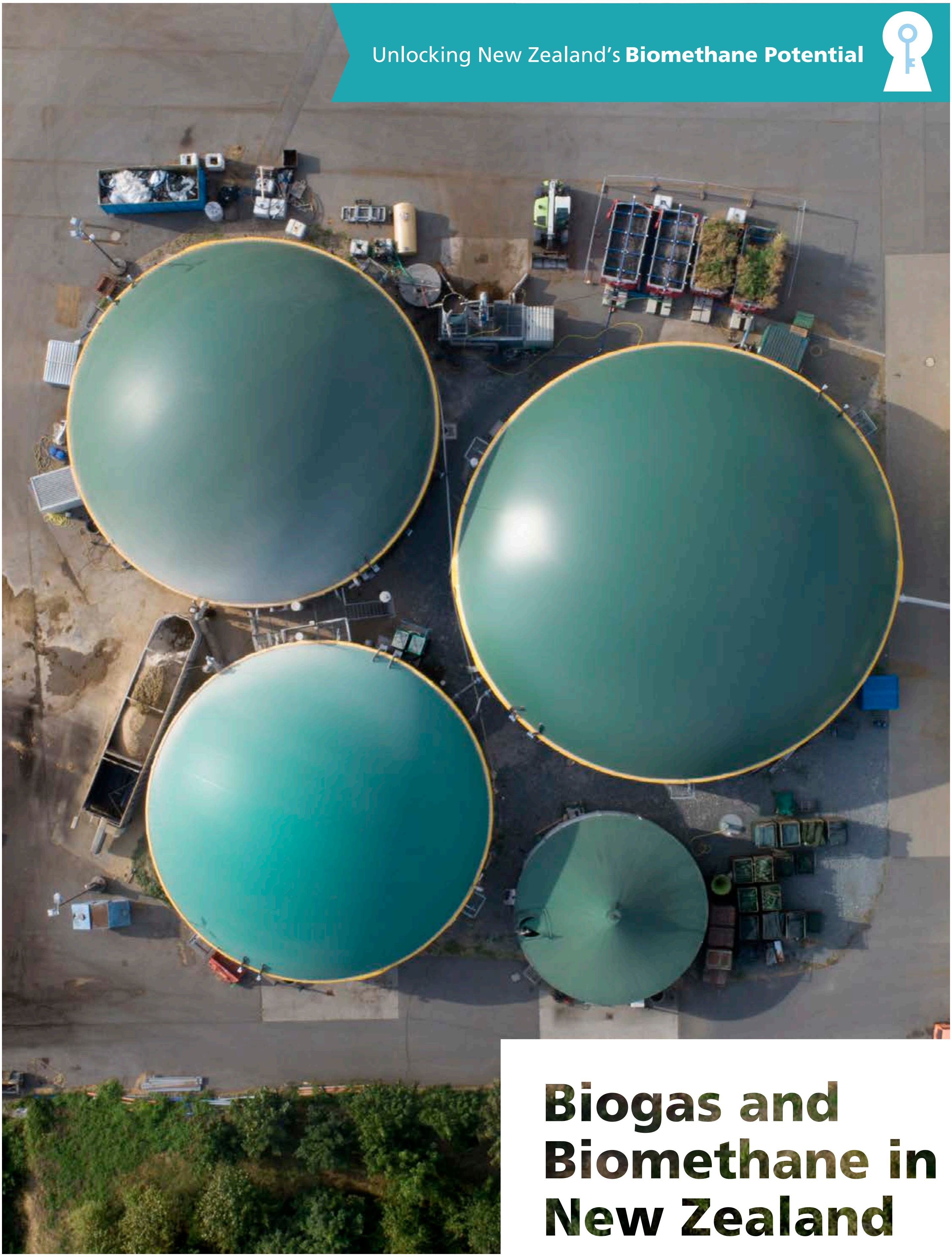
Unlocking New Zealand's **Biomethane Potential**



Biogas and Biomethane in New Zealand

TE TARI TIAKI PŪNGAO
ENERGY EFFICIENCY & CONSERVATION AUTHORITY

Dairy for life

Executive Summary

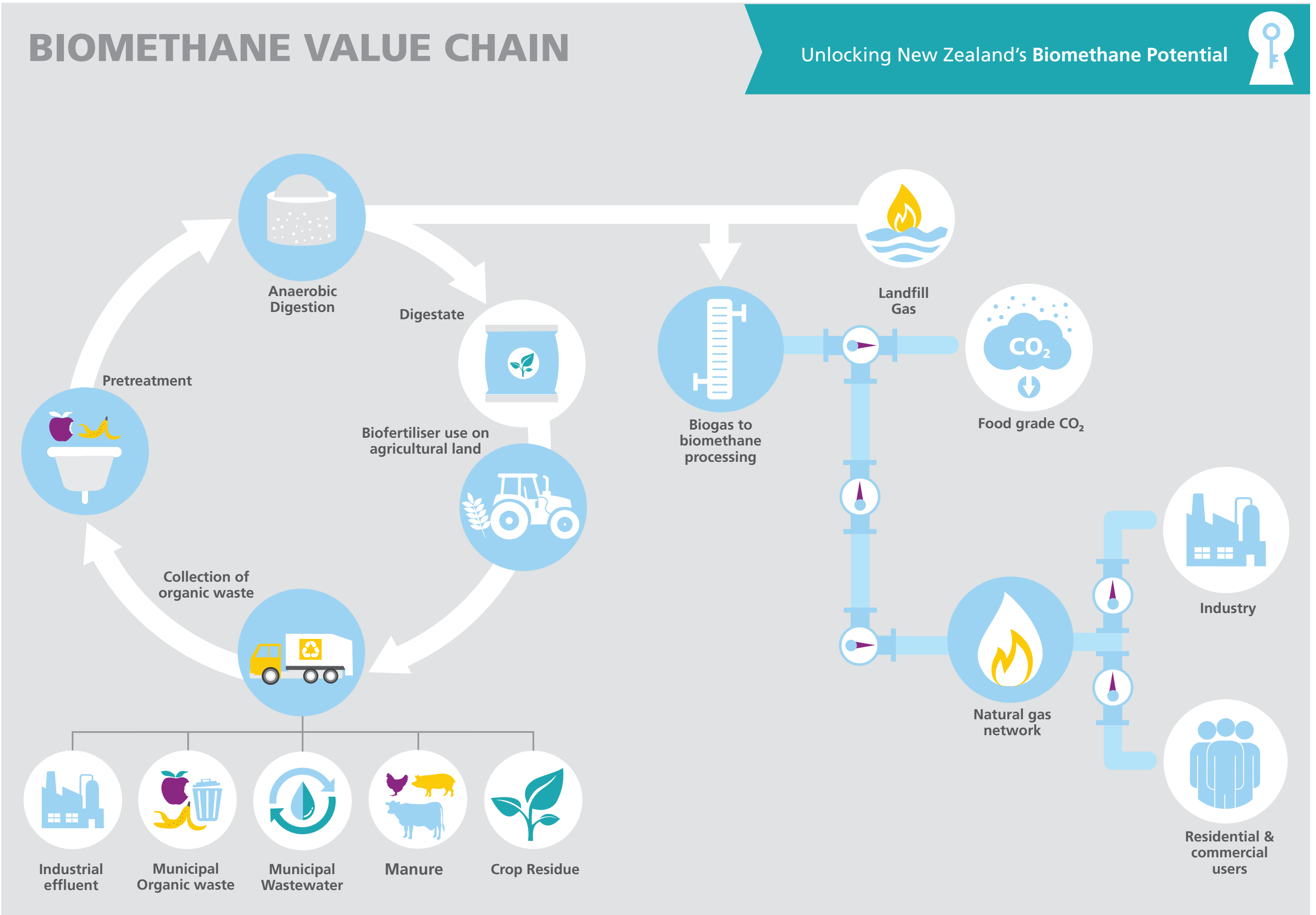
Natural gas is a key component of New Zealand's energy system; it provides heating to homes, businesses and **powers a large part of our industry. As well as being used for heat, methane is an important feedstock for some of New Zealand's largest chemical processing operations.**

Natural gas is both a fossil fuel and greenhouse gas. If New Zealand wishes to fully decarbonise its energy sector then a transition away from natural gas to lower emitting gases will be an essential step.

