wasted on site, do not divert crops from food sources. Sequential cropping is the cultivation of a second crop before or after harvest of the main food or feed crop on the same agricultural land during an otherwise fallow period, not triggering additional demand for land. This sequential cropping does not impact existing food or feed markets as no existing food is utilised as a feedstock (Guidehouse, 2022). Sequential cropping provides key feedstock potential that feeds into the EU-27 biomethane production targets.

Standard agricultural cropping practice utilises crop rotation to ensure disease resilience and appropriate nutrient levels in soils. Rotation length depends on crop type, but can be in the order of 5 years, meaning that 1/5th of farmland is planted in the target crop at any one time. Target crop is followed by a different crop type to break disease cycles, and often includes maize or similar crop. Prior to re-planting in target crop, land is often planted in short-rotation grassland. This grass is often harvested and sold as hay or silage for stock feed. This represents a resource that could be utilised as a feedstock for digestion, fitting with current farming practices. This would minimize the impacts on the food production pathways, though it would be diverting grass utilised for animal feed.

New Zealand has 381,000 ha of short-rotation crop land, with 65% of this in Canterbury. If 1/5th of the short rotation crop land (as opposed to long-rotation land such as orchards and vineyards) in New Zealand was planted in grass at any one time (on a rotational basis), this represents 76,000 ha (6.7 PJ/year). There is some uncertainty in this estimate based on the productivity and yield from crop land compared to typical grassland. Consideration of higher yield crops could also boost the biogas potential.

Another type of crop would be a crop planted at the end of the harvest of a regular crop but is not expected to mature, it will just be put into silage. These types of crops need not be monocultures, in fact there may be benefits if they are mixed crops. Crop waste not recovered after harvesting and wasted, which may include this supplementary crop, is estimated by Worley (2021) as 500,000 t/year but is likely considered in the agricultural residues section (4.3.1), hence has not been accounted for here.
Barriers to this feedstock include required adoption of different crop farming practices not common in New Zealand, diversion of stock feed from secondary crops intended for silage etc. When implemented in a sustainable way with digestate being returned to the land as an organic fertiliser, sequential cropping can bring additional benefits for farmers such as reduced erosion as the land is not left fallow, as well as soil quality and biodiversity benefits (Guidehouse, 2022). Education programmes and incentives for the agricultural industry to uptake sequential cropping would be enablers to cultivation of these feedstocks.

Some land is not suitable for production of food crops or grazing for animals due to higher risk for or actual levels of contaminants. Examples of this include mine rehabilitation land, caps on landfills etc. There is 16,100 ha of defined as surface mine or dump, or “bare surfaces arising from open-cast and other surface mining activities, quarries, gravel-pits and areas of solid waste disposal such as refuse dumps, clean-fill dumps and active reclamation sites” (StatsNZ 1, 2021; LAWA, 2021). Of this, 2,500 ha (16%) is in Otago, 3,000 ha (19%) is in Waikato, and 3,400 ha (21%) is on the West Coast. Plantation of crops with shallower roots (e.g. lucerne grass) reduces risks of contaminant uptake into the crop, and subsequent dispersal of this contaminant through the digestate. If grass was to be planted on all landfill and mine surfaces, this represents 1.4 PJ/year.

This land presents the opportunity for production of crops as a feedstock for anaerobic digestion. This energy crop activity is not displacing land otherwise used for food production and does not redirect food crops suitable for human consumption therefore removes some of the barriers present for energy crops on other land sources. The land available for cropping would increase as various mines stop production and require rehabilitation, though the timescale of this production shift has not been considered in detail in this report.

An additional concept is to digest unfavourable crops that currently render the land unusable. One example is alligator weed, an amphibious plant, meaning it grows in water and on land in wet soils. Alligator weed is very hardy and out-competes other species. It is highly tolerant of a wide range of environmental conditions and disturbances such as flooding and submergence (Northland Regional Council, n.d.). This plant is toxic to mammals. It is a pest plant in Northland. This could provide opportunity for digestion however, the plant propagates from stem sections, and further investigation into the inactivation through the digestion process would be required before consideration of its use as an AD feedstock. Biogas potential of this source uncertain due to unknown dry matter and digestibility of the plant matter, and total viable areas of harvest, regrowth rates, etc.

A summary of supplementary crop biogas potential is shown in the table below. This assumes grass growth on the areas identified. Higher yields may be feasible depending on crop planted. This would need more detailed analysis and location-specific information on the best crops to plant in particular locations, and their yields based on local soil and climatic conditions.

Estimated Supplementary Crop Land Areas and Biogas Potential

Land Type	Potential Land Area (ha)	Biogas Potential (PJ/year)
Short-rotation crop land	76,000	6.7
Rehabilitated land – Mines and landfills	16,000	1.4
Total	**92,000**	**8.1**

Energy Crops

Agricultural energy crops (e.g., grains, beets, grasses and oil seeds) provide higher biogas potential than agricultural wastes. Energy crops are common in other countries, with fermentation of grain crops and sugar beets for ethanol production being common in USA, Australia, Canada, France and Sweden (Hall & Gifford, 2007). More recently, energy crops for biogas production have been taking focus in the EU, with acknowledgement of sustainable farming practices and consideration of diverting resources from food production (Guidehouse, 2022). The potential contribution of this biomass to New Zealand's energy needs will depend on competing land-use options, demand for food crops, crop yields, biodiversity concerns and the needs for conserving soil and water (Hall & Gifford, 2007). Energy crops can provide feedstocks for biogas production via anaerobic digestion, but also oil crops can provide feedstocks for biodiesel production (refined to rLPG). Oil crops are discussed further in Section 4.5.2.

A barrier of energy crops is the negative perception of diverting food-producing land to produce energy crops. This has negative social implications, as well a financial factor. Land is only likely to switch to growing energy crops if the gross margin from bioenergy farming is greater than the gross margin than the gross margin of any other suitable land use and the labour and management inputs are not vastly different. The cost of energy produced from energy crops would need to consider the economic potential of that land if used for food production. Highly productive land would incur a greater cost.

Data on the economic potential of dairy farming land is readily available and varies across the country with a national average operating profit of $2,856/ha. Canterbury is the most profitable at $4153/ha operating profit in 2020/21 financial year, Taranaki $3084/ha, and Waikato $2729/ha (DairyNZ 1, 2021). Development of more intensive farming practices in Canterbury and the irrigation infrastructure have increased profit in this region over time.

Planting of energy crops should therefore be focused on land area that is low producing or otherwise unusable for food-production, such as rehabilitated mines, capped landfills etc as discussed in Section 4.3.3.

The yield and energy potential from energy crops has not been quantified in this report as energy crops represent a future feedstock that has too many barriers currently to be considered for mature technologies.

Future AD Feedstocks – Alternative Land Types for Crop Plantation and Harvest

c. Peatlands

Peatlands are areas of boggy soil, where organic matter builds up in an anaerobic environment due to the saturated soil conditions. Some of which are being farmed. However, farming practices, including draining

of the peat lands increases CO_2 emissions by speeding up decomposition of the organic matter stored in the peat. Current pastural farming practices require drainage of peat lands which leads to shrinkage of the peat. Once drained, peat can be difficult to re-wet, making rehabilitation difficult.
Reduction in farming of peat lands is gaining momentum, which may provide an opportunity to harvest a crop that has less impact on the peatlands. This represents potential land area for crop growth of 89,000 ha, with the majority in the Waikato (Meduna 2021).

This needs further research on timeframe of remediation of peatland, what crops would be feasible to enhance the peatland in New Zealand, considering native species, and provide a feedstock. Some wetland crops utilised overseas include:

- Reed canary grass
- Common reed
- Sedges
- Cattail/bulrush
- Alder
- Willow
- Peat mosses

This is something to consider in the long-term future for New Zealand. However, internationally, wetland agriculture (paludiculture) describes the productive use of wet and rewetted peatlands closer to their natural permanently wet state. Paludiculture harvests the above ground biomass while below ground biomass remains for peat formation, conserving peat-forming conditions (Farm Carbon, n.d.).

d. Riparian Boundaries

Riparian lands are hard to quantify due to the extensive amount of stream and rivers in New Zealand. Also, the extent of riparian boundaries is dependent on orientation of the river/stream and required setbacks from the water depending on the activity. This includes riparian land in farms, which already is required to be planted under the Regional Plans to improve water quality and control run-off. This could be harvested as a feedstock for digestion, but further research is required on the quantity of this feedstock, and detrimental impacts of harvesting on the other benefits of riparian planting (such as bank stability and nutrient control).

e. Nitrogen Hotspots

Nitrogen hotspots are areas where nitrate levels are elevated due to intensive farming. Steps are being taken internationally to reduce nitrogen emissions, with Dutch government recently proposing a radical cut in livestock, with some farms needing to close, and others reducing livestock numbers.
The future of New Zealand farming is uncertain due to high nitrogen emissions and elevated nitrates in waterways and ground water. Therefore, a shift in farming intensity may be required in the future. However, a reduction in dairy farming would likely see increase in other farming, such as crops, as the land is highly productive. Plant based protein production is more efficient per hectare and therefore opening up productive land for other uses such as energy.
Utilising nitrogen hotspots for farming energy crops is likely to still have the barriers that converting farmland has, including high feedstock cost to incentivise farmers to plant energy crops over other types, and diverting food for energy.

Animal Manure

As a highly agricultural country, New Zealand produces a significant amount of animal manure. This is mostly deposited onto grazed pastures which makes collection and utilisation of this feedstock more difficult and the full potential from this feedstock cannot be feasibly realised compared to overseas where

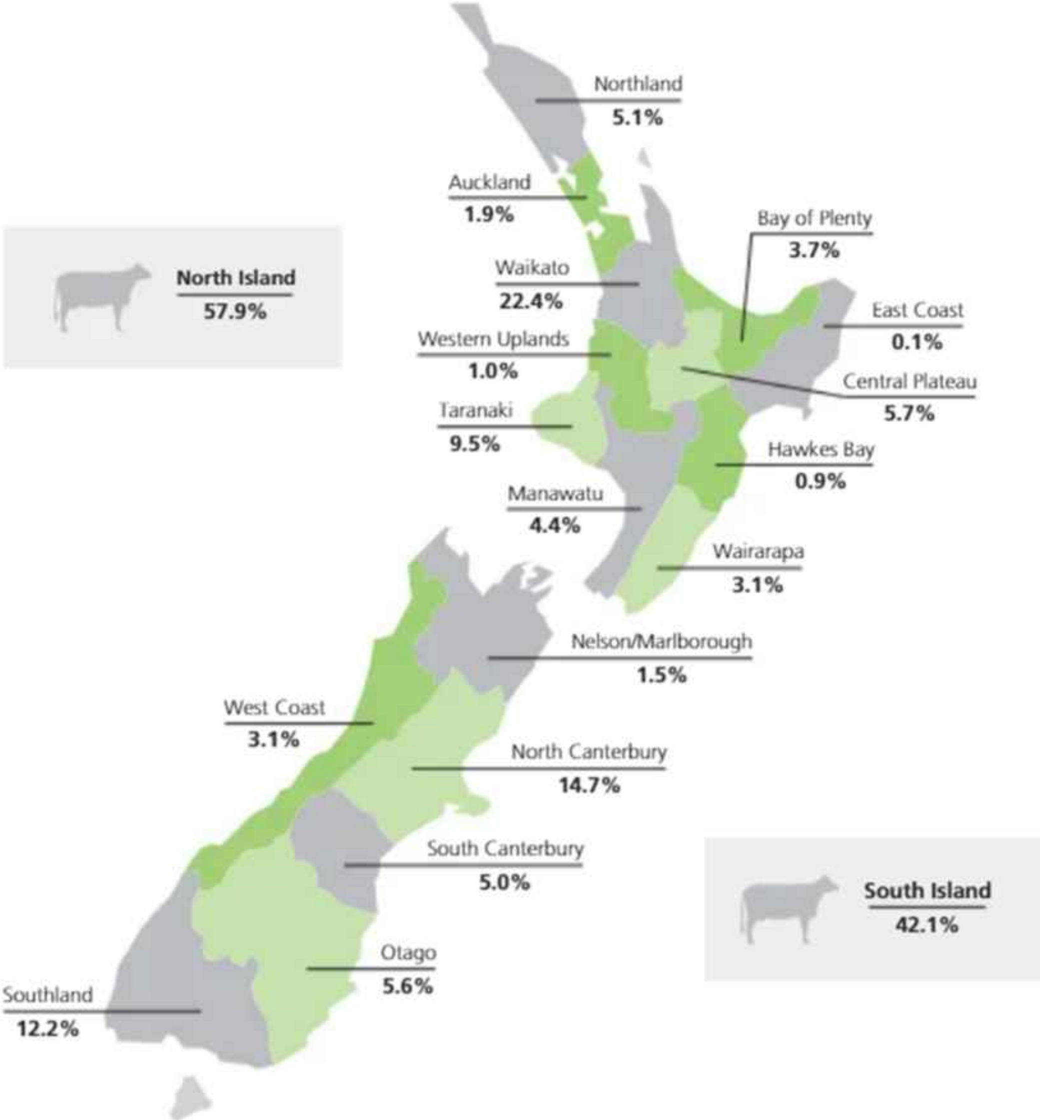
feedlot farming practices are more common. However, the impacts of current farming practices on nitrate levels and regulations to control this will develop which may drive changes in farming practices.
Beef and sheep livestock numbers are high, but the manure form these sources have been excluded as the feasible recovery portion is negligible based on the pastural agricultural practices commonly used. Dairy cattle are predominantly grazed on pasture, but there is an opportunity for manure recovery from the milking shed, which is estimated to be 10% of the total manure produced by dairy cattle (Ministry of Agriculture & Forestry, 2008). In New Zealand, pigs and poultry are mostly farmed in shelters or barns, which allows for a higher fraction of waste to be collected. Beca et al. (2021), estimated the manure recovery for dairy, pig and poultry manures with updated livestock numbers (DairyNZ, 2021; NZ Pork, 2020; FigureNZ, 2022) shown in the table below. Future changes to farming practices and increasing preferences for free-range may change the availability of pig and poultry manure in future.