As discussed in the Climate Change Commission's (CCC) final advice report, low emission gases may have a part to play in New Zealand's decarbonisation. The CCC have indicated that the economics and feasibility of these technologies in a New Zealand context are not well understood, and more work is required to evaluate what role they may be able to play.

A popular low emission gas overseas that has seen little interest to date in New Zealand is biomethane; a renewable green methane substitute produced by biologically digesting organic waste materials and upgrading the gas produced. It is chemically identical to natural gas, but over the full biomethane value chain it prevents up to 95% of associated carbon emissions.

This study, conducted by Beca, Firstgas Group, Fonterra and EECA, explores the potential presented by biomethane in New Zealand. While this report is not a response to the CCC, we believe it outlines a potential pathway and **the high level economics required to evaluate the part biomethane could play in New Zealand's energy transition.**



Why Biomethane?

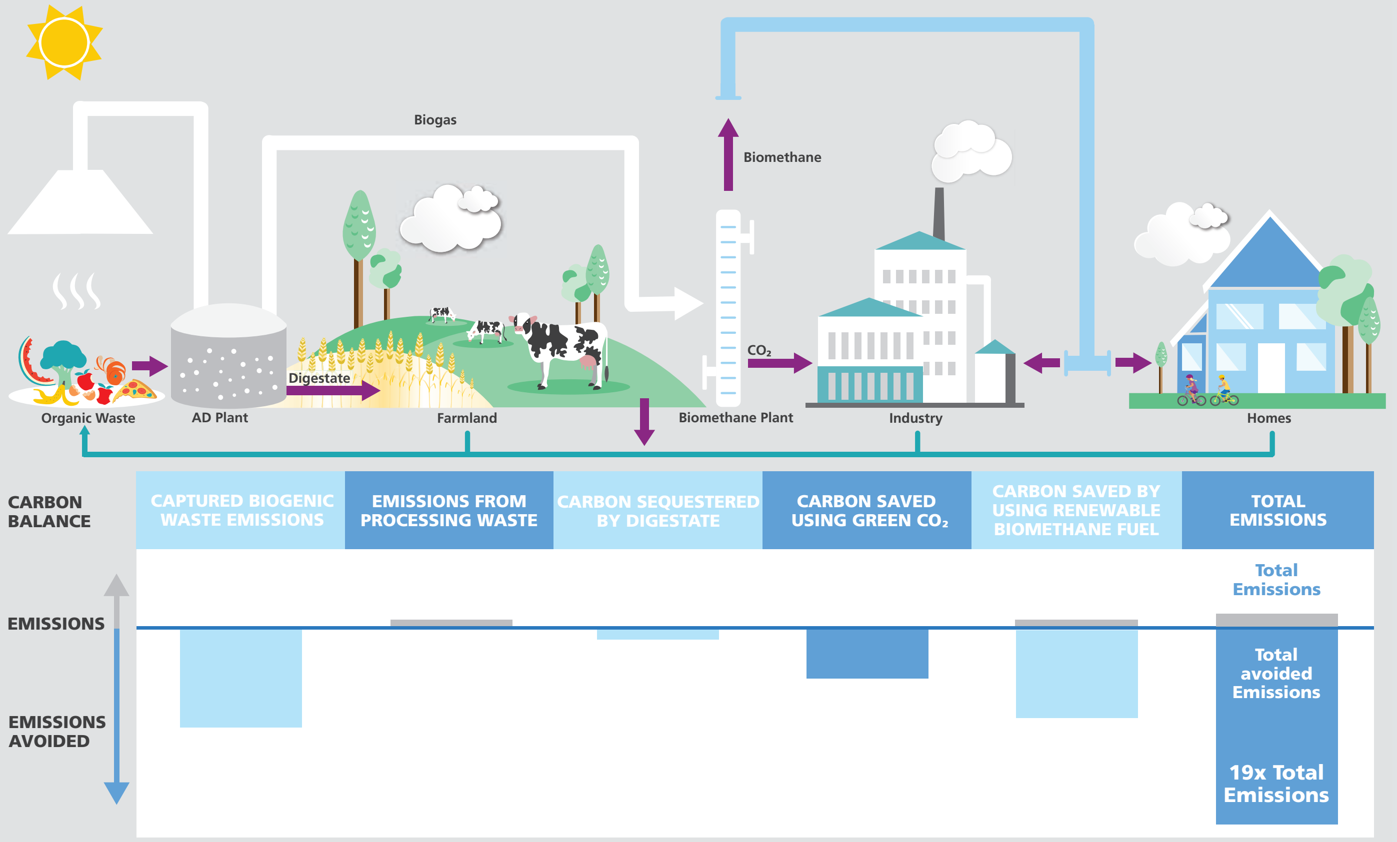
Production and utilisation of biomethane via digestion of organic wastes and processing the raw biogas **creates benefits for gas users, waste generators, asset owners, their communities and the environment.**

Diverting organic wastes from landfills or other end locations to anaerobic digestion **decreases associated biogenic emissions for that waste by up to 95%**. The methane captured from the waste being processed in an anaerobic digester can then be treated and used to offset fossil fuel consumption, **which more than doubles the carbon savings**.

A positive upside for boiler operators is the chance to use upgraded biomethane as a drop-in replacement for their natural gas with none of the emissions. This provides an invaluable opportunity to decarbonise their energy use without needing to make any changes to their onsite assets.

Key differentiators between biogas and biomethane generation and other popular renewable fuel sources is the creation of other valuable by-products through the biomethane value chain. The creation of valuable products like digestate and green CO_2 **bolster the financial and environmental benefits of biomethane production, and combined with the capture of biogenic emissions more than double the total emissions avoided throughout the product lifecycle.**

> "The methane captured from the waste being processed in an anaerobic digester can then be treated and used to offset fossil fuel consumption, which more than doubles the carbon savings".



Biogas and Biomethane: Technologies and Use Internationally

Biogas can be created by anaerobic digestion of many types of high-energy organic wastes, such as:

- **Food wastes;**
- **Animal manures;**
- **Wastewater treatment sludges;**
- **Crop residues; and**
- **Industrial effluents with lots of dissolved organic material.**

Biogas can also be collected from landfills that receive organic wastes – this gas is very similar to biogas but contains other contaminants from non-organic material in the landfills. One of the differences between biogas creation via anaerobic digestion (AD) and collection of landfill gas **is the creation of a solid residue called digestate, a processed and inert material that can be used as a fertiliser supplement.**

After biogas has been created, it can either be used for direct energy or cleaned and refined into biomethane. **This process enables the gas to be injected into natural gas networks, transported and used as a direct substitute for natural gas.**

Internationally, biogas and biomethane have been identified as key mechanisms for decarbonisation and energy independency in a number of countries. Denmark is currently using biomethane to supply 20% of its natural gas grid, with a goal to completely displace its fossil-methane consumption with biomethane by 2050. Other countries are also committing to legally-binding biomethane grid injection targets, like France which in 2015 set a target to rapidly expand its biomethane production and reach 10% biomethane in its grid by 2030.

Commercially, biomethane is becoming an important part of the development strategies for many large international oil and gas companies. **Companies like Total and Chevron are investing in biomethane projects to support development of new biofuel technologies and enable a transition to greener fuels.**