Animal Manure Solids Potential by Livestock Type adapted from Beca et al. (2021).

Feedstock	Population	Manure (kg/day/head)	Manure Recovery	Total solids % of fresh	Total Solids (tDS/year)	Total Biogas Potential** (PJ/year)
Dairy Manure	4,904,000*	35	8.5%	25%	1,027,000	5.3
Pig Manure	621,000	3.3	91%	25%	170,000	0.9
Poultry Manure	23,694,000	0.1				
Total					1,379,000	7.5

* Population of milking cows (not total dairy cattle). It is assumed remaining non-milking dairy cattle (e.g. herd replacements not yet milking, and dry portion of total herds) remain on pasture
**Assumes all collectable manure is anaerobically digested

Distribution of dairy farms in 2020/21 is shown in the following figure. The majority of dairy herds (71.1%) are located in the North Island, with the greatest concentration in Waikato (LIC & DairyNZ, 2021). Poultry farms are clustered around urban centers, and distribution by region can be estimated by population. 66% of pigs are produced in the South Island, and 34% are produced in the North Island.



Regional Distribution of Dairy Cows (Percentage of Total Herd) in New Zealand (LIC & DairyNZ, 2021).

Note that there is uncertainty around easily accessible manure. It is likely that only a portion of the feasibly collectable manure would be able to be feasibly utilised as a feedstock due to location constraints, availability of other feedstocks for co-digestion within a reasonable distance. It may be more feasible to consider capture and utilisation of manure in high-density farming areas, such as Waikato and Taranaki, where a centralised digestion facility could be considered to take manure from many farms. Co-digestion of manure with other agricultural feedstocks would improve the biogas yield.

Small scale “micro-digesters” are becoming common in the UK for on-farm digestion of manure, with gas being utilised for on-farm heating or electricity requirements (AHDB, 2022). Studies suggest these are economically feasible for herds of 80 animals, but it should be noted farming practices in UK differ from New Zealand, with significantly less pastoral grazing, hence better manure recovery opportunities.

Feedstocks from Forestry Sector

Summary

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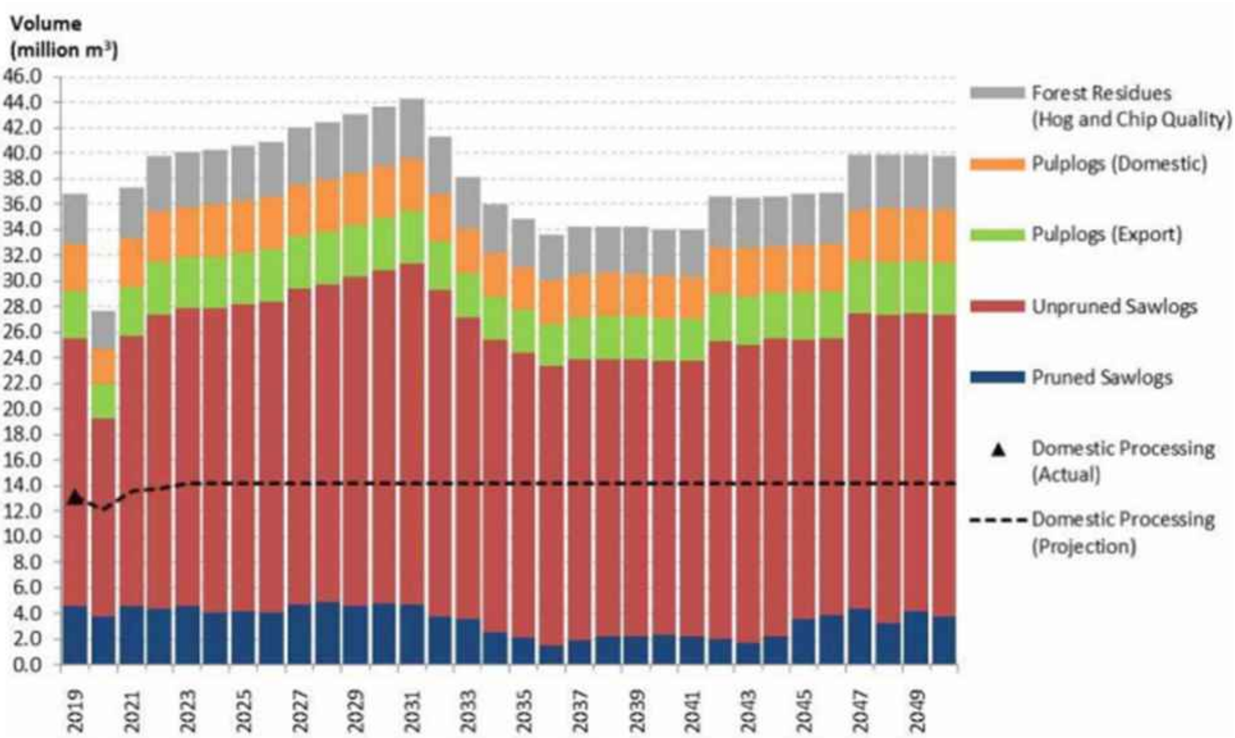
Woody biomass feedstocks are derived from New Zealand's existing forestry industry. Wood availability forecasts indicate a total harvest of 28,600,000 to 39,400,000 m³/year between 2021 to 2060 (with variations each year based on portions of total reaching maturity) (Scenario 3 in wood forecast) (MPI, 2021). The percentage of roundwood (i.e. pre-processed wood) by wood supply region (MPI, 2018), had ~75% production in North Island, 25% South Island. 47% of total production was from Central North Island, 12% from Nelson / Marlborough, and 8% from Southland / Otago.

Woody biomass is difficult to digest due to the lignocellulosic material, hence is better suited to converting to syngas via gasification, pyrolysis, or similar processes. There will be competition for this feedstock in solid-fuel heat users. Gasification would add significant cost, compared to use as a solid fuel. Sawmill residues are normally utilised on site for process heat for drying. Additionally, the coal boiler conversions in the 1st emissions window (to 2035) would consume available wood chip/pulp logs for direct use as solid fuel (especially in the South Island where solid fuel boilers are common).

Woody biomass feedstocks can arise from various stages of timber production from harvest, including forestry residues, processing residues, and wood products, which are described below. A breakdown of expected volumes is shown in the figure below. Export wood chip and pulp logs are considered, but sawn timber and other timber products have not been considered as a viable feedstock due to the strong market demand and high-quality products that would need to be displaced from the market. A summary of the scale of the woody biomass feedstocks is in the table below.



New Zealand Wood Availability Forecasts by Type of Biomass (2019-2050) (Indufor, 2022).

Scale of Timber Production and Feedstocks

	Amount	Source
Roundwood removal year ending June 2022	35,642,000 m³/year	MPI, 2022
Amount Processed in NZ	12,826,000 t/year	Forest Owners Association, 2021
Amount Exported as Logs	20,083,000 t/year	Forest Owners Association, 2021
Forestry Residues	Unavailable	
Landing Residues	1,604,000 – 2,850,000 m³/year (wet)	MPI, 2022; Farm Forestry New Zealand, 2007

	Amount	Source
Processing Residues	3,676,000 t/year (wet)	Forest Owners Association, 2021
Pulp (Exported)	3,275,000 t/year (wet)	Forest Owners Association, 2021
Wood Chip (Exported)	200,000 t/year (wet)	Forest Owners Association, 2021

Wood Fiber Futures Stage 1 Report (Bio Pacific Partners et al., 2021) analyses available woody biomass residues available for biofuels. This report notes that in the short-term horizon (5-10 years) New Zealand has the capacity to supply additional industries requiring woody biomass. Those trees are already in the ground, hence the ability to secure biomass will be driven by its location and an investor's or user's ability to pay.

In the longer-term horizon (20-30 years) it is highly probable that such resources will still be available, but there may be other factors that could influence that, ranging from government policies, the value of carbon, market demand, the global trading environment, and the impact and speed of new technology implementation.

Utilisation of woody biomass in the short-term should focus on unutilised residues, and future feedstock demands may require diversion of exported chip and pulp logs in addition to the existing residues.

Forestry Residues

Woody biomass from forestry residues includes the branches, cutover (broken sections of trees), trimmings, and other tree material left in forest at the site of harvesting. These residues can be difficult and costly to collect due to the difficult terrain and remote locations of the logging sites (Hall & Gifford, 2007).

Further residues are produced at central landing sites where the trees taken once felled are cut into logs for transportation to processing sites or for export. Residues include off-cuts from base and tip, bark, branches etc. As these landing sites are centralised processing sites, recovery of residues from these locations is easily. Wood residues created at forest landings during logging range from 4.5 – 8% of total volume (Farm Forestry New Zealand, 2007). MPI (2022) quarterly roundwood (i.e. pre-processed wood) removals indicated 35,642,000 m^3 of roundwood was removed from New Zealand forests in year ending June 2022, representing 1,604,000 m^3/year to 2,850,000 m^3/year of landing residues. Systems are already in place to utilise these logging residues. Utilisation of these resources is driven by large, centralised processing sites which have wood-burning heat and power plants on site.

Processing Residues

Wood processing residues occur at sawmills and processing sites. This includes wood chip (up to 26% of log input volume ends as chip or 3,334,760 t/year, of which 6% or 200,000 t/year is exported), saw dust, bark, shavings, off-cuts (Hall & Gifford, 2007). All have current uses and established markets. Most of this residue is utilised onsite for heat required for drying.

Hall and Gifford (2007) estimated 0.8 million tonnes of unutilised residues (4% of harvest), mostly from smaller sawmills (scattered and sometimes remote processing), though an updated amount of un-utilised residues has not been found, it is expected to be small. The distribution of wood processing residues is summarised in the following figure. Note the production volumes are from 2007, and wood production has increased since, but the distribution of products and residues is expected to have remained proportional.

Wood product exports in 2020 included 200,000 t chip exported (0.1% total volume processed), and 3,275,000 t pulp (26% total volume processed), 8,168,000 t saw logs and peelers (64% of total volume processed) which could be diverted. Additionally, a further 20,083,000 t logs exported and not processed in New Zealand (61% of total harvested) hence removing the opportunity for residue production in New Zealand (Forest Owners Association, 2021).

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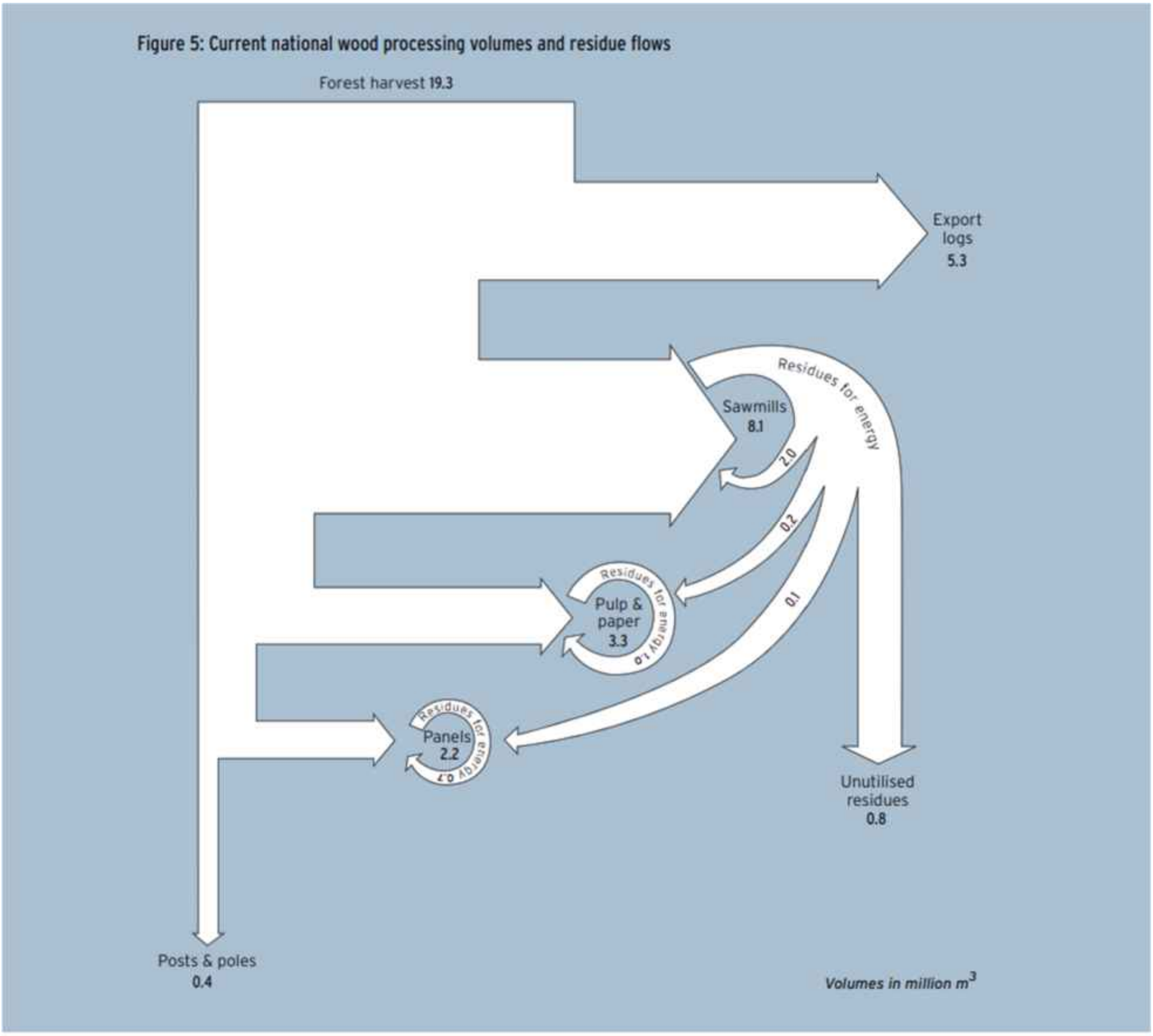

2007 National Wood Processing Volumes and Residue Flows (Hall & Gifford, 2007).

Feedstocks from Oils and Fats

Oils and fats provide feedstock for producing rLPG through various technology pathways, with intermediate steps of biodiesel via different technologies (Worley, 2021). This can then be refined to produce liquid fuels, with a resultant light fraction that could be utilised as for rLPG.