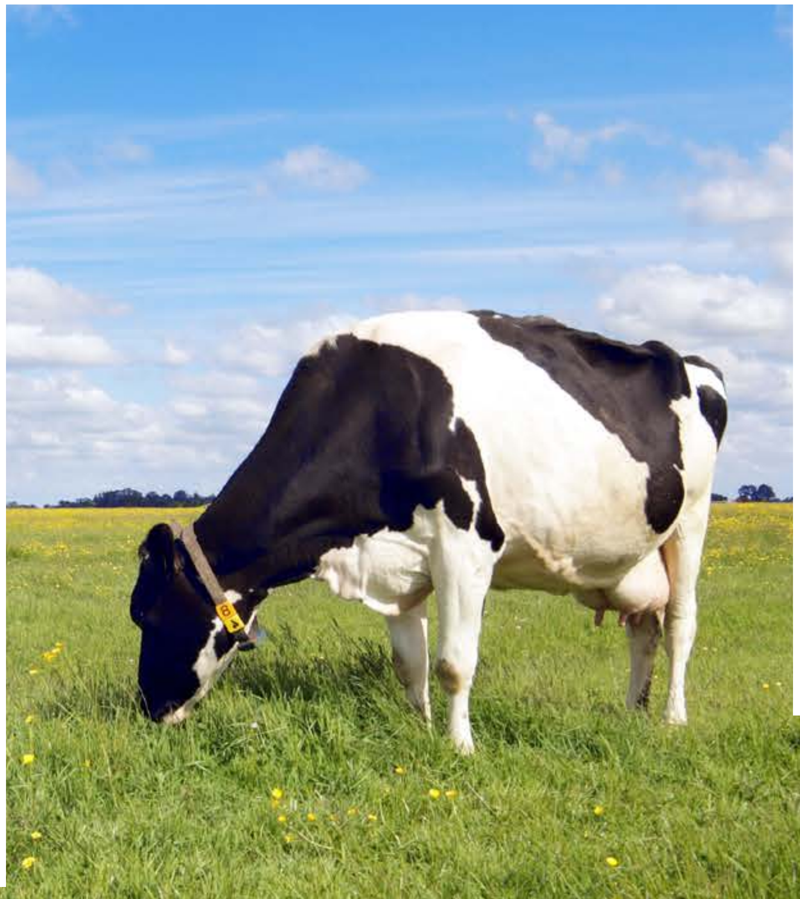
The Size of The Biogas Prize in New Zealand

We have reviewed available quantities of feedstocks in New Zealand to understand the **maximum achievable biogas generation with existing waste streams.**

The only key feedstock popular overseas that we did not consider a large contributor to New Zealand's possible biomethane future is the use of purpose-grown biomass or energy crops for biogas generation, as energy crops are not an established agricultural product in New Zealand and are unlikely to take off in New Zealand given our already highly-productive agricultural sector occupying the majority of available land for energy crops.

Our estimates indicate that implementation of wide-scale anaerobic digestion in New Zealand could produce between 13 and 17 PJ of biogas energy per year, as well as large quantities of CO_2 and digestate as valuable by-products. This estimate excludes current biogas generation via landfills (around 3 PJ), which may decrease over time as a result of diverting food waste to AD facilities.

The most significant sources of biogas identified in our analysis were Dairy Manure (5-6.8 PJ), Dairy and Meat Industry Effluents (2.6 PJ) and Source-Segregated Food Waste (1.5 PJ).



Category	Feedstock Type	Biogas Potential (PJ/year)
Municipal Waste	Municipal Wastewater solids	0.6 to 0.9
	Source-Segregated Food Waste	1.5
Industrial Wastewater*	Dairy	1.1 to 1.9
	Meat	0.7
	Pulp and Paper	0.6
	Dairy Manure	**6.8**
Agricultural Waste	Pig Manure	0.4
	Poultry Manure	1.3
	Crop Residue	1.4 to 2.9
	Total	**12.6 to 16.9 PJ**
Landfill Gas	Existing Landfill Gas Capture	3
	Total	**15.6 to 19.9 PJ**

These figures are based on a set of assumptions around achievable collection of different feedstocks in a New Zealand context, typical conversion rates and technical limitations on processing different waste streams.

Implementation of Biomethane + Uptake Towards 2050

Today in New Zealand biogas and biomethane are not part of the main zero-carbon energy conversation, **and this has meant that biogas has been championed by only a few private companies and experts in the field.**

To date, the majority of New Zealand's biogas generation has been from wastewater treatment plants (WWTPs), a few private companies like Fonterra (at their Tirau and Darfield sites), small piggeries and from landfill gas capture operations. None of these operations currently upgrade their biogas to biomethane.

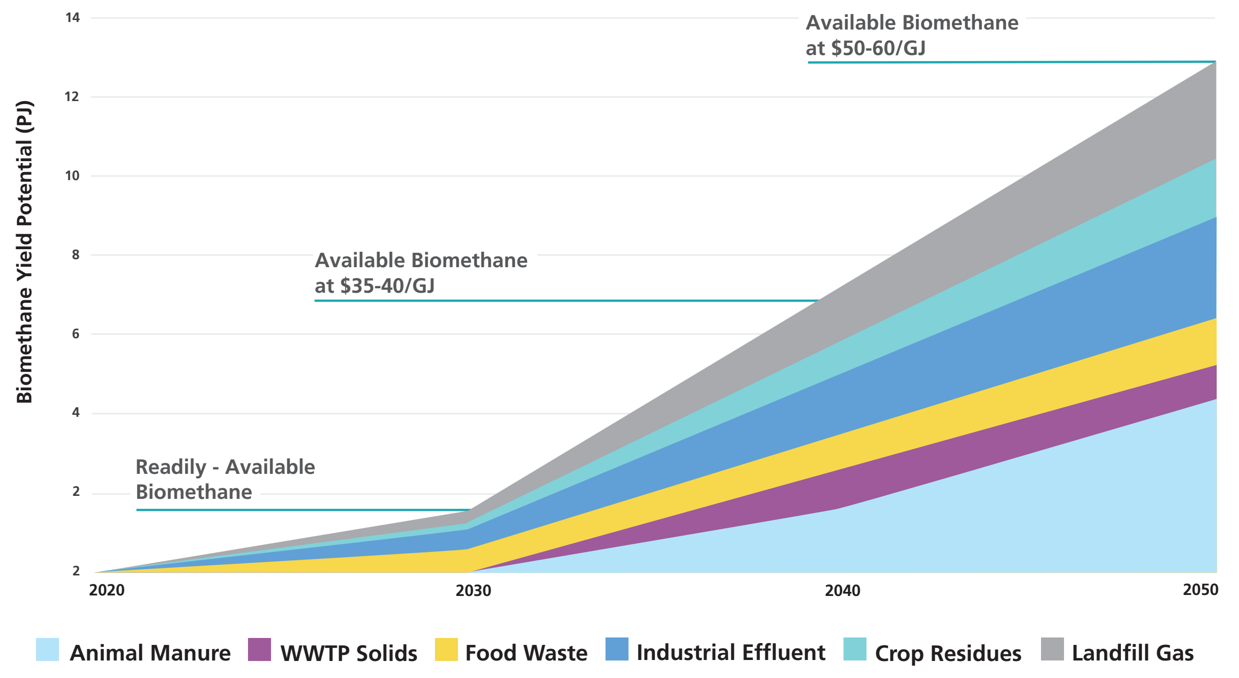
Our analysis shows that digestion plants producing biomethane can become profitable today if supported by charging a gate fee for reception of wastes as well as also selling CO_2 and digestate as a by-product.

We estimate that a biomethane sale price similar to current natural gas prices could allow up to 1.6 PJ could be made using readily available feedstocks.

A further 5.6 PJ would become available in coming decades as natural gas prices increase above $35 /GJ, driven by Emissions Trading Scheme (ETS) price rises and natural gas scarcity. Out to 2050, 13 PJ could become available as hard-to-utilise feedstocks like animal manure and crop residue, which don't stack up economically today, become viable at biomethane prices of $50-60 /GJ. **These high prices help to provide revenue for new plants that cannot charge a gate fee or maximise their digestate value.**

Separate from these totals, large percentages of our identified feedstocks can be used for small-scale biogas generation for heating or Combined Heat and Power (CHP). Small-scale on farm digesters or digesters at small industrial sites can still be used to reduce emissions and create clean energy at scales where biomethane creation and injection to the natural gas pipeline is too difficult.

Biomethane Potential Over Time



Barriers to Maximising Biomethane and How They Can be Overcome

Biogas and biomethane are well-established overseas, but the technology has not experienced the same success in New Zealand.