Tallow

Tallow is a triglyceride fat produced as an abattoir by-product at rendering plants throughout New Zealand, see Figure below. The majority (estimated 83%) of tallow produced is exported, with total exported tallow of 132,400 tonnes in 2021 gives estimated total production of 160,000 t/year (StatsNZ, 2022; Worley, 2021).

This represents a biodiesel potential of 122,000 t biodiesel/year (4.5 PJ/year) (scaled from biodiesel production indicated in Worley (2021).

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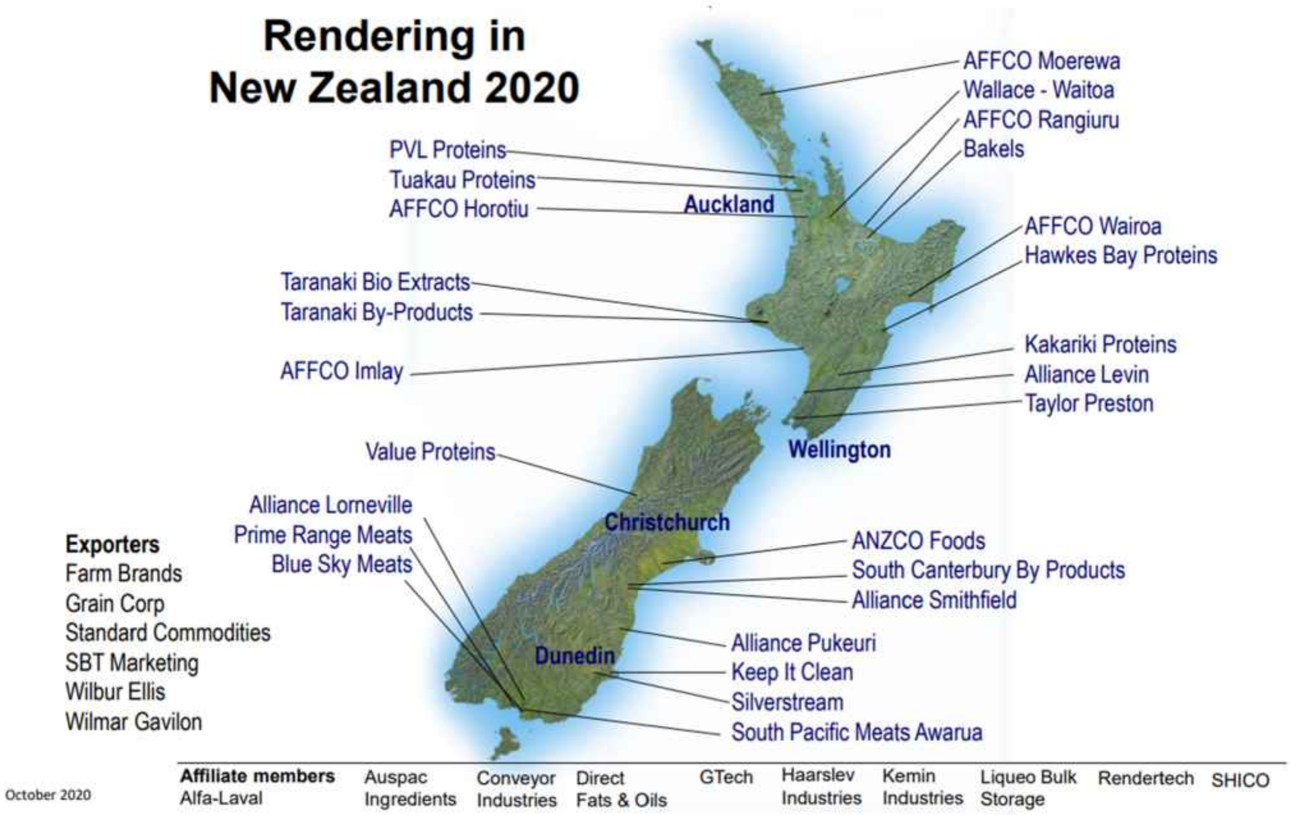

Figure 13-3: Rendering Facilities in New Zealand as of 2020 (Meat Industry Association, 2020)

There is concern around the economics of converting tallow to rLPG. Tallow can be directly utilised as a liquid fuel which has opportunity in the transition from solid fuels (i.e. coal users), or liquid fuels (i.e. diesel users). Upgrading tallow to biodiesel then further refining would attract a cost premium which may inhibit its utilisation for this purpose. Tallow in its own right with minimal further processing represents a liquid fuel source, which creates competition with the feedstock for processing to a gaseous fuel.

The global tallow cost has increased significantly in recent times, leading to the hibernation of Z Energy's Wiri Biodiesel Plant in 2020 as the production of biodiesel has not been economic (Z Energy, 2022). However, the Government's Sustainable Biofuels Obligation coming into effect from 1 April 2023 may see a change in the market for biodiesel.

Vegetable Oil Crops and Waste Cooking Oil

The volume of vegetable oil feedstock in New Zealand is very limited. New Zealand currently produces around 15,000 t/year of rapeseed (canola) in the South Island, the majority of which is sold as edible oil. Worley (2021) discussed in the rLPG report that diverting this oil from export to biofuel production would require long-term diesel pump price close to $2 per litre to be financially sustainable (at the time of writing the report). However, there are additional barriers with diversion of oil from food markets to energy markets which would require additional regulatory support or subsidies to incentivise.

Additional oil seed cropping to support biofuel industry growth is highly unlikely. However, as discussed in Section 4.3, changes in land use could occur for land area otherwise unfavourable for food production. With greater technical maturity of anaerobic digestion technologies over refining of biodiesel, any additional energy crops would more likely be digested as opposed to converted to biodiesel.
Worley reports that nearly 5,000 – 7,000 tonnes of waste cooking oil is available out of an approximated national total of 30,000 tonnes (Worley, 2021). Much of what exists is already allocated to use within industries for a heat source (such as cement and asphalt manufacture, greenhouse heating). There is also

small-scale fuel producers collecting waste cookin
existing market (Green Fuels located in Christchurch) (GreenFuels, 2022).

It is unlikely that New Zealand can domestically source enough vegetable oil feedstocks to justify the development of a production plant (Worley, 2021), hence has not been considered further.

Algae

Algal biomass has a high lipid content, making it a potential feedstock for liquid fuel production. Oxidation ponds used for wastewater treatment are ideal for algal biomass production. Algae can be grown on tertiary treated effluent, hence gas gain biogas potential from digestion of wastewater, followed by fuel potential from growth of algae on tertiary effluent (Hall & Gifford, 2007). High-Rate Algal Ponds (HRAP) increases algae production.

The technology for production of liquid fuels from algal biomass is not technically mature and has been attempted before but failed to reach commercial scales (NXT Fuels).

Harvesting microalgal biomass is difficult. Algae do not floc readily and are hard to separate with dissolved air flotation (DAF) and settling. Drying is required prior to processing which is energy intensive. The conversion to crude bio-oil using super critical water removes requirement for drying step, making it the more promising pathway.

Due to the above barriers, algal biomass is not considered a viable feedstock in the near future, hence has not been considered further in this report.

B

Appendix B Technology Descriptions

Tier 1 - Anaerobic Digestion

Process Description by Technology Type

Anaerobic digestion technologies can be categorised into the following process types:

- "Wet": Dry Solids [DS] <15 to 20 percent or "Dry": DS >20 percent
- Batch or continuous
- Single-stage vs multi-stage
- Thermophilic vs mesophilic

Table 13-2 summarizes the relative advantages and disadvantages of these process types.

Table 13-2: Comparison of Digestion Processes (Beca et al., 2021)

Process	
Dry vs Wet Digestion	
Dry AD Technologies	• Used when TS% >20 • Occurs in plug flow systems or batch-type reactors • More labour-intensive than wet digestion as feedstocks cannot be pumped and must be manually moved usually via front end loader
Wet AD Technologies	
Batch vs Continuous Digestion	
Batch	• For high solids feedstocks (TS > 30%) • Low-CAPEX alternative to a fully mixed reactor system or plug flow reactor • Must be initialized with a sample of bacteria from a completed batch • Processor easy to construct and operate • Requires more space than continuous
Continuous	
Thermophilic vs Mesophilic Digestion	
Thermophillic	• Thermophilic digesters can produce much larger yields of biogas and process more organic material than mesophilic digesters with similar volumes (Bekkering et al., 2010) • Requires more energy than mesophilic process to maintain the higher digester temperature, which creates a larger parasitic load on energy produced from biogas production • More susceptible to temperature swing upsets than mesophilic digesters
Mesophillic	
Single-Stage vs Multi-Stage	
Single-Stage	• Simpler processing arrangement where all four reaction steps proceed in the same conditions • Less capital intensive, but reaction proceeds overall at a slower speed • Larger equipment needed to facilitate longer residence times
Multi-Stage	• Require more upfront costs and smarter plant control to operate efficiently compared to single stage • Multiple unit operations i.e. there are multiple digestion stages for the feedstock • Allows stage of the reaction to proceed at optimized rates and decreases the overall retention times of the feedstock which decreases the total installed volume of the digester(s) (McConville et al., 2020). • This in turn reduces the footprint of the AD plant and can be installed in smaller land space.

The growth of the industry differentiated by digestion process type is depicted in Figure 13-4. The first installations used the “dry”/high solids continuous AD process type. “Dry”/high solids continuous AD and “wet”/low solids continuous AD installations grew together in the late 1990s and early 2000s. In the late 1990 a new AD process, “dry”/high solids discontinuous/batch AD process entered the market with its first installations. By the year 2000, the total processing capacity of organic waste AD plants had grown to almost 2.3 million tonnes/year. The growth of the “dry”/high solids continuous AD process type increased significantly in the late 2000s. By the end of 2017, more than 480 AD installations had processing capacity of almost 20 million tonnes/year.

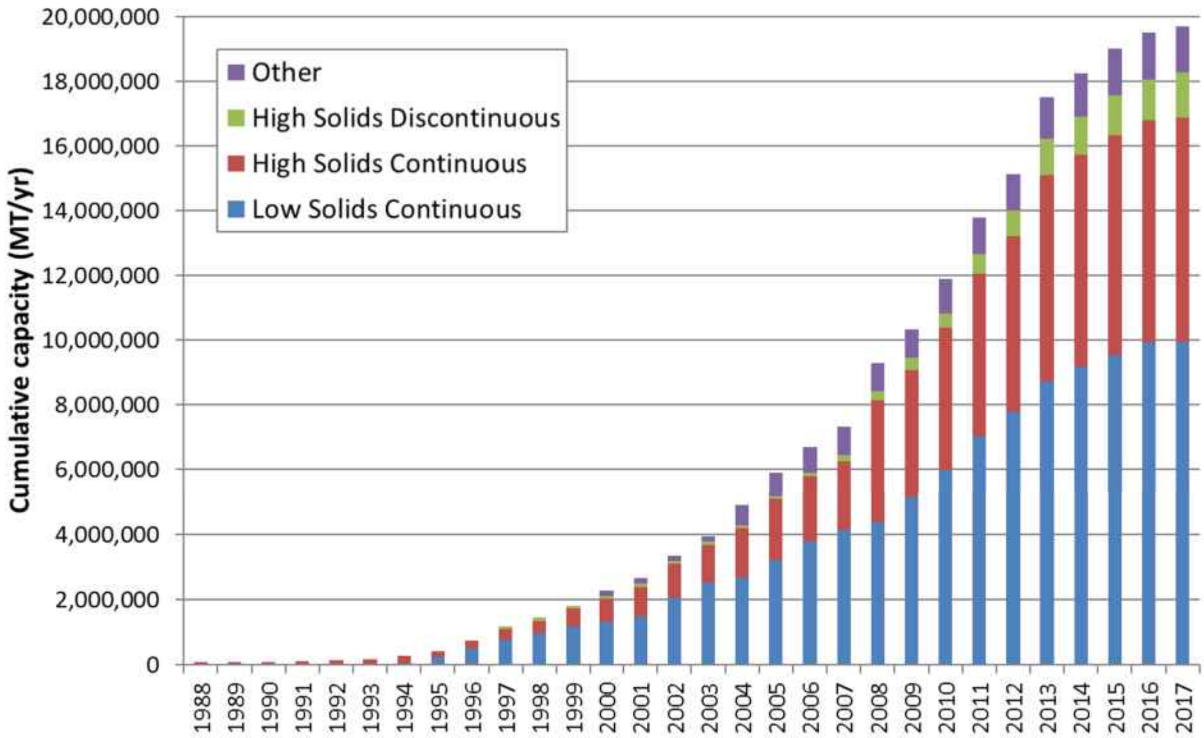

Figure 13-4: Growth of the Organic Waste Anaerobic Digestion Industry

“Wet”/low-solids versus “dry”/high-solids AD Process operation

As illustrated in Figure 13-5 the initial capacity was provided by the “dry”/high solids continuous AD process. The “wet”/low solids continuous AD process overtook “dry” systems in the mid-1990s. However, both approaches have continued to increase in total capacity. With dry”/high solids discontinuous/batch AD facilities adding to the worldwide AD processing capacity in the end 1990s both AD process types, “wet”/low solids and “dry”/high solids contributed to the worldwide processing capacity in 2017 as follows:

- 51% from “wet”/low solids continuous process,
- 31% from “dry”/high solids continuous process,
- 7% from “dry”/high solids discontinuous process, and
- 11% from other processes (representing the balance including co-digestion at WWTPs; not shown in Figure 13-5).

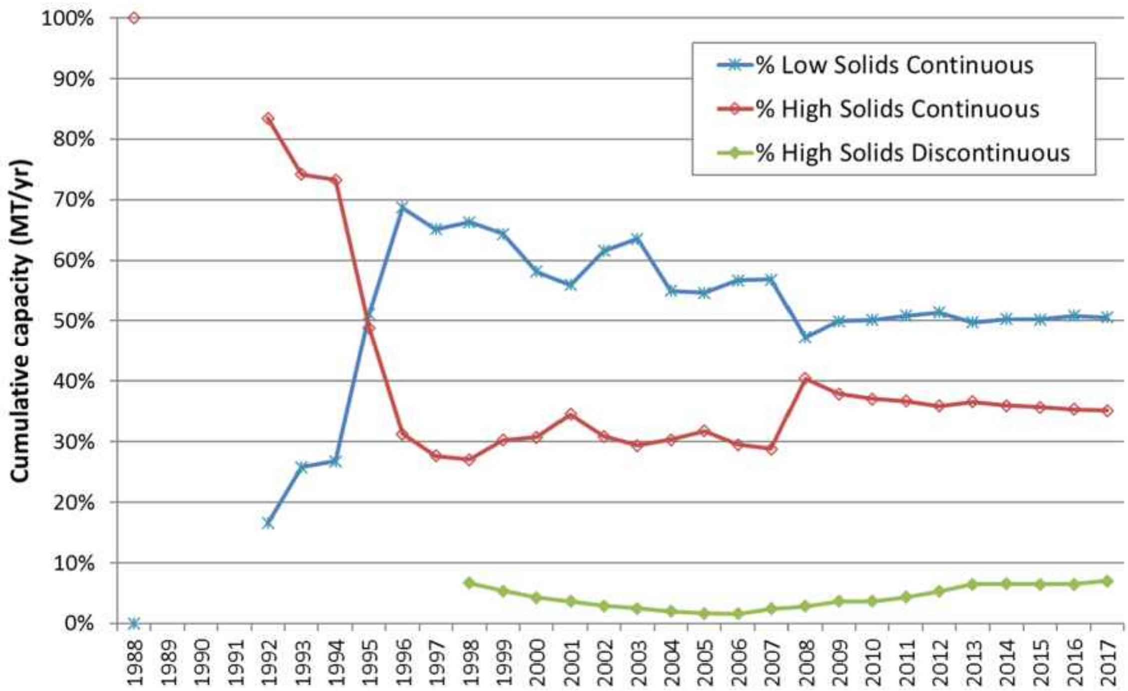

Figure 13-5: Historic Process Capacity Allocation for Different AD Processes

The development of suitable process reactors allowed the realisation of the advantages of the "dry"/high solids continuous AD as described in Table 13-2 and contributed to its fast growth in the industry. Increase in Source Separated Organics (SSO) collection programs in Europe is another factor causing its growth. On the residential side, these programs often allow co-collection of (light) yard waste with food waste. "Dry"/high solids continuous AD is well suited to process yard waste co-collected with food waste (which is more difficult to process via "wet"/low solids continuous AD). Furthermore, "dry"/high solids (continuous or discontinuous) AD processes have been added upstream of existing compositing facilities. They have also the advantage of operating with little to no wastewater treatment or discharge compared with "wet"/low solids continuous AD process.

Beca et al. (2021) summarises the best-fit standardised processing configurations for various feedstocks. This is summarised in Table 13-3.

Table 13-3: Standard Digester Technology/Configuration by Feedstock Source Type and Volume (Beca et al., 2021)

Feedstock	**Technology Choice**		
	Small (<5,000 t/year)	**Medium (<25,000 t/year)**	**Large (>30,000 t/year)**
WWTP Sludge	Single-stage fully-mixed digester	Single-stage fully-mixed digester	Multi-stage fully-mixed digester
Animal Manure	Farm-scale anaerobic lagoon or PFR digester	Single-stage fully-mixed digester or continuous dry reactor	Multi-stage fully-mixed digester
Food Waste	Dry batch reactor	Single-stage fully-mixed digester or multiple dry batch digesters	Multi-stage fully-mixed digester
Crop Silage	Dry batch reactor	Single-stage fully-mixed digester or multiple dry batch digesters	Multi-stage fully-mixed digester or large-scale dry batch reactors

Feedstock	Technology Choice Small (<5,000 t/year)	Medium (<25,000 t/year)	Large (>30,000 t/year)
Industrial Wastewater[1]	Single-stage small High-Rate Hydraulic Digesters	Single stage High-Rate Hydraulic Digesters or large Anaerobic Lagoons	Multi-stage High-Rate Hydraulic Digesters, or large Anaerobic Lagoons

Pre-Treatment Methods for Feedstocks

Wet digestion systems often require pre-treatment of feedstocks to prepare them for mixing and processing (Beca et al., 2021). A summary of the pre-treatment methods is shown in Table 13-4. Pre-treatment will depend on the feedstock source, and technology.

Table 13-4: Pre-Treatment Methods for Feedstocks (Beca et al., 2021)

Treatment	Objective/Process
Preparing Feedstocks for Digestion	Pre-treatment to make organic wastes suitable for biological digestion – removing impurities and increasing processibility
f. Mechanical Pre-Treatment	• Usually first stage of pre-treatment • Physically screen the feedstock for non-organics or impurities and then physically re-size solid feedstocks
Optimising Feedstocks for Digestion:	Pre-treatment prior to digestion to make it easier to process into methane by the bacterial cultures inside the reactors
g. Thermal Pre-Treatment	• In feedstocks that contain biomass with resistant/complex cell structures or quantities of lignin, thermal pre-treatment can assist acidogenic bacteria in decomposing feedstocks by breaking up molecular structures before the feedstock enters the digester
h. Chemical or Biological Pre-Treatment	• Use of chemical reagents to break up cellular structures (lignocellulose) and reduce the downstream work for the anaerobic digester
i. Pasteurisation	• Removes any possible biological contaminants from feedstocks before passing them into a digester* • Usually involves elevating the feed material to a set temperature and keeping the temperature stable for a set period of time • The higher the temperature, the shorter the holding duration (Wood Environment & Infrastructure Solutions UK Limited, 2019).

* Pasteurisation can also be completed post-digestion (after thickening or dewatering to save some energy)

Examples of Organic Waste AD Facilities

AD for use in municipal wastewater treatment is used throughout New Zealand, see Section 4.1.1. This discussion is regarding anaerobic digestion of other organic wastes. According to our in-house data (2017), there are over 480 organic waste AD plants in operation worldwide. 85% of them are in Europe, 9% in North America, 5% in Asia, and 1% in the rest of the world. The top three countries with the highest number of installations are Germany, Switzerland, and the United Kingdom. Table 13-5 summarises the key information of some selected installations.

For source separated food waste AD installations, there are 190 plants with a capacity less than 25,000 tonnes/year (including co-digestion at WWTPs).

[1] Note: with high-rate hydraulic systems (TS <1-2%), the feed rates in tonnages should be considered the solids feed rate only – industrial wastewater digestion plants can process millions of tonnes per year of liquid feed, but average liquid residence times are less than a day.

The Ecogas organic waste digestion plant a Reporoa is the first of its kind in New Zealand, with construction recently completed. See Section 5.7.1 for further information on this plant.

Table 13-5: Food Waste Anaerobic Digestion Plant with Capacity <25,000 tonnes/year Installed in Other Countries

Other Countries	Key Information About Reference Plant
Kompogas (HZI) Waste Treatment Plant in Jona, Switzerland	• 5,000 tonnes/year capacity • Treats source separated organic waste • Facility opened in 2005 • AD Technology: "dry"/high solids, thermophilic, one 330m^3 horizontal concrete digester • Biogas is utilised in a CHP with a capacity of 235kWe; surplus electricity it fed into the local electricity grid
Kompogas (HZI) Plant in Winterthur, Switzerland	• 23,000 tonnes/year capacity • Processes source separate food and green waste from more than 78,000 households in the Winterthur and Frauenfeld areas • Facility commissioned in 2014 • AD Technology: "dry"/high solids plug flow, thermophilic, one 1,500m^3 horizontal steel digester • Biogas is compressed and fed into the municipal gas grid • Digestate is turned into compost that is collected by nurseries, market gardens and farmers for use as fertiliser
OWS AD Plant in Kempten-Schlatt, Germany	• 24,000 tonnes/year capacity • Processes biowaste (residential food scraps co-collected with light yard waste) from households from the City of Kemten • Facility commissioned in 1992 • AD Technology: "dry"/high solids plug flow, thermophilic, one 1,300m^3 vertical steel digester • Biogas temporarily stored in a ground-mounted gas membrane buffer is utilised in 3 CHPs, each with a capacity of 310kWe; surplus electricity it fed into the local electricity grid, surplus heat is used at an adjacent nursery • Produced compost is marketed as Allgäu Compost for local gardening and landscaping
Thöni AD Plant in Roppen, Austria	• 10,000 tonnes/year capacity • Processes source separated biowaste from households of the Roppen region and green waste • Facility commissioned in 2001 • AD Technology: "dry"/high solids plug flow, thermophilic, one horizontal steel digester • Biogas produced in the digester is converted via CHP system into thermal and electric power (330kWe). Part of the heat and electric power is used for the AD plant process and the surplus electric power goes to the public power grid
Thöni AD Plant in Gävle Forsbacka, Sweden	• 25,000 tonnes/year capacity • Processes kitchen waste, biowaste, green waste from the region • Facility commissioned in 2017 • AD Technology: "dry"/high solids plug flow, thermophilic, one horizontal steel digester (active volume 2,250m^3) • Biogas produced is processed into 99.9% bio-methane (27.3 million kWh/year) in a biogas treatment plant. As there is no local gas grid, bio-methane is filled into portable tube trailers and used in local gas filling stations • Solid composted digestate and fertiliser-grade liquid digestate are used by local farmers.

Other Countries	Key Information About Reference Plant
Anaergia AD Plant in Glenfarg, Scotland	• 16,000 tonnes/year capacity • Processes commercial and residential SSO • Facility commissioned in 2011 • AD Technology: "wet"/low solids continuous, mesophilic, a 1,500m3 primary digester and a 1,500m^3 secondary digester • Biogas is utilised as fuel for the onsite CHP system (800kW renewable energy and 800kW renewable heat). Generated electricity is sold to the local grid while the heat recovered is used for substrate heating and to maintain the temperature of the digesters. • Digestate from secondary digester is dewatered, pasteurised, composted and sold as fertiliser to local farms. Liquid stream is held in a holding tank until it is sold to local farms as a liquid fertiliser.
Co-digestion Baden-Baden WWTP, Germany	• 5,000 tonnes/year capacity • Processes biowaste (residential SSO mixed with some yard waste; commercial SSO – primarily restaurants and cafeterias) and sewage sludge from wastewater treatment plant • Facility commissioned in 1993 • Applies the BTA International hydropulper pre-treatment system; produced organic slurry is dewatered; centrate is sent to digesters for co-digestion; dewatered digestate is sent off-site for composting • AD Technology: "wet"/low solids continuous, mesophilic, make use of the free digestion capacity in the existing two digesters • Generated digester gas is used in CHP system. Both generated heat and power are used to operate the WWTP and the source separated organics treatment facility
Co-digestion at South Pest WWTP in Budapest, Hungary	• 12,000 tonnes/year capacity • Processes a variety of commercial organic waste including packaged food, bread, vegetables, meats slaughter house runoff etc. and trucked sludge, concentrated septage • Commissioned in 2004 • AD Technology: "wet"/low solids continuous, mesophilic, make use of the existing digesters of the WWTP • Biogas is converted to energy for the WWTP use (energy neutral)

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Tier 1 -Biogas Upgrading

Process Description by Technology Type

The following description of technologies is taken from the Beca Biogas Report (Beca et al., 2021).

Pressure Swing Adsorption (PSA)

Pressure swing adsorption upgrading is based on the concept of different sized gas molecules being selectively adsorbed to a solid surface at high pressure, then released using a reduction in pressure. PSA can be used to upgrade raw biogas by adsorbing other gas molecules like CO_2, N_2, and O_2 from the larger methane molecule (Adnan et al., 2019).

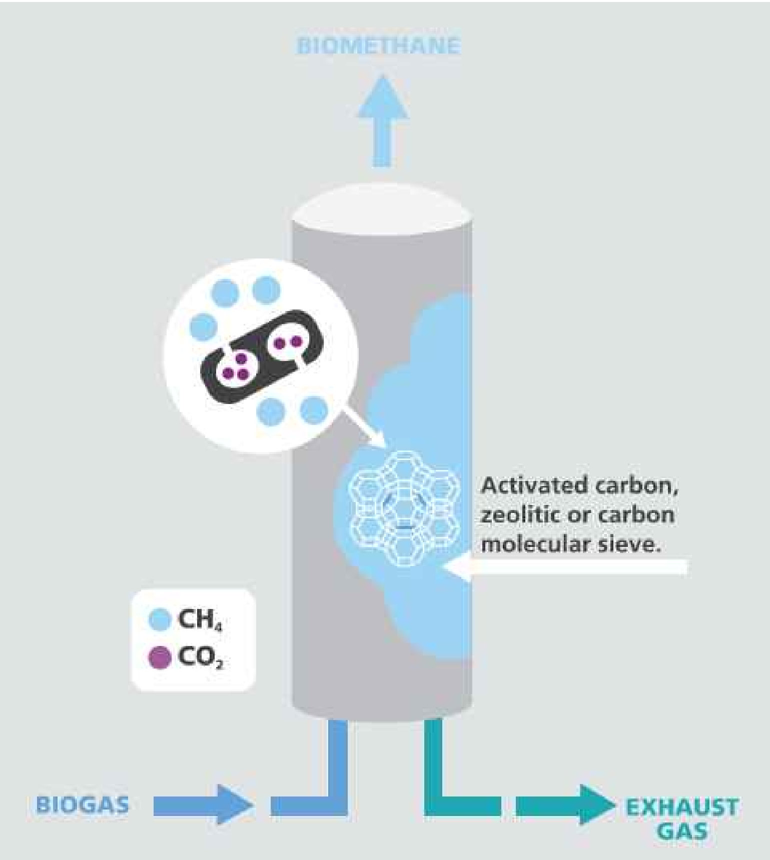

Figure 13-6: PSA sieve pressurization (UNIDO & German Biogas Association, 2017)

The solid material used to adsorb the molecules requires a large surface area, and the adsorption column can be filled with activated carbon, zeolitic molecular sieves or carbon molecular sieves. The pressure swings are used to deposit and release the adsorbed molecules, so the batch process has multiple columns operating at different phases to produce a constant output (UNIDO & German Biogas Association, 2017). PSA sieves permanently adsorb H_2S so pre-treatment must remove this contaminant prior to the process (Adnan et al., 2019). These characteristics allows PSA additional capability to remove inert gases from raw biogas sources that include higher levels from feedstocks such as WWTP and landfill gas.