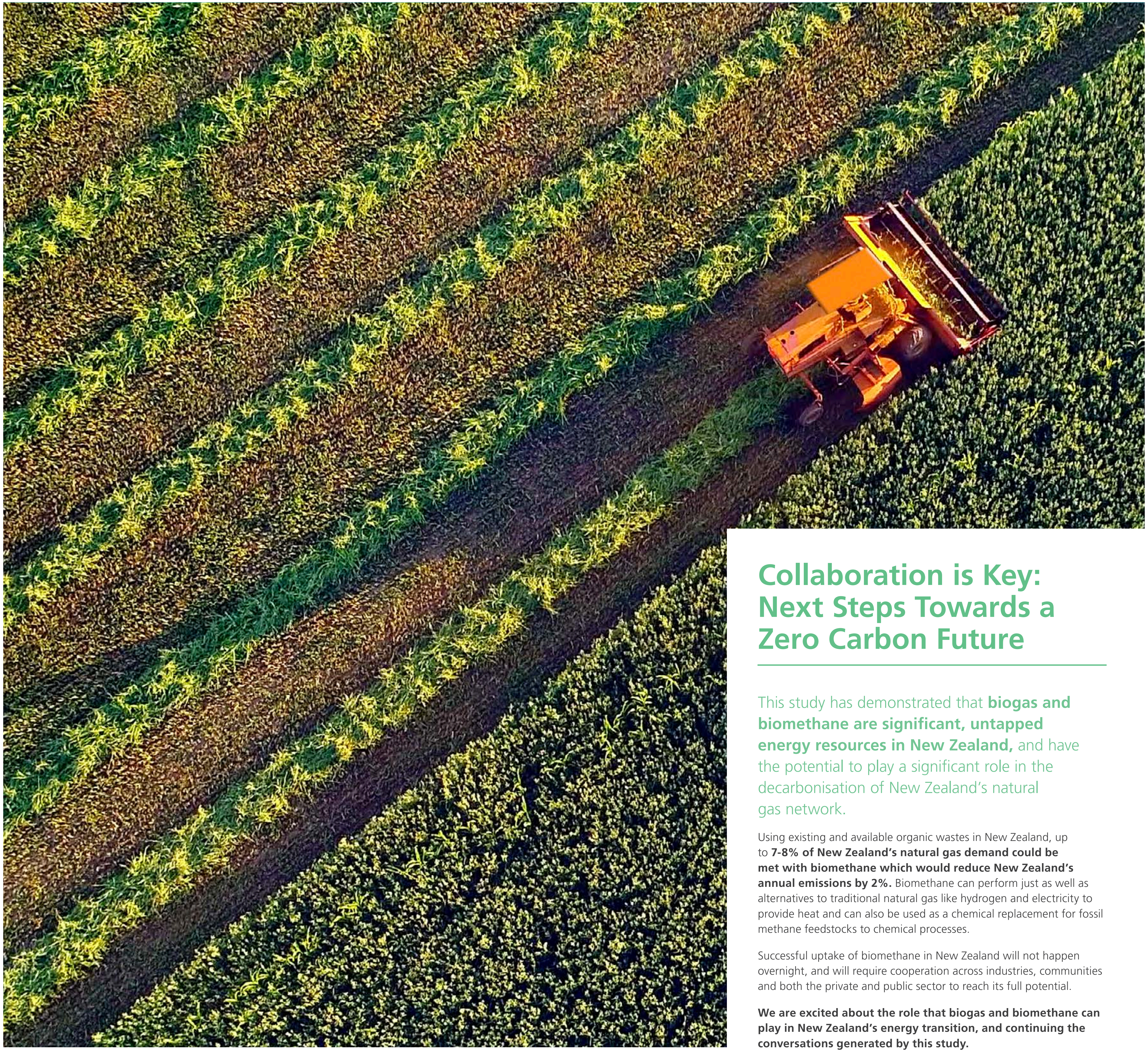
New Zealand's low landfill taxes mean that it is easier and more convenient to simply send organic waste to landfill, whereas overseas high landfill taxes, bans on organic materials to landfill and more regenerative and circular approaches to waste management have **created demand for alternative technologies like anaerobic digestion.** Promotion of more circular economies for all kinds of waste in New Zealand would create a more sustainable approach to waste management and allow a more regenerative economy to develop. Coordinating separate waste collection for suitable organic wastes can also be a logistical barrier to building the case for a large-scale plant, especially if the individual wastes are all different in composition.

> **"Promotion of more circular economies for all kinds of waste in New Zealand would create a more sustainable approach to waste management and allow a more regenerative economy to develop."**

One of the key differences between New Zealand and other countries overseas is the lack of green gas and high-quality digestate certification systems locally. **Overseas, companies can sell the biomethane they generate as a premium product, supported by the trading of green gas credits which can benefit purchasers in their emissions reporting etc.** Additionally, digestate created by processing clean organic wastes can be certified and sold as a fertiliser supplement for use in agriculture. In particular, digestate represents a large value stream that should be monetised, but requires support to realise its full value and address the barriers affecting its uptake in New Zealand. **If not enabled, the loss of potential revenue from digestate can significantly affect the profitability of biogas and biomethane generation.**

These two schemes support additional revenue generation of biogas and biomethane plants, boosting profitability and returns for investors, and also create additional ways for these plants to support New Zealand's other primary industries. It is promising to see Certified Energy and the Bioenergy Association's recent steps to publish draft proposals for these schemes in recent months, and suggests this barrier may be removed in the near future.

Financially, countries that have experienced the fastest and most transformative uptakes in biogas and biomethane production have been supported by central government via green investment schemes, guaranteed Feed-In Tariffs and further taxes on top of ETS schemes for producers of fossil fuels/heavy emitters of GHGs. This helps make alternative biofuels more cost-comparative with incumbent fossil fuels in the early stages of investment, as markets develop and adjust to these new fuels and particularly other by-products of biogas and biomethane processing.



Collaboration is Key: Next Steps Towards a Zero Carbon Future

This study has demonstrated that **biogas and biomethane are significant, untapped energy resources in New Zealand,** and have the potential to play a significant role in the decarbonisation of New Zealand's natural gas network.

Using existing and available organic wastes in New Zealand, up to **7-8% of New Zealand's natural gas demand could be met with biomethane which would reduce New Zealand's annual emissions by 2%.** Biomethane can perform just as well as alternatives to traditional natural gas like hydrogen and electricity to provide heat and can also be used as a chemical replacement for fossil methane feedstocks to chemical processes.

Successful uptake of biomethane in New Zealand will not happen overnight, and will require cooperation across industries, communities and both the private and public sector to reach its full potential.

We are excited about the role that biogas and biomethane can play in New Zealand's energy transition, and continuing the conversations generated by this study.

Contents

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Acronyms and Units

AD = Anaerobic Digestion

BIP = Biomethane Injection Point

CAPEX = Capital Expenditure

CBG = Compressed Biogas

CH_4 = Methane

CHP = Combined Heat and Power

CNG = Compressed Natural Gas

CO_2 = Carbon Dioxide

CO_2e = Carbon Dioxide-equivalent (referring to Greenhouse gases in terms of their GWP)

COD = Chemical Oxygen Demand

CV = Calorific Value

EJ = Exajoules ($1x10^{18}$ Joules)

EPA = Environmental Protection Agency

EROI = Energy Return on Investment

ETS = Emissions Trading Scheme

EU = European Union

EV = Electric Vehicle

FIT = Feed-In Tariff

GHG = Greenhouse Gas(es)

GJ = Gigajoule ($1x10^9$ Joules)

GWh = Gigawatt hours ($1x10^9$ Watt hours)

GWP = Global Warming Potential

H_2S = Hydrogen Sulfide

Ha = hectare

kW = Kilowatt ($1x10^3$ Watts)

kWh = Kilowatt hours ($1x10^3$ Watt hours)

kt = kiloton

LCOE = Levelised Cost of Energy

LFGR = Landfill Gas Recovery

LNG = Liquified Natural Gas

LPG = Liquified Petroleum Gas

MAC = Marginal Abatement Cost (Undiscounted)

MSW = Municipal Solid Waste

MW = Megawatt (1x10^6 Watts)

MWh = Megawatt hours (1x10^6 Watt hours)

Nm^3 = Normal cubic metres (i.e. at standard conditions)

NPV = Net Present Value

ODM = Organic Dry Matter

OECD = Organisation for Economic Co-operation and Development

OLR = Organic Loading Rate

PAS = Publicly Available Standard

PJ = Petajoules (1x10^{15} Joules)

ppm = Parts per Million

RNG = Renewable Natural Gas

SO_2 = Sulphur Dioxide

t = Metric Tonnes

TS = Total Solids

TJ = Terajoules (1x10^{12} Joules)

TWh = Terawatt hours (1x10^{12} Watt hours)

VAT = Value-added Tax

VFA = Volatile Fatty Acids

WACC = Weighted Average Cost of Capital

WWTP = Wastewater Treatment Plant

Context

Biogas is a renewable, reliable and local source of energy. Overseas, the biogas industry provides an alternative route for the treatment of organic waste while supporting the development of local economies and providing clean energy to millions of people. Biogas can also be refined into biomethane by removing contaminants and impurities, which makes it a direct substitute for natural gas allowing for injection into existing pipeline systems with the only required modification being the tap-in point which supports a greater variety of gas end-users. Globally, worldwide biogas production is estimated to be equal to around 2 EJ (or 2,011 PJ), with total potential being equal to fifteen times this amount (30 EJ).

In New Zealand, biogas is an established industry with significant unrealised potential; only 3.5 PJ of biogas is collected and utilised from landfills, wastewater treatment facilities industrial manufacturing sites across the country annually. In 2020 New Zealand's first commercial anaerobic digestion plant for source-segregated food waste was announced in Reporoa which will divert an estimate 75,000 t of food waste from landfill annually, and generate around 0.3 PJ of biogas alone.

Most of the OECD leads New Zealand in terms of biogas and biomethane generation. Most parts of New Zealand still dispose of most of their organic wastes to landfill which leads to large volumes of fugitive emissions. The non-circular, non-regenerative approaches to managing these waste streams contribute to some of the largest measured GHG sources in New Zealand.

Additionally, while New Zealand may have one of the most renewable electricity networks in the world, in terms of gross energy potential New Zealand uses more natural gas than electricity per annum, including non-energy uses of natural gas e.g. as a chemical feedstock.

This report stems from a shared interest of multiple organisations to evaluate the potential contribution of biogas and biomethane to decarbonising our primary energy by supplementing fossil methane with biogas. The study partners realise the complexities of these opportunities and believe that this report is the first step to quantifying the opportunities presented by biogas/biomethane technologies.

The preparation of this report employed a variety of approaches, including:

- Engagement with New Zealand biogas industry stakeholders: potential generators, distributors and users, to gain insight into how a market for biomethane and other anaerobic digestion products could develop in New Zealand and support decarbonisation of the natural gas network
- Review of academic literature and technical reports on the development and implementation on biogas and biomethane technology around the world, and opportunities for New Zealand based on these findings.

This report is not intended for use as a policy document or official directive to industry stakeholders; it is intended to demonstrate the potential and benefits of biogas and biomethane in New Zealand and highlight the key enablers and barriers to the continued growth and development of biogas and biomethane as a low emissions fuel source and the success of this technology in New Zealand between now and 2050.

1 Introduction to Biogas and Biomethane

1.1 What is Biogas?

Biogas is an energy-rich mixture of gases produced as biological materials are broken down by bacteria in the absence of air or oxygen. Previously called 'marsh gas', it was discovered and analysed in the 1800's by scientists investigating the sources of flammable gases emitted from swamps.
Some speculate that biogas produced in covered marshes and swamps may have been the source of ancient myths and legends such as dragons and will-o-the-wisps. The biogas emitted from underground would occasionally ignite after mixing with air, producing short-lived flickering flames.

The main gaseous components of biogas are methane (CH_4) which makes up 60-70% of the gas, carbon dioxide (CO_2) which usually accounts for 25-35% of the biogas produced, and the remainder being water vapour and impurities e.g., nitrogen or hydrogen sulphide, depending on feedstock and digester design.

Biogas was discovered, produced and utilized as a source of heat and lighting long before petrochemical methane. Biogas from processing of sewage sludge was used for street lighting in Exeter, England as early as 1896.

Biogas produced from many different sources has been a key energy source for both developing and developed countries for over 100 years. Rural communities in developing countries utilize biogas produced from animal manure and crop residues to provide a reliable supply of gas for heating and cooking, even in locations far from anything resembling a national or regional gas supply network.

In developed countries around the world, biogas generated in large-scale digestion plants or from landfills provides a source of energy for electrical generation, process heat and transportation.

1.2 How is Biogas Produced?

Biogas production is a biological process where carbohydrates, proteins and fats in organic material are consumed and broken down in a series of stages by bacteria. This process involves several different bacteria working in series to convert the material step-by-step, all in the absence of oxygen.

Inside an anaerobic digester, long-chain organic molecules are broken down into their simple repeating monomer units before conversion into Volatile Fatty Acids or VFAs. Then, the VFAs are split into acetic acid, carbon dioxide and hydrogen before being recombined into methane.

As the organic material is decomposed in the digester by the bacteria, biogas is produced and continually drawn off from the digester. Generally, the gas is cleaned to remove any dangerous or volatile chemicals before being burned to create heat or electricity or flared.

1.2.1 Biogas Feedstocks

There are several different materials used today to produce biogas at scale. The main sources of biogas processing feedstock material are:

- Animal/Livestock Manure
- Wastewater Treatment Sludge
- Industrial Effluent/Wastewater
- Food Waste
- Energy Crops or Crop Residues

All these materials are processed slightly differently, but the key biological steps are the same. In many cases, biogas may be a by-product of a plant's primary objective which is waste processing and treatment.

Some organic materials cannot be converted easily into biogas including wood or other materials with high amounts of lignin. Lignin is a complex organic molecule that is not easily broken down by the bacteria responsible for creating biogas, and feedstocks that have high amounts of lignin need large amounts of energy-intensive pre-treatment to process.

1.3 What is Biomethane?

Biomethane (or Renewable Natural Gas [RNG]) is the name given to concentrated methane derived from biogas or landfill gas. Chemically, it is undistinguishable from natural gas extracted from natural gas fields and is a direct substitute, meeting the AS/NZS 5442 specifications.

Compared to biogas, biomethane has many properties that make it much more useful than unrefined biogas:

- Higher energy content – after the non-combustible components of biogas have been removed, biomethane contains much more energy per volume/weight. This enables it to burn hotter and enable more energy to be stored in smaller tanks or vessels.
- Less corrosive – depending on the feedstock being processed, biogas can often have high levels of H_2S or hydrogen sulfide. This chemical can cause corrosion and damage to mechanical equipment, and large amounts of H_2S can be deadly. By treating the biogas to remove this contaminant, the risk to operators and equipment where the gas is transported, stored and used is decreased.
- Better compressibility – As well as removing non-combustibles and H_2S, the removal of other gas components with different boiling points means that biomethane can be compressed and stored at high pressure or even as a liquid much more readily than biogas. This enables it to be economically transported via pipeline at high pressure and used in applications like transportation fuels.
- Dehumidification – With the dewpoint sufficiently reduced water vapor is less likely to condense inside pipelines, tanks and components, this also lowers the possibility of freezing during winter conditions.

While biogas must be handled and processed in specialized equipment, biomethane can be easily integrated with existing assets used to transport and use natural gas. Cleaned or scrubbed biogas can have some of the above advantages which makes it more useful than raw biogas, but it is not able to be injected and transported in natural gas networks (see Section 5.3)

1.4 Other Products from Anaerobic Digestion and Biomethane Processing

1.4.1 Digestate

Anaerobic digestion of organic feedstocks is primarily a process designed to break down organic material and remove the volatile organic components of said material. As organic material is decomposed to create biogas, the feed material becomes a nutrient-rich and biologically-inert material which can be used as a fertiliser. Digestate produced from some organic wastes cannot be used as a fertiliser on land used for agriculture in some countries (see Section 6.2), especially if the material is from WWTPs.
Both solid and liquid digestate can be used as an organic replacement or supplement to chemical fertilisers, boosting crop growth and remediating marginal land into fertile and nutrient-rich soils. Depending on the processing arrangement and physical qualities of the incoming organic waste, solid and liquid digestate will be produced in different ratios and qualities.

Some countries have legislation that allow for certification of digestate produced from anaerobic digestion of a given quality, which allows the digestate to be certified as a bio-fertiliser and sold as a competitor to chemical fertilisers on the open market. In other countries, biogas plants processing manures and crops will often have agreements with their organic waste suppliers to return digestate in exchange for organic waste materials to feed the plants.

1.4.2 Carbon Dioxide

After raw biogas is produced, the removal of contaminant gases to produce biomethane can create some additional value streams. Liquid CO_2 for example, is a very valuable revenue stream for a plant equipped with the right technology to collect and compress CO_2 of sufficient quality.

Some technologies for biomethane refining like Cryogenic Separation (see Section 5.3.4) allow biogenic food-grade CO_2 production, which is carbon-neutral.

Smaller biogas processing operations that do not have the scale to economically produce biomethane will instead burn their biogas to create electricity or heat, and the high CO_2 fraction in the gases produced after combustion makes it possible to use this gas to feed greenhouses.