Water Scrubbing

Water scrubbing is based on the physical solubility of gas components into a solvent solution. The direct contact between the raw biogas and water solvent dissolves CO_2 and other contaminants, such as H_2S (up to 0.05 %mol), ammonia and particulates, from the biogas stream. The solubility of CO_2 in water is improved at higher pressure, so the operating pressure for the process is between 4 – 10 barg.

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The process takes place in a scrubbing column where water is sprayed downwards while raw biogas is directed upwards. The upgraded biomethane is released from the top of the scrubbing column and the water with dissolved CO_2 and other components is collected at the bottom of the scrubbing column. The remaining gas components are removed in a flash column and collected water with dissolved components is sent to a stripping column.

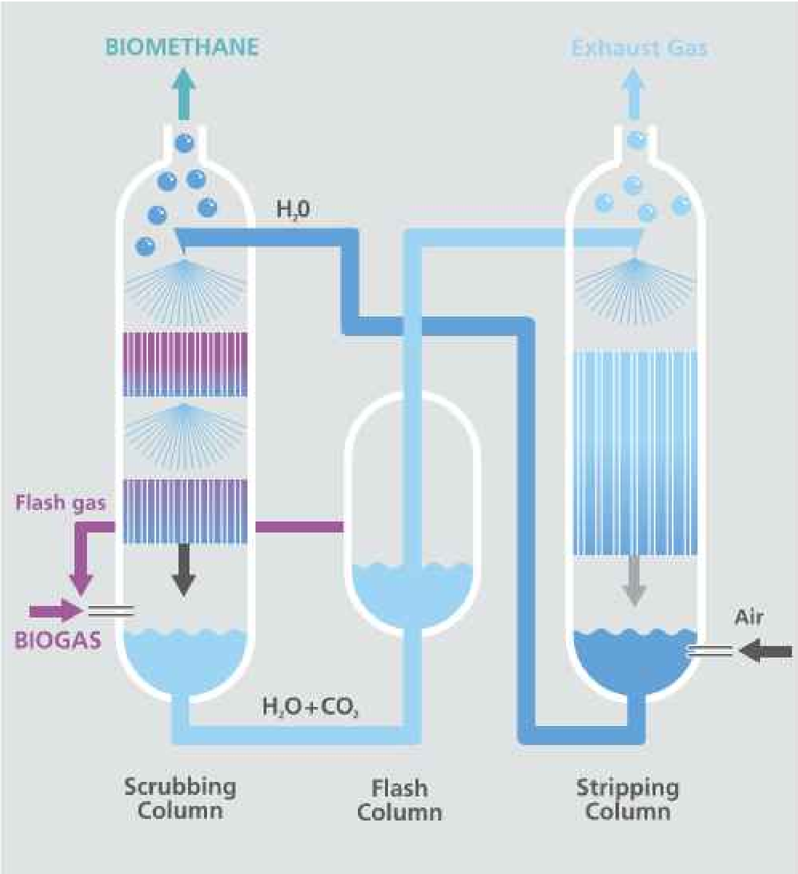

Figure 13-7: Scrubbing technologies schematic (UNIDO & German Biogas Association, 2017)

In the stripping column, the water, CO_2 and other dissolved components are sprayed downward while air is directed upwards and the CO_2 and other gases are released from the top of the column as exhaust gases, and the water is collected at the bottom of the column (UNIDO & German Biogas Association, 2017). The CO_2 released from water scrubbing is usually not collected for further use unless an air stripping unit is fitted to further process CO_2 (Sun et al., 2015b). This comes at high cost and is not economic compared to other pathways for capturing CO_2.

Physical Scrubbing

Same as pressurised water scrubbing but using organic solvents such as “Selexol” for enhanced selective absorption of $CO_{2,}$ able to run at lower operating pressures but requiring a heat source for regeneration of the solvent.

Chemical Scrubbing

Chemical scrubbing uses similar principle as water scrubbing except the solvent is a chemical mixture which reacts to absorb components from the gas with the solvent. The chemical types include monoethanolamine (MEA), diethanolamine (DEA) and methyldiethanolamine (MDEA) mixed with water (UNIDO & German Biogas Association, 2017). The amine solution reacts selectively with CO_2 and H_2S, so the scrubbing process takes place at lower pressures (Sun et al., 2015b). To strip the CO_2 and other components from the amine solution to be reused for further scrubbing requires elevated temperatures between 120 – 160°C

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(Angelidaki et al., 2018). This upgrading technology typically requires additional pre-treatment to remove larger proportions of N_2 and other inert gases.

Membrane Separation
Membrane gas separation uses selective permeability to separate larger molecules such as methane and smaller molecules such as CO_2, H_2S, and O_2 (Angelidaki et al., 2018). The raw biogas is pressurised and fed through a membrane designed to allow the smaller gas molecules to permeate faster through the membrane, while the larger molecules are retained in the tube bundle.

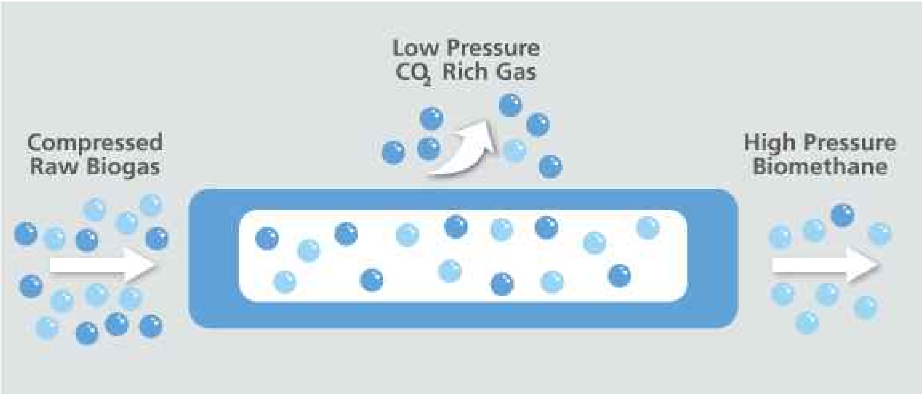

Figure 13-8: Membrane Separation Fundamental (Pentair Haffmans)

The permeation rate of different size molecules through the membrane is a key design parameter that determines the materials for the membrane. The process requires operating pressures between 7-20barg and can use multiple passes through membranes to achieve higher methane purity (UNIDO & German Biogas Association, 2017). Membranes have been used for upgrading for all feedstocks with varying degrees of pre-treatment equipment.

Hydrogen sulfide (H_2S) removal, volatile organic carbon (VOC) and moisture remove are typically required pre-treatments as their presence at the membrane can cause selective permeation over CO_2, therefore affecting final upgrade biomethane quality and shortening the lifespan of the materials in some scenarios.

Tier 2 - Biodiesel Production

Production pathways for biodiesel include hydrotreated esters and fatty acids (HEFA), hydrotreated vegetable oil (HVO), and fatty acid methyl esters (FAME). In terms of output, HEFA/HVO and FAME pathways are technically different as a result of the differences in production process, cleanliness, and quality. However, because feedstocks for these pathways are renewable and can produce biocrude, they will be considered as methods for rLPG production. In New Zealand, HVO is not regarded to be a viable production pathway for biocrude due to the limited volume of vegetable oil feedstocks as discussed in Section 4. The hydrogenation process also benefits from scaling, is capital intensive, and requires hydrogen as a secondary feed. Therefore, HEFA and FAME pathways will be focused on.

Biodiesel produced through HEFA has lower nitrogen oxide emissions, better storage stability and better cold flow properties than FAME biodiesel. The main difference between HEFA and FAME diesel lies in the oxygen content. HEFA is essentially oxygen-free and can substitute diesel in ground transportation and up to 50% of the petrol in aviation jet fuel due to its lower cloud point. Both types have the same carbon chain length and similar specific energies, but HEFA diesel contains more cetane while FAME diesel has more sulphur. In terms of feedstock, HEFA utilises waste and residue oils and fats while FAME, which involves esterification, restricts the use of poor-quality raw materials and thus waste.

Via the FAME pathway, biodiesel is typically produced through transesterification, a process which involves converting fats and oils into biodiesel and glycerin. Glycerin is a co-product produced in an approximate 1:10 ratio to biodiesel. It can be used to manufacture pharmaceuticals and cosmetics and added to food. Alongside the feedstock, transesterification requires the addition of a short chain alcohol, like methanol, and a basic catalyst to be present in most commercial-scale cases. The cost effectiveness of biodiesel production through this method is normally limited by the cost and access to feedstock.

There are five stages in the FAME transesterification pathway, (1) treatment of raw materials, (2) alcohol-catalyst mixing, (3) chemical reaction, (4) separation, and (5) purification. The first step is dependent on the feedstocks free fatty acid content as described below. Prior to the reaction, the catalyst is completely dissolved in excess alcohol to increase the rate of reaction. The chemical reaction is then carried out at higher temperatures and under continuous stirring to allow mixing of the alcohol and oils. The product of transesterification is a mixture of fatty acid esters. Biodiesel is obtained after the esters and glycerin mixture is separated and then purified by reducing the concentration of contaminants to comply with international standards

The HEFA biodiesel production process is relatively simple. Feedstock is pretreated before being hydrotreated. Hydrotreatment is where the feedstock is reacted with hydrogen in the presence of a catalyst under high pressure to remove the oxygen. The output is a chemically equivalent hydrocarbon fuel to fossil diesel fuel rather than alcohols or esters.

Tier 3 – Biomethane via Methanation

Biomethane is a near-pure source of methane. It is indistinguishable from natural gas and therefore offers an ideal substitute which does not require any changes in transmission and distribution infrastructure. Biomethane is produced via the methanation reaction, alternatively it can also be produced by upgrading biogas which is further explained in Section 5.

Methanation refers to the conversion of carbon dioxide (or carbon monoxide) to methane through hydrogenation. This is commonly known as the Sabatier Process. To produce a pure stream of biomethane, the syngas feedstock is cleaned to remove any acidic and corrosive components prior to methanation. The methanation process then uses a catalyst to promote a reaction between the hydrogen and carbon monoxide or CO_2 to produce methane. Any remaining CO_2 or water is removed at the end of this process.

Similarly to the Fisher-Tropsch process, the syngas feed may be obtained through a variety of pathways. These are outlined in Section 7.2. The feed is typically compressed and heated prior to undergoing pre-treatment to remove impurities. The methanation is highly exothermic, and the process takes place in a series of adiabatic reactors with interstage heat recovery. Due to the large amounts of water produced by the reaction, the produced methane is dried before leaving the methanation system.

$$CO_2 + 4\,H_2 \rightarrow CH \;\; + 2\,H_2O \qquad thanation\ Equation)$$
$$CO \;\; + 3\,H_2 \rightarrow CH \;\; + \; H_2O$$

Methanation is a well-proven and standard technology to convert gasified coal and biomass into synthetic natural gas, however its use to convert the CO_2 fraction of biogas into biomethane with green hydrogen is less mature. The contaminants in the syngas from woody biomass can promote deterioration of the methanation reactor, which has limited commercialization of woody biomass gasification and methanation to date.

Tier 3 - Methanol and Dimethyl Ether (DME) (via Catalytic Conversion)

The simplest alcohol, methanol (CH_3OH) has been produced by humans since antiquity. Traditionally it was obtained from the pyrolysis of wood, but in modern times it has primarily been produced from syngas derived from the reforming of methane. The building blocks of methanol are thus the same as the methanation and Fischer-Tropsch processes. The gasification, methane reforming and the power-to-X pathways may be used to supply syngas for methanol production.

Methanol is formed through the reaction of hydrogen and carbon monoxide (and/or carbon dioxide) over a catalyst. Methanol, normally a liquid, can be dehydrated via catalytic conversion to form dimethyl ether ($(CH_3)_2O$), the simplest ester and a colourless gas. As a gas, dimethyl ether is a substitute for propane found in LPG and may replace LPG in household and industrial applications.

Dimethyl ether (DME) can be produced directly from syngas or indirectly by the dehydration of methanol. Both processes are commonly used in industry and, at its simplest, DME may be produced from methanol via a dehydration reaction. An added benefit of methanol and DME synthesis, is the reaction pathways to convert syngas to methanol/DME are less sensitive to contaminants than the methanation and, moreso, Fischer-Tropsch processes. This makes methanol/DME synthesis a more attractive pathway for impure, contaminated syngas streams such as those produced from gasification.

In additional to being an LPG replacement, as DME is a promising diesel alternative requiring minimal modifications to a standard diesel engine, it is more beneficial to use DME as a liquid fuel then a gaseous fuel. The widespread acceptance of DME is limited by its availability. The driver for DME production in future may be for a direct diesel fuel replacement, as opposed to a gaseous fuel. Production of DME could be driven by liquid fuel markets, and consideration of biomethane reforming to provide additional feedstock for DME production may be a future pathway, though this is highly dependent on the future energy split between gaseous ad liquid fuels, product values, and external market drivers.

Tier 3 - Fisher- Tropsch (FT) Process

The Fisher-Tropsch (FT) process is a catalysed chemical reaction using syngas as a feedstock. The FT gas-to-liquids process converts hydrogen and carbon monoxide into long-chain hydrocarbons (synthetic crude oil). LPGs are a by-product of the process. An example of how LPGs are produced via FT is illustrated below.