1.5 Benefits of Biogas and Biomethane Production

Utilising organic wastes and using them to create a renewable energy source in New Zealand would have a wide range of environmental, social and economic benefits. The below are all observations from the use of biogas technology internationally.

1.5.1 Economic Benefits

- Creation of valuable products from current wastes
- Decreased asset modifications on behalf of natural gas users switching from natural gas to biomethane to decarbonise their operations
- Continued use of natural gas distribution assets and appliances
- Renewable Energy storage is an intrinsic benefit of biomethane delivered via existing natural gas distribution assets.

1.5.2 Social Benefits

- Job creation in construction and operation of these new processing facilities across numerous dispersed locations, both urban and rural.
- Creation of Circular, self-sustaining economies
- Opportunities to utilise transferrable skills from industries at risk of closing e.g. oil and gas industry
- Energy supply to consumers protected as fossil fuels phased out
- Less land required for new landfills or landfill expansions – Food waste contributes to 17% of waste sent to landfill in New Zealand alone (Ministry for the Environment, 2011)

1.5.3 Environmental Benefits

- By displacing natural gas consumption, biomethane greatly reduces the carbon emissions associated with process heat, electricity generation, residential/commercial space heating & chemical feedstock utilisation.
- Less organic material sent to landfill, and less biogenic methane emissions from landfill
- Better management and reduction of volatile organics in industrial waste streams, improving water quality
- Reduction in agricultural emissions by utilisation of collectible manure
- Digestate product creation and use
  - Less required synthetic fertiliser
  - Improves soil health
  - Potential for carbon sequestration in soil
  - As a result of the above, improved waterways

2 Biogas and Biomethane on the World Stage

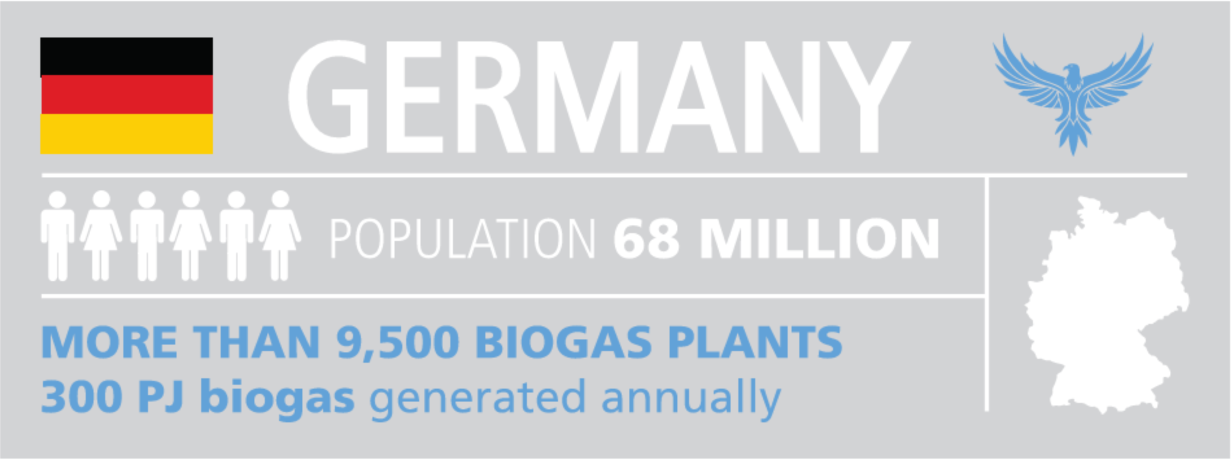
Internationally, biogas and biomethane production provides over 2,011 PJ of energy annually which is used for electricity and heat generation and as a vehicle fuel. According to the IEA, this is predicted to increase to 9,260 PJ by 2040 – a 360% increase over the next two decades (IEA, 2020b).

By 2040, over half of the biogas produced internationally is expected to be converted into biomethane and used as a natural gas substitute (IEA, 2020a). This will require not only a massive uptake in biogas generation, but the conversion of many existing biogas production facilities to biomethane upgrading plants. Internationally, several countries are leading the uptake of biogas and biomethane production – the drivers of these countries to adopt biogas and biomethane, and the mechanisms they are using to drive this change are explored in the section below.

2.1 Germany

Germany is the clear leader in global biogas/biomethane production, representing more than 50% of production in the EU (Banja et al., 2019). There are more than 9500 biogas plants in Germany which generate a total of 30.1 TWh of electricity and 5.4 PJ of biomethane as an end product (Budde & Newman, 2019; Decorte et al., 2020). Assuming a 40% conversion from raw energy to electricity, this represents over 300 PJ of raw biogas. In comparison, Germany used 3,105 PJ of natural gas in 2020, so the energy supplied by biogas is equal to around 10% of the energy Germany gets from natural gas (Appunn et al., 2020). The majority of biogas in Germany is generated from the anaerobic digestion of energy crops and biowaste. Over 1.26 million hectares of land (10.7% of Germany's total arable land) were used for the cultivation of biogas feedstock crops in 2015 (German Biogas Assocation, 2021). A total of 17.5% of Germany's total arable land is used for the cultivation for biogas and biodiesel crops (Federal Agency for Nature Conservation, 2016). This has led to conflict between the agricultural industry and biogas producers regarding best uses of land.

Germany also produces biogas from other sources of organic waste materials like manure (around a quarter of all livestock manure in Germany is digested), source segregated organic waste and industrial effluents like spent grain, pulp from juices and dairy waste.



2.1.1 How Germany Became a World-leading Producer

A major contributor to the proliferation of biogas for electrical generation in Germany was the Renewables Energy Act of 2004, which provided biogas generators a financial benefit based on the net amount of electricity their plants produced (Fulton et al., 2012). In 2015, these tariffs provided 6.2 billion euros to biogas plants across Germany, at an average of $300 NZD/MWh(Geerolf, 2018).

However, in 2014 it was announced that the tariffs would be restructured resulting in less guaranteed incentives for biogas plants primarily fed by energy crops, but maintain current incentives for plants fed by waste materials. This led to a decrease in the construction of new biogas plants.

At the same time, the changing incentives in Germany have led to an uptake of biomethane production. In 2018, Germany produced 36 PJ of biomethane from 213 biomethane production facilities, although the majority of this biomethane was still converted into electricity (Regatrace, 2020). The removal of historic tariffs for maximising biogas production and implementation of new tariffs for electricity generation via biomethane and grid injection has caused many new biogas projects to be cancelled and existing plants to change the way they operate. As subsidies continue to change, it is expected that existing biogas CHP plants will continue to transition to biomethane production and then grid injection if they have the scale to do so.

2.1.2 Biomethane Exports in Germany

Germany is a net exporter of biomethane, producing around 36 PJ of biomethane per year and exporting an average of 0.5 PJ per year (Decorte et al., 2020). The end destination of this biomethane is commonly countries like Sweden where incentives are geared towards using biofuels instead of towards generation. For more info on Sweden's biomethane consumption, see Section 2.7.

2.1.3 How Biogas fits in to the Overall Energy Strategy

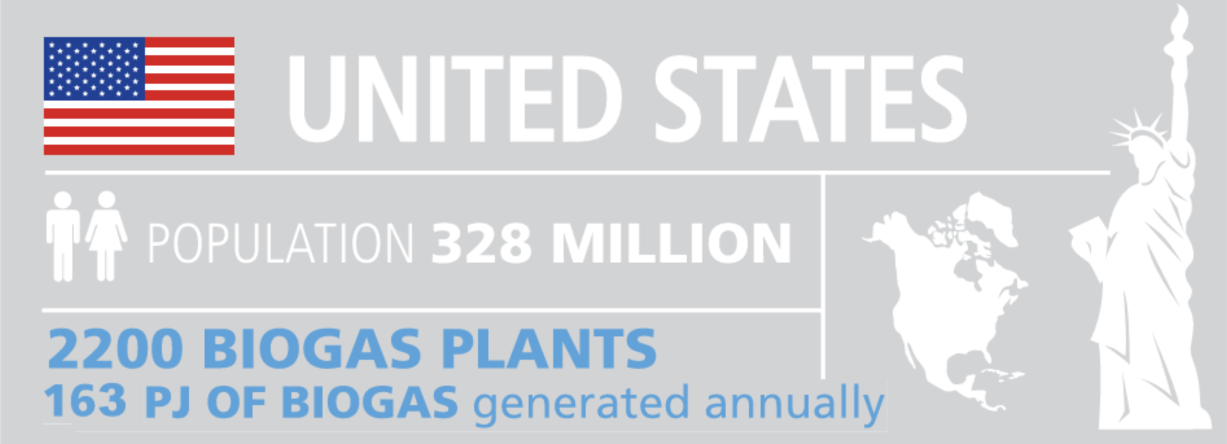
Expanding renewable electricity, including power from biogas CHP plants, has been a very strong focus of the German government for some time. One of the strongest motivators for the expansion of renewable electrical generation has been the planned decommissioning of the country's remaining nuclear power plants by 2022. In contrast to countries like France, Germany does not see the continuation of its nuclear reactors as a suitable mechanism to achieve energy independence and decrease emissions associated with its energy consumption.

2.2 United States

The United States produce approximately 163 PJ of biogas annually (IEA, 2020a). There are four main sources of biogas used to produce biomethane or Renewable Natural Gas (RNG) in the United States: municipal solid waste (MSW) landfills, anaerobic digestion at WWTPs, anaerobic digestion at livestock farms and anaerobic digestion at stand-alone organic waste management operations (United States Environmental Protection Agency, 2020).

In 2019, approximately 5% of the energy generated in the United States was derived from biofuels and wastes, this corresponds to 1260 TWh or 4,540 PJ.

As of February 2020, across all feedstocks, there are over 100 operational RNG facilities, with an additional 40 under construction in North America (United States Environmental Protection Agency, 2020). In addition, the United States currently have 2,200 operating biogas systems across all 50 states and have the potential to add over 13,500 new systems (Environmental and Energy Study Institute, 2017). RNG could replace up to 10 percent of the natural gas used in the United States (Environmental and Energy Study Institute, 2017).



2.2.1 Biogas and Biomethane Feedstocks in the United States

- **Food Waste:** In 2010, the United States produced approximately 66.5 million tonnes of food waste, primarily from the residential and commercial food sectors. Anaerobic digestion of 100 tonnes of food waste per day can generate enough energy to power 800 to 1,400 homes each year, so if this entire feedstock was utilised this would power 1.4-2.7 million homes (Environmental and Energy Study Institute, 2017).
- **Landfill Gas**: Landfill gas (LFG) generates in the United States about 17 TWh of electricity per year and 98 billion cubic feet of gas, which is distributed via natural gas pipelines or directly to end-users each year (Environmental and Energy Study Institute, 2017).
- **Livestock waste:** The United States Environmental Protection Agency have estimated a potential for 8,241 livestock biogas systems based on livestock numbers and the amount of recoverable manure available. This could generate over 13 TWh each year (Environmental and Energy Study Institute, 2017).
- **Wastewater Treatment:** Many WWTPs already have on-site anaerobic digesters, however, much of this biogas is flared due to not having the equipment to use the biogas produced. This is largely due to most of these anaerobic digesters never being installed with the intention to recover the biogas produced, it was only considered as a by-product. Around 860 of the 1,269 WWTPs using an anaerobic digester use their biogas produced. WWTPs equipped anaerobic digestors treat over 19 million litres of wastewater per day. If all 1,269 sites were installed with an energy recovery facility, this could reduce annual CO_2 emissions by 2.3 million metric tonnes (Environmental and Energy Study Institute, 2017).
- **Crop Residue:** The United States have an estimated 104 million tons of crop residues available for sale. Crop residue contains a high lignin content which is difficult to break down via anaerobic digestion. Therefore, crop residue tends to be co-digested with other organic waste (Environmental and Energy Study Institute, 2017).

2.2.2 Commercial Developments in the United States

In October of 2020, Chevron USA and Brightmark formed a joint venture, Brightmark RNG Holdings to own, operate and sell biomethane from dairy digestion plants across the United States (Bioenergy Insight Magazine, 2020).

This strategic decision from Chevron represents a growing interest from energy companies around the globe to diversify and develop new low-carbon technologies and leverage the experience and technical skills in fast-developing sustainable energy technology providers like Brightmark.

Anaergia is a company with staff based in North America, Europe, Africa and Asia. In January of 2021, it announced that in partnership with Universal Waste Systems Inc. it will construct a new organic waste digestion plant in Los Angeles capable of receiving up to 300 t of organic material per day in support of California's organic waste reduction targets.

the facility will reduce California's emissions by 70,000 tCO_2e and produce up to 300 TJ of biomethane per year (Anaergia, 2021).

Both of these examples show a growing appetite for both energy companies and waste management companies in the United States to diversify and invest in biogas and biomethane technology as a way to create valuable by-products from their wastes and decrease their carbon emissions.

2.2.3 Incentives in the United States

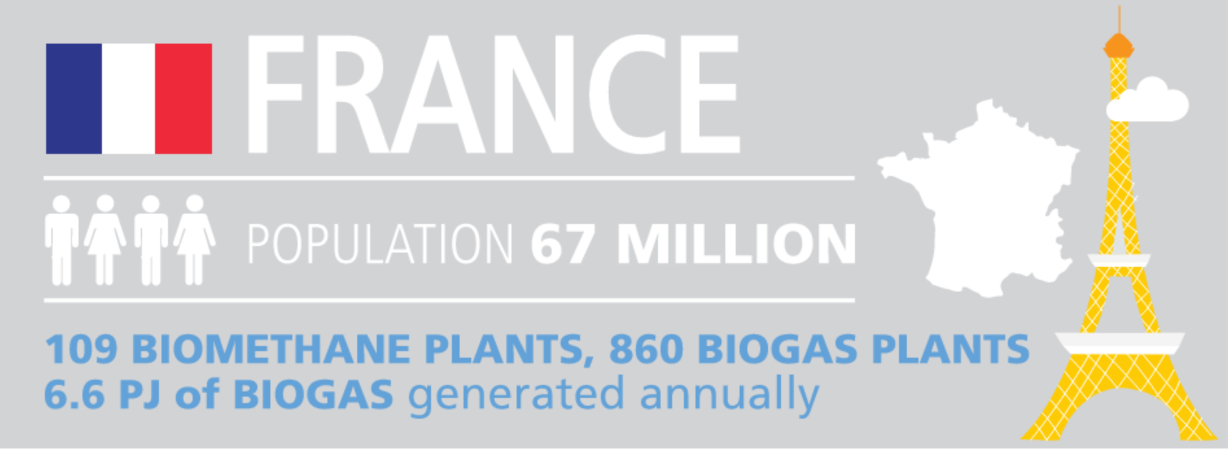
There are a few incentives (both federal and state specific) in the United States to encourage the use of RNG as transportation fuel. These include tradeable credits knows as Renewable Identification Numbers (RINs), and programs such as Renewable Fuel Standard (RFS), The Rural Energy for America Program (REAP), Landfill Methane Outreach Program (LMOP), and Municipal Natural Gas Fleet Conversion (United States Environmental Protection Agency, 2020). However, the incentives and subsidies for RNG projects appear to be less in comparison to its European counterparts. California has the largest incentives for use of biomethane as a transport fuel, and many biomethane projects in other states sell their credits to gas users in California to achieve best returns for their plant.

2.3 France

2.3.1 Production Capacity & Feedstocks

As of 2019, France produces approximately 6.6 PJ of biogas per year (Frédéric Simon, 2019). France produced 2.6 TWh of electricity from biogas in 2019, accounting for approximately 0.45% of France's total electricity production (Heiberger & Holland, 2019). Since biomethane was granted access to the national grid in 2011, growth in production has been considerable. In response to France's set biomethane target for 29 PJ biomethane production by 2023, the number of biomethane plants has increased from seven in 2015 to 107 in 2019 (Decorte et al., 2020).

As of December 2019, there were a total of 860 biogas plants operating in France. 123 of these plants injected 4.4 PJ of biomethane into French distribution networks. By the end of 2019, there were 738 biogas units producing electricity and heat, accounting for 86% of all biogas plants in France (Biogas World, 2020).



Biogas and biomethane in France is predominantly produced from waste and agricultural, industrial or municipal by-products (Biogas World, 2020). In 2017, 75% of biogas generated in France came from landfill gas capture (Geerolf, 2018). Today the majority of biogas plants use agricultural feedstocks such as manure, agriculture residues and wastewater sludge from the regions the plants are located in (Biogas World, 2020).