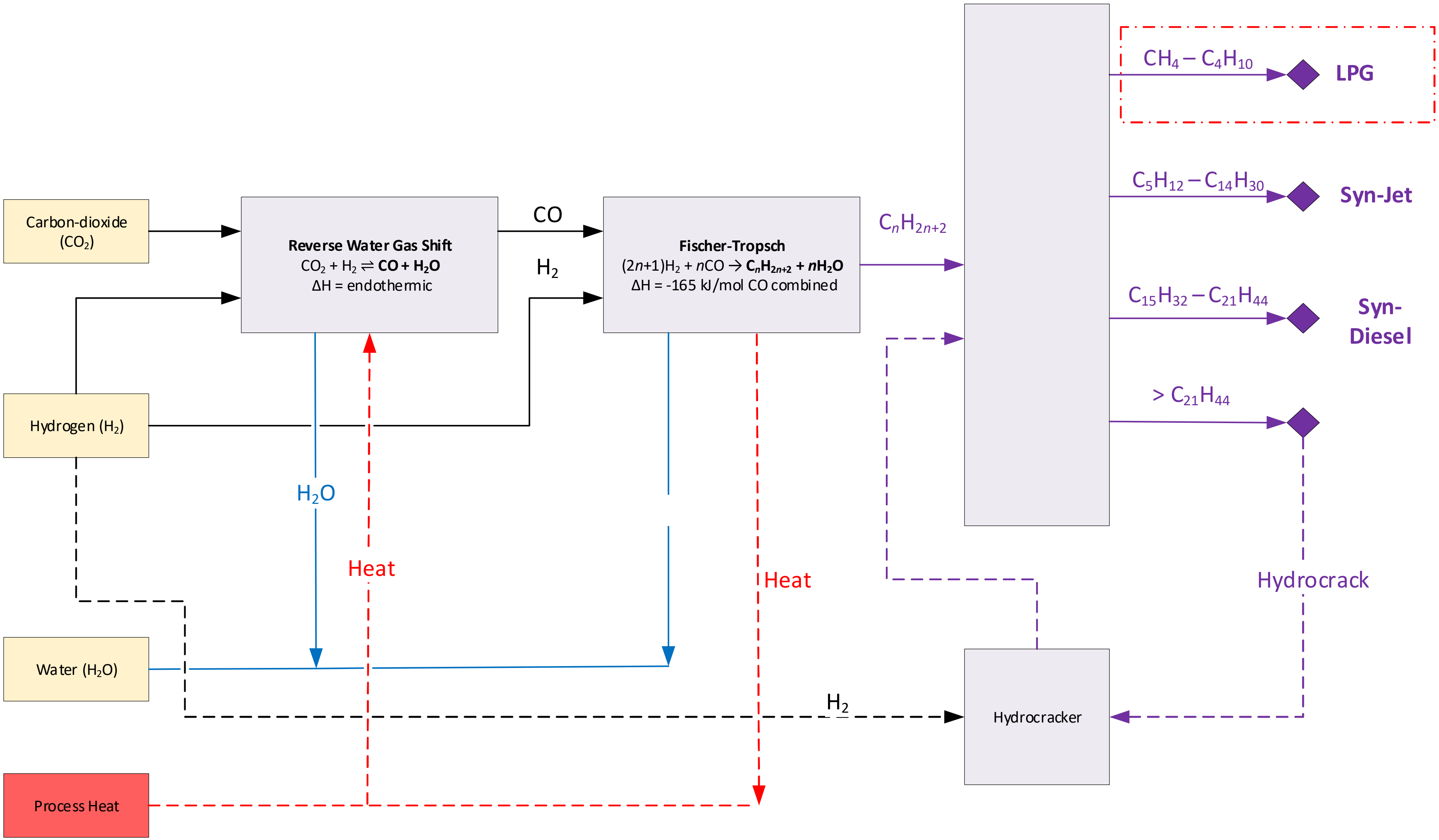

Figure 13-9: Process Schematic of Fisher-Tropsch Process

The syngas feed may be obtained through a variety of pathways – including gasification and power-to-X technologies. Where hydrogen and carbon dioxide are extracted from the environment using electricity, water and air as feedstocks, the resulting products are known as e-fuels.

Syngas can also be obtained from the reforming of methane into hydrogen and carbon monoxide. As such, biogas and biomethane are also potential feedstocks into the synfuels process. Again, this process is primarily converting gaseous molecules into liquid fuels and thus is not an ideal pathway where gaseous products are desired.

Fisher-Tropsch (FT) is a well-proven technology used by the petrochemical industry. However, the technology benefits from scale and lacks maturity for biomass facilities. There is ongoing development in improving the scalability of FT. At present, biomass gasification and conversion of syngas via FT is very capital extensive.

C

Appendix C Case Studies

Landfill gas to Biomethane

Kate Valley Landfill Case Study

Kate Valley is the South Island's biggest landfill, with a 37-ha site located in North Canterbury (Transwaste, n.d.). Kate Valley landfill receives approximately 300,000 tonnes of waste each year and has consent to operate for the next 18 years until 2040. This landfill has been receiving waste for the past 16 years, and captures landfill gas, generating electricity. A small portion of the electricity is used onsite, and the remainder is fed into the grid. Installed generation capacity is currently approximately 4MW utilizing raw landfill gas. Any surplus landfill gas is flared.

Landfill gas (LFG) production in 2019 was approximately 2,700 m^3/h (Transwaste 2, n.d.) (approximately 24,000,000 m^3/year or 0.4 PJ/year). With existing generator operation, there is an excess of 700 m^3/h (6,100,000 m^3/year or 0.1 PJ/year).

This case study looks at a project to upgrade the LFG to biomethane in the South Island. This includes cleaning the LFG of contaminants, separating methane and CO_2. Biomethane will be compressed for transport as the Kate Valley Landfill is not in proximity to the natural gas grid. CO_2 will be liquified for storage and transport.

Some barriers to consider:

- The existing landfill gas capture system provides beneficial reuse of the gas (electricity generation) which would be displaced if landfill gas is to be upgraded and converted to biomethane.
- The location is not in proximity to the existing natural gas grid

Assumptions:

- Landfill gas composition of 50% methane
- Landfill gas production remains stable for next 10 years
- Total landfill gas produced will be upgraded, resulting in the need to import electricity to site
- Landfill gas will be pre-treated to remove contaminants prior to upgrading
- Landfill gas will be upgraded using membrane separation and PSA (based on contaminants present), with ~0% methane slip due inclusion of cryogenic condensation of CO_2
- CO_2 will be liquified and stored
- Biomethane will be compressed to 250barg for transport as no gas grid in location of landfill

Table 13-6: Case Study Summary - Kate Valley Landfill

Parameter	Description
Case Study Description	• Landfill in North Canterbury with existing landfill gas capture • Installation of landfill gas upgrading plant • Compression of biomethane for transport
Feed Stock	• Landfill gas from existing municipal solid waste • 300,000 tonnes/year MSW
Biomethane potential (PJ/year)	• 0.4 PJ/year

Hampton Downs Landfill Case Study

The Hampton Power and Resource Recovery Centre is the North Waikato landfill located at Hampton Downs, which services a large part of the upper North Island, including Auckland. It is one of the largest landfill sites in the southern hemisphere at over 80 ha and will take waste up to 2030 (Taylor, 2019). Hampton Downs receives approximately 600,000 tonnes waste per year (Waikato Regional Council, 2022).

This landfill also captures landfill gas and generates electricity through seven engines, totaling 7MW of installed capacity. Electricity produced supplies the site, with excess fed to the grid.

Total landfill production was unavailable but is estimated at approximately 5,200 m^3/h based on comparison between waste volumes sent to Hampton Downs and Kate Valley landfills. This equates to 47,300,000 m^3/year or 0.8 PJ/year. The Hampton Downs landfill is in proximity of the natural gas grid, hence biomethane produced could be injected into the grid, which removes the requirement for compression of the gas for transport.

This case study looks at a project to upgrade the LFG to biomethane, located in the North Island in proximity to the existing natural gas grid. This includes cleaning the LFG of contaminants, separating methane and CO_2. Biomethane will be injected into the grid, and CO_2 will be liquified for storage and transport.

Some barriers to consider, which are similar to Kate Valley:
- The existing landfill gas capture system provides beneficial reuse of the gas (electricity generation) which would be displaced if landfill gas is to be upgraded and converted to biomethane.

Assumptions:
- Landfill gas composition of 50% methane
- Landfill gas production remains stable for next 10 years
- Total landfill gas produced will be upgraded, resulting in the need to import electricity to site
- Assumed landfill gas production of 5,200 m^3/h, scaled from Kate Valley
- Landfill gas will be pre-treated to remove contaminants prior to upgrading
- Landfill gas will be upgraded using membrane separation and PSA (based on contaminants present), with ~0% methane slip due inclusion of cryogenic condensation of CO_2
- CO_2 will be liquified and stored
- Biomethane will be direct injected into the natural gas grid
- Biomethane will be sold to the grid, and food grade CO_2 will be sold for beverage production

Table 13-7: Case Study Summary – Hampton Downs Landfill

Parameter	Description
Case Study Description	• Landfill in North Waikato with existing landfill gas capture • Installation of landfill gas upgrading plant • Injection of biomethane to national grid
Feed Stock	• Landfill gas from existing municipal solid waste • 600,000 tonnes/year MSW
Biomethane potential	0.8 PJ/year
Gas Cost*	$10/GJ
Emissions Intensity	9 kg CO_2e/GJ

* To achieve an IRR of 10% at 13 years, just after the capital has been fully depreciated.

Biogas to Biomethane

Māngere WWTP Case Study

Māngere WWTP is the largest WWTP in New Zealand located in Auckland, treating municipal wastewater from almost 27% of New Zealand's population. This site is located in proximity to the natural gas grid.

Māngere currently has eight mesophilic anaerobic digesters (at 37°C), producing on average 57,600 m^3 biogas/day (2,400 m^3/h) (based on internal sources), approximately 0.5 PJ/year. Māgnere has four 1.7 MW gas engines, providing electricity to meet 50-60% the site's needs, and heat recovered for the digestion

process. This site cleans the biogas prior to use, and has H_2S filters, coalescing (for particle removal) and siloxane filters to remove contaminants from the gas.
This case study looks at a project to upgrade the biogas to biomethane, located in the North Island in proximity to the existing natural gas grid. This site already includes biogas cleaning, so this project focuses on separating methane and CO_2. Biomethane will be injected into the grid, and CO_2 will be liquified for storage and transport.

Some barriers to consider include:

- Upgrading the gas will divert biogas from electricity generation. Therefore, the site will require import of more energy, which would increase operating costs. Consideration of the sale of biomethane to the grid would be required to incentivise the upgrading and grid injection of the gas over consumption on site.
- On-site power generate provide some security of power supply for an essential service, and the owner may be reluctant to let this go.
- Waste heat from the engines is utilised for heating the digesters. If the gas is to be upgraded rather than used in the engines, and alternative heat source would be required. This may be a parasitic load on the gas produced (i.e., burn biogas to meet digester heating requirements), or installation of a heat pump to utilise electricity to heat the digesters.

Assumptions:

- Hot water heat pumps are installed for heating to maximise biomethane production
- Biogas pre-treatment already provided is sufficient for upgrading
- Biogas will be upgraded using membrane separation, with ~0% methane slip due inclusion of cryogenic condensation of CO_2
- CO_2 will be liquified and stored
- Biomethane will be injected into the grid, so no compression for transport has been allowed
- Biomethane will be sold to the grid, and food grade CO_2 will be sold for beverage production

Table 13-8: Case Study Summary – Māngere WWTP

Parameter	Description
Case Study Description	• Municipal WWTP located in Auckland with existing AD • Installation of biogas upgrading plant • Injection of biomethane to national grid
Feed Stock	• Biogas from digestion of municipal wastewater • 115 million m^3/year wastewater
Biomethane potential	0.5 PJ/year
Gas Cost*	$15/GJ
Emissions Intensity	14 kg CO_2e/GJ

* To achieve an IRR of 10% at 13 years, just after the capital has been fully depreciated.

Centralised Southland Biomethane Upgrading Case Study

This case study looks at establishing a biomethane network by combining and upgrading biogas produced at a number of facilities in the Southland Region. Each site would have a containerised upgrading plant installed onsite. These individual plants would be owned and operated by a biomethane supplier, which is common operating model in Europe. A biomethane pipe network would be installed to collect biomethane from the various sources and piped to local users within the locality of the plants.

This option would need economic analysis to compare the option of a centralised upgrading facility, collecting biogas from all the sources. This would require a larger pipeline (as biomethane is only 60% the total volume of biogas). The benefit would be simpler operation with a single specialised upgrading plant as opposed to the dispersed containerised plants, which in turn allow a smaller pipeline to be installed.

A limitation of this option, as with all other South Island cases presented is there is no existing natural gas grid in Southland. The utilisation of biomethane locally would therefore not be acting to transition existing gas users to a renewable alternative, but rather off-setting other fuel sources (such as solid fuel boilers which may be running on coal or wood). For this reason, the economics of this case study have not been developed.

Biogas from the following sites is proposed. The locality of the sites is shown in the table below.

Biogas Sources for Combined Upgrading

Plant Name	Description	Biogas Potential	Current Biogas Use	Distance from Clifton WWTP
Clifton WWTP	Municipal WWTP, with 3 anaerobic digesters	0.02 PJ/year	Utilised onsite as boiler fuel for heating	N/A
Blue Sky Meats	Meat processing plant with onsite wastewater treatment with covered anaerobic lagoon including biogas capture	1,900 m^3/day (0.01 PJ/year)	Flared. No utilisation on site	30 km
Alliance Lorneville	Meat processing plant with onsite wastewater treatment with uncovered anaerobic lagoon (no biogas capture). Treats 17,00 m^3/day wastewater from plant, and municipal wastewater from site and nearby Wallacetown (PDP 2015).	30,200 m^3/day (0.2 PJ/year)	Not currently captured or utilised.	15 km
South Pacific Meats	Meat processing plant with onsite anaerobic pond-based pre-treatment of wastewater prior to discharge to municipal sewer (LOWE Environmental Impact, 2018).	0.08 PJ/year (scaled from Lorneville based on production capacity)	Utilised onsite in hot water boiler*	6 km
Combined		0.3 PJ/year		

* Successful in GIDI funding round 1 for project relating to installation of dual fired LPG and biogas hot water boiler, hence have assumed this will be in place for this case study (Beehive, 2021)

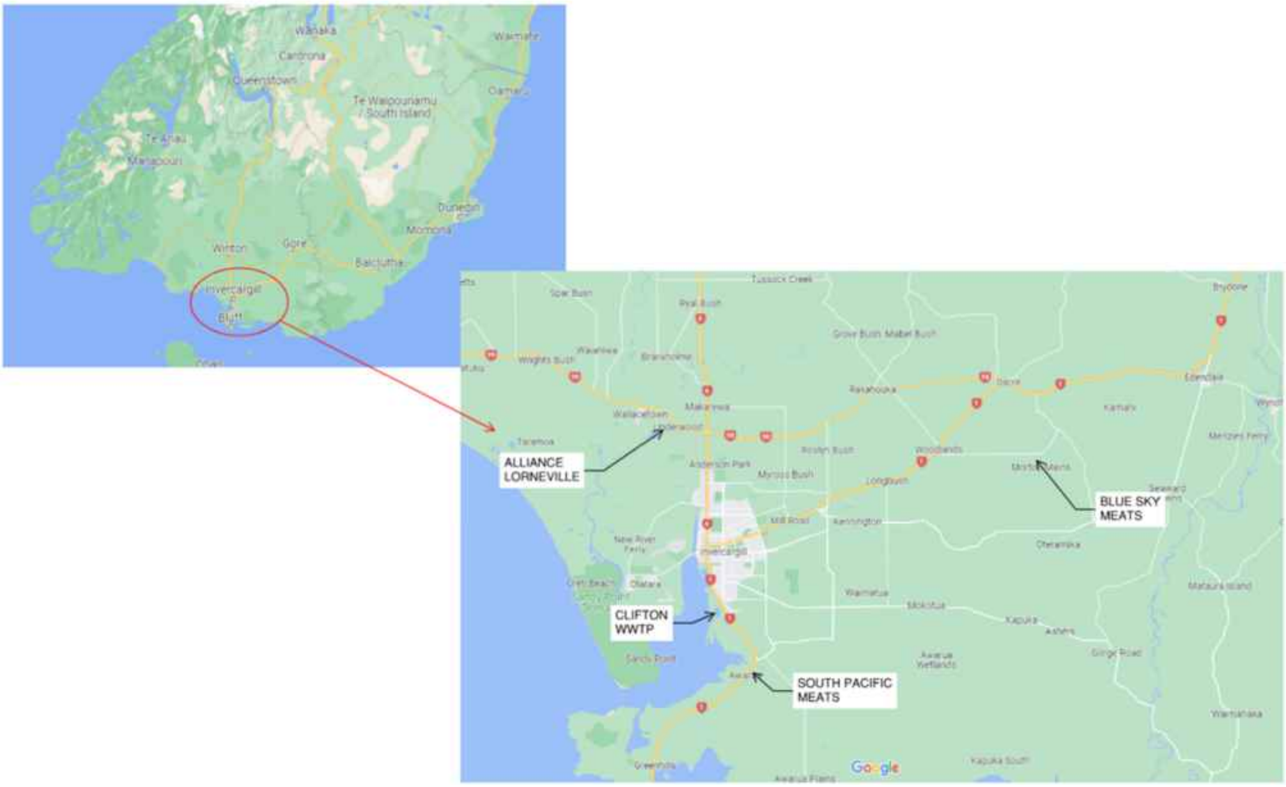

Figure 13-10: Location of Plants with Existing Biogas Generation

Barriers:

- No natural gas grid in the area, hence need to develop a reticulation and will be creating new gas user (e.g. converting solid fuel users).
- Biogas production from meat processing sites has seasonal variability, with more production during peak processing, and negligible production during plant shut downs, compared to more consistent production from municipal sources at Clifton WWTP. This will mean there is variable gas availability across the season. If gas supply can align with gas demand (e.g. providing gas to meat works) this barrier is avoided.
- Operational complexity of containerised plants, which may inhibit installations on sites that do not specialise in wastewater treatment of biogas – this is overcome by an operational model where a company owns and operates the upgrading plant which is located at the processing plants.
- Some plants have beneficial use of biogas which will be off-set by upgrading.

Assumptions:

- All biogas produced at the facilities would be utilised for upgrading
- Alliance Lorneville will cover their anaerobic pond and capture the biogas produced for upgrading
- The plants will sell biogas to a network provider who will upgrade to biomethane and sell into the reticulation
- Biogas will be pre-treated to remove contaminants prior to upgrading at each site
- Biogas will be upgraded using membrane separation, with ~0% methane slip due inclusion of cryogenic condensation of CO_2. This will be achieved using containerised plants at each processing plant
- Biomethane will be injected into a new, local reticulation

Table 13-9: Case Study Summary – Combined AD Plants

Parameter	Description
Case Study Description	• Combined biomethane potential from three meat processing plants and Clifton municipal WWTP, all with existing onsite anaerobic wastewater treatment and biogas production

Parameter	Description
	• Installation of biogas upgrading plant • Injection of biomethane into a newly established, localised reticulation network
Feed Stock	• Biogas from digestion of municipal wastewater and meat processing wastewater
Biomethane potential	0.3 PJ/year

Food waste to Biomethane

Wellington Food Waste Case Study

Wellington has a population of 419,000 people, hence produces an estimated 12,200 tonnes food waste per year. This case study assumes a source separated food waste collection system is rolled out in the region. The pre-consumer food waste from supermarkets, based on population, is 5,500 tonnes/year. A portion of this is donated for human consumption through community organisations, hence 4,500 tonnes/year is available for digestion.

Southern Landfill has an existing landfill gas capture system. The gas is currently generating electricity with 1MW installed capacity, with any surplus gas being flared. The landfill produces 4,000,000 m^3/year of landfill gas, representing biomethane potential of 0.07 PJ/year.

It is proposed the collected food waste is digested in a new AD facility, collocated at the Southern Landfill to utilise the existing landfill gas production. This case study looks at a project to develop the AD facility, including cleaning the biogas and landfill gas of contaminants, separating methane and CO_2. Biomethane will be injected to the grid. The CO_2 will be liquified for storage and transport.

This facility would include:

- Feedstock pre-processing including de-packaging, magnetic removal of ferrous items, and some form of homogeniser such as a macerator or pulper
- Mesophilic, continuous, wet digestion
- Heat pump for digester heating to maximise biogas yield
- Biogas upgrading plant
- Biogas compression for transport
- CO_2 liquefaction and storage

Barriers:

- Effective uptake of food waste collection, and effective source separation by participating households
- Preference for home composting as opposed to collection
- Pre-consumer food waste diverting feedstock from animal feed
- Existing utilisation of landfill gas produced, hence diverting the gas from electricity production

Assumptions:

- 90% recovery of household food waste, allowing some to landfill, and some to household composting
- Pre-consumer food waste excludes portion donated for human consumption (82% of total), scaled for population of Wellington metro population
- Digestate to be marketed to local horticultural industry for soil enhancement (as opposed to fertilisers or composts)
- Biogas and landfill gas will be pre-treated to remove contaminants prior to upgrading
- Biogas will be upgraded using membrane separation, with ~0% methane slip due inclusion of cryogenic condensation of CO_2. This will be achieved using containerised plants at each processing plant

- Biomethane is compressed for transport (no grid injection)

Table 13-10: Case Study Summary – Wellington Food Waste Digester and LFG

Parameter	Description
Case Study Description	• Installation of new AD facility in Wellington to digest organic waste co-located with Southern Landfill • Upgrading of landfill gas from Southern landfill • Installation of biogas upgrading plant • Compression of biomethane for transport
Feed Stock	• Pre-consumer food waste from supermarkets: 4,500 tonnes/year • Post-consumer food waste from source separated food waste collection scheme: 11,000 tonnes/year (Total food waste – 15,500 tonnes/year) • 4,000,000 m^3/year landfill gas
Biomethane potential	0.1 PJ/year
Gas Cost*	$31/GJ
Emissions Intensity	12 kg CO_2e/GJ

* To achieve an IRR of 10% at 13 years, just after the capital has been fully depreciated.

Taranaki Organic Waste Case Study

Taranaki region has a population of 127,300 people, hence produces an estimated 3,700 tonnes of post-consumer food waste per year. This case study assumes a source separated food waste collection system is rolled out in the region. The pre-consumer food waste from supermarkets, based on population, is 1,600 tonnes/year. A portion of this is donated for human consumption through community organisations, hence 1,400 tonnes/year is available for digestion.

To boost biogas production, manure collection from dairy farms located South Taranaki is proposed. It is proposed the collected food waste, manure is digested in a new AD facility. This includes cleaning the biogas of contaminants, separating methane and CO_2. Biomethane will be injected into the grid, and CO_2 will be liquified for storage and transport.

There is also industrial wastewater from plants in South Taranaki which could provide an additional 0.1 PJ/year of biogas potential. However, as opposed to pumping this wastewater long distances to a centralized treatment plant with AD, a more sensible solution would be onsite AD at the industrial factories to treat the wastewater locally. Onsite containerized upgrading plants, and direct injection into the grid would be the most feasible solution, as opposed to piping biogas to a centralized upgrading plant. The addition of this feedstock has not been considered in the project proposed below due to the decentralized nature of the solution.

This centralised facility would collect food waste from across the region, and would consist of

- Feedstock pre-processing including de-packaging, magnetic removal of ferrous items, and some form of homogeniser such as a macerator or pulper
- Mesophilic, continuous, wet digestion
- Heat pump for digester heating to maximise biogas yield
- Biogas upgrading plant
- Biogas compression for transport
- CO_2 liquefaction and storage

Barriers:

- Effective collection of manure from farmers – this would be diluted during collection (i.e. hosed down in milking shed). Some settling would be required to thicken for transport. Decanted liquid stream could be irrigated to farmland
- Utilisation of manure collected on farm, with typical practice utilising manure as fertiliser on farm
- Effective uptake of food waste collection, and effective source separation by participating households
- Existing
- Preference for home composting as opposed to collection
- Pre-consumer food waste diverting feedstock from animal feed

Assumptions:

- Plant to be located in Stratford as a half-way point for Hawera and New Plymouth food waste collection
- Dairy manure to be collected from South Taranaki only to minimise transportation of dilute manure
- 90% recovery of household food waste, allowing some to landfill, and some to household composting
- Digestate to be marketed to local agricultural industry for soil enhancement (as opposed to fertilisers or composts). Digestate for manure system could be established to incentivise manure as a feedstock
- Biogas will be pre-treated to remove contaminants prior to upgrading at each site
- Biogas will be upgraded using membrane separation, with ~0% methane slip due inclusion of cryogenic condensation of CO_2. This will be achieved using containerised plants at each processing plant
- Biomethane is compressed for transport (no grid injection)
- Biomethane will be sold to the grid, and food grade CO_2 will be sold for beverage production

Table 13-11: Case Study Summary – Taranaki Organic Waste Digester

Parameter	Description
Case Study Description	• Installation of new AD facility in Stratford, Taranaki to digest organic waste • Installation of biogas upgrading plant • Injection of biomethane into the grid
Feed Stock	• Pre-consumer food waste from supermarkets: 1,400 tonnes/year • Post-consumer food waste from source separated food waste collection scheme: 3,300 tonnes/year (Total food waste – 4,700 tonnes/year) • Dairy manure: 49,000 tDS/year
Biomethane potential	0.3 PJ/year
Gas Cost*	$67/GJ
Emissions Intensity	19 kg CO_2e/GJ

* To achieve an IRR of 10% at 13 years, just after the capital has been fully depreciated.

Organic/Agricultural Waste to Biomethane

Waikato Organic/ Agricultural Waste Case Study

Waikato is a heavily agricultural region, with the highest proportion of New Zealand's dairy cows. Therefore, Waikato presents a god case study for a centralised digestion facility for manure collected off farms, mixed with other organic material including grass cut from fields, and green waste. Additionally, Waikato has access to the existing natural gas grid. The amounts of feedstocks are summarised in the table below.

Feedstock Amounts – Waikato Case Study

Feedstock	Amount (t/year)	Basis
Dairy Manure	904,000	• 22% of New Zealand's dairy cows located in Waikato • Assumes fresh manure has 25% solids

Feedstock	Amount (t/year)	Basis
		• Assumes all manure produced in milking sheds is feasible to collect
Pig Manure	116,000	• 17% of New Zealand's pig farms located in Waikato • Assumes fresh manure has 25% solids • Assumes 91% of pig manure is feasible to collect
Grass Crops	120,000	• 85:10:5 manure: grass crop: green waste feed ratio • Requires 3,500 ha or 0.3% of Waikato grassland to be cut for feedstock
Green Waste	60,000	• 85:10:5 manure: grass crop: green waste feed ratio

It is proposed the collected manure, organic waste, and grass crops are digested in a new AD facility. This includes cleaning the biogas of contaminants, separating methane and CO_2. Biomethane will be injected into the grid, and CO_2 will be liquified for storage and transport.

This facility will include:

- Feedstock reception facilities
- Mechanical pre-treatment for green waste, including some form of homogeniser such as a macerator or pulper
- Mesophilic, continuous, wet digestion
- Heat pump for digester heating
- Biogas upgrading
- Biomethane injection to grid.

Barriers:

- Utilisation of manure collected on farm, with typical practice utilising manure as fertiliser on farm
- Effective collection of manure from farmers – this would be diluted during collection (i.e. hosed down in milking shed). Some settling would be required to thicken for transport. Decanted liquid stream could be irrigated to farmland
- Conversion of grazing land to provide grass for feedstock
- Low solids content of manure for collection increasing volumes. This may limit the feasible collection efficiency for more remote farms in the region

Assumptions:

- Digestate is provided back to farmers to create circular economy for the supply of manure
- Injection to existing grid
- Assume all manure produced in milking sheds can feasibly be collected and transported
- Assume all pig manure produced can be feasibly collected and transported
- Assume transportation of manure by truck to centralised digestion and biogas upgrading facility
- Biogas will be pre-treated to remove contaminants prior to upgrading at each site
- Biogas will be upgraded using membrane separation, with ~0% methane slip due inclusion of cryogenic condensation of CO_2. This will be achieved using containerised plants at each processing plant
- Biomethane will be sold to the grid, and food grade CO_2 will be sold for beverage production

Table 13-12: Case Study Summary – Waikato Organic and Agricultural Waste Digester

Parameter	Description
Case Study Description	• Installation of new AD facility in central Waikato as a centralised facility to digest organic waste • Installation of biogas upgrading plant • Injection of biomethane into the grid

Parameter	Description
Feed Stock	• Dairy manure: 904,000 t/year (226,000 tDS/year) • Pig manure: 116,000 t/year (329,000 tDS/year) • Green waste: 60,000 t/year • Grass Crops: 120,000 t/year
Biomethane potential	2.0 PJ/year
Gas Cost*	$36/GJ
Emissions Intensity	20 kg CO_2e/GJ

* To achieve an IRR of 10% at 13 years, just after the capital has been fully depreciated.

Canterbury Case Study

Like Waikato, Canterbury is also a highly agricultural region. Canterbury has the majority of pig farms in the country, and also has a significant number of dairy farms. In addition to livestock, Canterbury has the majority of New Zealand's grain crops. Grain crops, once harvested, leave behind grain stubble in the fields, which could be collected for a feedstock. A notable difference is that Canterbury has no access to the existing natural gas grid, hence will require compression of the biomethane for transport. A summary of feedstocks is shown in the table below.

Feedstock Amounts – Canterbury Case Study

Feedstock	Amount (t/year)	Basis
Dairy Manure	616,000	• 15% of New Zealand's dairy cows located in Canterbury • Assumes fresh manure has 25% solids • Assumes all manure produced in milking sheds is feasible to collect
Pig Manure	449,000	• 66% of New Zealand's pig farms located in South Island – all are assumed in Canterbury • Assumes fresh manure has 25% solids • Assumes 91% of pig manure is feasible to collect
Grain Stubble	125,000	• 85:10:5 manure: crop residue: green waste feed ratio • Requires 60% of grain stubble produced in Canterbury
Green Waste	63,000	• 85:10:5 manure: grass crop: green waste feed ratio

It is proposed the collected manure, organic waste, and crop residues are digested in a new AD facility. This includes cleaning the biogas of contaminants, separating methane and CO_2. Biomethane will be compressed for transport, as this plant is not in proximity to the existing natural gas network. The CO_2 will be liquified for storage and transport.

Barriers:

- Utilisation of manure collected on farm
- No natural gas grid present in the region, hence gas will need to be compressed for transport
- Grain stubble is often burnt in paddock, which returns nutrients to the soil and is effective part of weed control
- Utilisation of manure collected on farm, with typical practice utilising manure as fertiliser on farm
- Effective collection of manure from farmers – this would be diluted during collection (i.e. hosed down in milking shed). Some settling would be required to thicken for transport. Decanted liquid stream could be irrigated to farmland
- Low solids content of manure for collection increasing volumes. This may limit the feasible collection efficiency for more remote farms in the region

Assumptions:

- Digestate is provided back to farmers to create circular economy for the supply of manure
- Assume all manure produced in milking sheds can feasibly be collected and transported
- Assume all pig manure produced can be feasibly collected and transported
- Assume transportation of manure by truck to centralised digestion and biogas upgrading facility
- Biogas will be pre-treated to remove contaminants prior to upgrading at each site
- Biogas will be upgraded using membrane separation, with ~0% methane slip due inclusion of cryogenic condensation of CO_2. This will be achieved using containerised plants at each processing plant
- Compression of biomethane for transport

Table 13-13: Case Study Summary – Canterbury Organic and Agricultural Waste Digester

Parameter	Description
Case Study Description	• Installation of new AD facility in Canterbury as a centralised facility to digest organic waste • Installation of biogas upgrading plant • Injection of biomethane into the grid
Feed Stock	• Dairy manure: 616,000 t/year (154,000 tDS/year) • Pig manure: 449,000 t/year (112,000 tDS/year) • Green waste: 63,000 t/year • Grain stubble: 125,000 t/year
Biomethane potential (PJ/year)	2.1 PJ/year

Agricultural Feedstock to Biomethane

Hawkes Bay Agricultural Case Study

This project is for installation of a dry anaerobic digester which can produce 5 PJ/year from digestion of grass. This grass would be harvested and converted to silage for storage of feedstock to allow consistent feedstock availability year-round. The proposed location is in Hawkes Bay.

Hawkes Bay has 672,000 ha of highly productive grassland. Current land use for this is likely dairy farming or other grazing practices. It is proposed that 43,000 ha, or 6% of this land be diverted from active grazing land to provide feedstock for digestion.

Barriers:

- Based on the operating profit for dairy farming in Hawkes Bay, a premium of $3,000/ha would be required to effectively purchase the grass from farmers (DairyNZ 1, 2021). This is a premium on top of the other operating costs to produce biomethane of $26/GJ.
- Diversion of land currently used for food production (via animal grazing) is likely to experience negative public perception. Additionally, growing grass for energy would need to be economically incentivized to encourage farmers to uptake this.

Assumptions:

- Digestate is provided back to farmers to create circular economy for the supply of grass
- Injection to existing grid
- Assume transportation of silage by truck to centralised digestion and biogas upgrading facility, with grass collected from a number of properties to minimise impact on one location (i.e. not a full conversion of a single farm
- Biogas will be pre-treated to remove contaminants prior to upgrading at each site
- Biogas will be upgraded using membrane separation, with ~0% methane slip due inclusion of cryogenic condensation of CO_2. This will be achieved using containerised plants at each processing plant
- Biomethane will be sold to the grid, and food grade CO_2 will be sold for beverage production

Table 13-14: Case Study Summary – Hawkes Bay Grass Digester

Parameter	Description
Case Study Description	• Installation of new AD facility in Hawkes Bay to digest grass/silage • Installation of biogas upgrading plant • Injection of biomethane into the grid
Feed Stock	• Grass or other energy crop harvested from 43,000 ha of productive grassland: 1,450,000 t/year grass
Biomethane potential	5.0 PJ/year
Gas Cost*	$68/GJ
Emissions Intensity	19 kg CO_2e/GJ

Woody Biomass to Biomethane

a. Landing Residues

Woody biomass is not suitable for anaerobic digestion due to the high lignocellulosic material content resulting in low digestibility without extensive pre-treatment. Therefore, this project looks at the conversion of woody biomass to biomethane via gasification and methanation pathways.

47% of total production was in Central North Island, hence this project focuses on collecting landing residues from Central North Island and processing at a centralized gasification and methanation plant. Biomethane produced will be injected into the grid as the plant will be in proximity of the existing natural gas network.

Barriers:

- Direct utilization of woody biomass as a solid fuel represents a lower cost alternative for utilization of this energy
- Existing users of landing residues will have solid fuel displaced for gaseous fuel production

Assumptions:

- 47% of national landing residues are located in the Central North Island (1,050,000 m^3/year). It is assumed 95% of these residues can be collected as a feedstock (995,000 m^3/year)
- It is assumed any existing utilization of these residues is diverted for use as feedstock
- Syngas cleaning prior to methanation to remove contaminants
- Biomethane produced to be injected into the existing natural gas grid.
- Assume 55% MC
- Assume landing residues can be provided at no charge (i.e. freely available feedstock)

Table 13-15: Case Study Summary – Central North Island Landing Residue Woody Biomass to Methane

Parameter	Description
Case Study Description	• Installation of new gasification and methanation facility in the Central North Island to produce syngas and process to methane via methanation process • Injection of biomethane into the grid
Feed Stock	• Woody biomass (landing residues) from harvesting sites • 995,000 m^3/year (184,000 dry t/year)
Biomethane potential (PJ/year)	1.4 PJ/year
Feedstock Costs ($/GJ CH_4)	$0/GJ

b. Landing Residues and Wood Chip/Pulp Logs

In addition to the case study mentioned above, a larger scale facility would be possible if lower value wood products are diverted for energy feedstocks.

This case study considers a gasification and methanation plant, located in Central North Island as above. Feedstock includes the landing residues quantified above, with the addition of pulp and wood chips that are currently exported. 200,000 t/year of woodchip and 3,275,000 t/year (wet) of pulp were exported in 2020. This represents an additional 3,500,000 t/year of woody biomass. Additionally, approximately 20,000,000 t/year of un-processed logs are exported. Therefore, the scale of feedstock available is limited by the amount of product that can be diverted from export. This will very depending on the government incentives in place to encourage utilisation of woody biomass as opposed to export.

Barriers:

- Direct utilization of woody biomass as a solid fuel represents a lower cost alternative for utilization of this energy
- Existing users of landing residues will have solid fuel displaced for gaseous fuel production
- Diversion of export products for domestic energy production. If these products are to be diverted, they will again be competing with solid fuel markets which could utilise the woody biomass as a heat source. The cost of diverted export product for a feedstock would be greater than unutilised residues.
- Different grades of woody biomass are likely to have different amounts of contaminants in syngas, and offer different yields.

Assumptions:

- 47% of national landing residues are located in the Central North Island (1,050,000 m^3/year). It is assumed 95% of these residues can be collected as a feedstock (995,000 m^3/year)
- It is assumed any existing utilisation of these residues is diverted for use as feedstock
- Diversion of 100% of exported woodchip, and 35% of exported pulp
- Syngas cleaning prior to methanation to remove contaminants
- Biomethane produced to be injected into the existing natural gas grid
- Quantities of woody products to be used as feedstock was determined based on the economic scale of plant. Due to the complexity of this technology, it is assumed at a product potential <1 PJ/year would not be sufficient.
- The plant would be located in proximity to an existing export port such that pulp and chip could be readily transported to the site for processing.
- Assume 50% MC – as forestry residues have ~55% MC and pulp ~40%MC
- Assume landing residues can be provided at no charge (i.e. freely available feedstock)
- Assume the cost of diverted export products represents feedstock costs

Table 13-16: Case Study Summary – Central North Island Landing Residue Woody Biomass to Methane

Parameter	Description
Case Study Description	• Installation of new gasification and methanation facility in the Central North Island to produce syngas and process to methane via methanation process • Injection of biomethane into the grid
Feed Stock	• Woody biomass (landing residues) from harvesting sites • 995,000 m^3/year (184,000 dry t/year) • Woodchip • 100,000 dry t/year • Pulp • 690,000 dry t/year • Total woody biomass • 970,000 dry t/year

Parameter	Description
Biomethane potential (PJ/year)	7.5 PJ/year
Feedstock cost ($/GJ CH_4)	$130/GJ

Woody Biomass to DME

Without access to existing natural gas infrastructure in the South Island, conversion of woody biomass to other fuels has also been considered.

This case study considers a plant situated in the Nelson region, which has the highest forestry production in the South Island. A plant will take woody biomass from landing residues, produce syngas via gasification, and produce DME via methanol synthesis step.

Approximately 270,000 m^3/year (110,000 t/year) of landing residues are produced in Nelson, based on 12% of wood supply being from the Nelson/Marlborough region. Due to the low quantity available, it is proposed to utilise some exported wood product. Consideration of approximately 1/3 of the exported pulp has bene included. Wood chip has not been included as it is assumed the available woodchip would be utilised by other processes before this technology would be developed enough to be operating at commercial scale, and the natural gas demand is greater than the LPG demand, hence more feedstock is diverted to methanation (as per case studies above).

The scale of this plant was considered to make a significant contribution to the current LPG demand, hence assumes utilisation of some exported wood products to meet a viable scale.

Barriers:

- Direct utilization of woody biomass as a solid fuel represents a lower cost alternative for utilization of this energy
- Existing users of landing residues will have solid fuel displaced for gaseous fuel production
- Diversion of export products for domestic energy production. If these products are to be diverted, they will again be competing with solid fuel markets which could utilise the woody biomass as a heat source. The cost of diverted export product for a feedstock would be greater than unutilised residues.
- Different grades of woody biomass are likely to have different amounts of contaminants in syngas, and offer different yields.

Assumptions:

- 12% of national landing residues are located in the Nelson/Marlborough region (270,000 m^3/year). It is assumed 95% of these residues can be collected as a feedstock (255,000 m^3/year)
- It is assumed any existing utilization of these residues is diverted for use as feedstock
- Syngas cleaning prior to methanation to remove contaminants
- DME is produced and bottled for LPG users
- Assume landing residues can be provided at no charge (i.e. freely available feedstock)
- Assume the cost of diverted export products represents feedstock costs

Table 13-17: Case Study Summary – Nelson Woody Biomass to DME

Parameter	Description
Case Study Description	• Installation of new gasification facility, and DME production plant utilising methanol synthesis pathway in Nelson region • Bottling of DME for LPG market
Feed Stock	• Woody biomass (landing residues) from harvesting sites • 255,000 m^3/year (47,000 dry t/year) • Pulp

Parameter	Description
	• 690,000 dry t/year • Total woody biomass • 735,000 dry t/year
DME potential	4.1 PJ/year
Feedstock cost ($/GJ DME)	$177/GJ

Tallow to rLPG

This project considers the conversion of South Island tallow in a centralized biodiesel production and refining plant located in Dunedin. Dunedin is central to the majority of the South Island rendering plants, which are located from Southland to Canterbury.

New Zealand produces approximately 160,000 tonnes per year, with the majority being exported. This case study assumes that the tallow produced in the South Island will be utilised at this plant, diverting some from the current export channels.

Barriers:

- Biodiesel is made from tallow via transesterification pathway. The crude biodiesel is then refined. This has a target product of liquid fuels, though a light fraction is produced. The yield of rLPG from crude biodiesel is only 5-10%. The light fraction is often consumed within the plant to provide process heat.
- This case study assumes the diversion of export tallow for fuel production. This would come at a high cost for the feedstock (to meet export prices) or economic incentives would be required to support national use of tallow over exporting.
- There is a small LPG reticulation network in Dunedin. However, if demand drops over time, these networks may diminish. Therefore, it has been assumed rLPG would be bottled for flexibility of use.

Assumptions:

- 50% of the total tallow production is produced in the South Island (80,000 t/year)
- 100% of South Island tallow production is utilised as a feedstock
- A new biodiesel plant will be built in Dunedin, including biodiesel refining
- rLPG separated during refining will be bottled for transport

Table 13-18: Case Study Summary – Dunedin Tallow to rLPG

Parameter	Description
Case Study Description	• Installation of new biodiesel production and refining facility in the Dunedin area • Bottling of rLPG
Feed Stock	• Tallow • 80,000 t/year
Biomethane potential	0.3 PJ/year
Feedstock cost ($/GJ rLPG)	$318/GJ