2.3.2 Local Schemes and Policy

There are many schemes, policies and incentives set up by the French government and local authorities which have helped to facilitate France's growth in biogas and biomethane production in recent years. An overview of some of the key schemes and policies is given below.

- France has an energy efficiency bonus system, which is determined by the overall efficiency of the biogas plant. Plants with an overall efficiency (including utilised electrical and thermal generation) of at least 40% are eligible for a bonus. The highest bonus requires an overall efficiency of at least 70% (Ecoprog, 2014).
- Fixed purchase tariffs give biogas producers certainty that they can sell their product at a fixed price for a fixed time. Different fixed purchase tariffs apply for biomethane injected into the national grid and for electricity produced from biogas. Duration of the tariffs is 15 years and 20 years respectively. For example, the purchase tariff for renewable natural gas plants on 31 December 2018 was between 45 and 139 €/MWh of gas produced, depending on the size of the plant. Depending on the type of feedstocks used, a bonus may be added. This scheme has helped to facilitate growth in electricity production from cogeneration in agricultural areas (Biogas World, 2020).
- Financial incentives are provided through grants and technical aids offered by the French Environment and Energy Management Agency (ADEME), local authorities, water agencies and others (Biogas World, 2020).
- Biogas or biomethane mixed with natural gas was exempt from the domestic consumption tax on natural gas (TICGN) until 1 January 2021 (Biogas World, 2020).
- In 2017, the French government also established a tariff rebate of up to 40% on the costs associated with connecting biomethane to the French distribution network. Biomethane injection was also permitted in underground storage locations (Biogas World, 2020).

2.3.3 Commercial Developments in France

In January of 2021, Total announced that it had acquired the French company Fonroche Biogaz, a company that designs, builds and operates anaerobic digestion facilities in France. Fonroche Biogaz is a large player in the French biogas industry, with 1.8 PJ of installed production capacity which doubled from 2019 to 2020. Fonroche Biogaz represents a 10% market share of biogas production in France (Total, 2021).

Total's President of Gas, Renewables and Power, Phillipe Sauquet, said *"In 2020, we stated our intention to contribute to the development of this sector, which we expect to become more competitive in the next few years.*
"We intend to produce 1.5 terawatt-hours (TWh) [5.4 PJ] of biomethane a year by 2025 and Fonroche Biogas is therefore the cornerstone of our development in this market."

Previously, Total had established partnerships with biogas company Methanergy and biomethane production and distribution company Clean Energy.
Through partnerships like these, Total plans to produce 14-20 PJ of biomethane per year across its portfolios (Total, 2021).
Companies like Total investing in bringing this technology to significant national scale is a massive enabler to effective and timely uptake of this technology in Europe, and the benefits of this investment extend well beyond the companies finding this technologies into the surrounding communities and consumers of gas, fertiliser and other by-products.

2.3.4 Future

France's plans for further development and expansion of biogas and biomethane include:

- The Energy Transition for Green Growth Act, which came into effect August 2015, sets a specific target for 10% biomethane in the grid by 2030 (Blaisonneau et al., 2017).

- The Energy Transition Law target of injecting 29 PJ/yr of biomethane into the grid by 2023, including 7.2 PJ/yr for transport purposes (Decorte et al., 2020; Geerolf, 2018). These commitments should see biogas production in France amounting to 54 PJ per year in 2022, including 4.4 TWh per year of electricity, 3.9 TWh per year of heat and 24 PJ year of biomethane (Geerolf, 2018).

Overall, the French government have shown strong support for biogas and biomethane, particularly through their ambitious, legally binding target of 10% biomethane grid-injection by 2030. This has facilitated a momentous uptake of biomethane to date, and the potential for prosperous growth in the future, primarily through the continued uptake of energy crops and agricultural residues as feedstock.

2.4 Italy

Italy has a population of 60 million people, and its economy is largely based around agriculture, viticulture, horticulture, and production of machinery and vehicles. Natural gas accounted for 45% of Italy's total electricity production in 2018. Among renewable sources, hydropower ranked first (16%), followed by biomass (9%) and solar energy (8.3%) (Statista, 2018). Italy's bioenergy growth in the last decade has primarily been focused on the transport sector (Eyl-Mazzega & Mathieu, 2019), resulting in Italy having the largest EU fleet of vehicles fuelled with biogas. Italy ranks second to Germany in terms of number of biogas plants in the EU and ranks third in the EU, behind Germany and the UK, in terms of installed electricity capacity (Benato & Macor, 2019).

Electricity generation in Italy from bioenergy was 19.5 TWh in 2016, making up 18.1% of Italy's total renewable production. Biogas plants generated 42.3% of total bioenergy generation (amounting to 84 PJ of biogas prior to electrical generation), while solid biomass and bioliquids contributed 33.6% and 24.1%, respectively, to total bioenergy generation (Benato & Macor, 2019).

As of 2016, Italy has 1,995 biogas plants, of which 49.6% use agriculture feedstock (crop residue), 27% use animal manure, 19.5% use source segregated organic waste and the remaining 3.9% use sludge as feedstock.

Agriculture is one of Italy's key economic sectors, which has driven the large uptake of crop residue as feedstock. It should be noted that Italy has a decentralised biogas sector, with many biogas plants traditionally being less than 1 MW in capacity. The main reason for this is the "all inclusive" feed-in tariff introduced by the Italian Government in 2008, which guaranteed 280 €/MWh for biogas plants with an installed capacity of less than 1 MW (Consorzio Italiano Biogas, 2016). This was the most generous support available among the EU and boosted the installation of small-scale biogas plants, especially in the agricultural sector. In 2012, the feed-in tariffs were replaced by less favourable feed-in premiums giving preference to by-products and farming waste over energy crops, which has led to a stagnation in growth of biogas production since 2012 (Eyl-Mazzega & Mathieu, 2019).

2.4.1 Biomethane in Italy

Priorities have shifted to biomethane production. At the start of 2019, Italy had only six biomethane plants, of which three used agricultural feedstocks, two used source segregated organic waste and one used landfill waste. All six of these plants sold biomethane to vehicle fuel stations and were not connected to the natural gas grid (Benato & Macor, 2019). The March 2018 Biomethane decree represents a fundamental step for the development of Italy's biomethane sector, promoting support for biomethane as biofuel for transport and facilitating the registration of over 900 preliminary gas grid connection projects (Eyl-Mazzega & Mathieu, 2019). As of 2020, there are eight full-scale biomethane plants and fifteen are under construction (Decorte et al., 2020).

The CIB (Consorzio Italiano Biogas) estimates Italy to have a biomethane production potential of 10 billion m³ in 2030. Italy plans to spend 4.7 billion euros from 2018 to 2022 on the production and distribution of advanced biofuels, including biomethane, to reach the EU energy and climate change goals (Biogas World, 2018).

2.5 United Kingdom

According to the European Biogas Association Statistical Report 2020, the UK has 715 biogas plants, of which 80 are biomethane plants (European Biogas Association, 2021).

Bioenergy and waste contribute 9.2% of the UK's primary energy, supplying 656 PJ of energy and just over 40% of the total renewable energy in the UK. A large portion of this energy comes from Waste to Energy generation (IEA, 2021).

2.5.1 Biogas Production in Recent Years

In 2016 the UK has 617 MW of installed biogas capacity (Business Energy, 2017). However, growth in biogas capacity has since been stalled due to subsidy cuts – mainly a result of concerns over limited agricultural land for food crops.

Bioenergy contributed about 31 TWh (10%) to the UK's total power usage in 2017. Of this 31 TWh, UK-produced biogas made up about a third (amounting to around 85 PJ of biogas prior to electrical generation), with the remainder being imported biomass for use at the Drax Power Station converted coal plant.

In 2019 around 3.6 TWh (13 PJ) of biomethane was injected into the national grid (Boykew, 2020), displacing around 0.6% of natural gas in the UK. This came from just under 90 agricultural biogas plants injecting biomethane into the UK gas grid (Business Energy, 2017).

In summary, it is evident that there has not been much growth in UK biomethane supply in recent years. However, the Green Gas Levy and Green Gas Support Scheme (announced in the March 2020 Budget) could potentially provide more momentum in the years to come (more details in policy section).

According to the ADBA (2020), the UK is currently only generating one fifth of its biomethane potential, but based on the analysis below its potential could be considerably higher.

2.5.2 Sources of Biogas and Biomethane

Biogas in the UK is mostly produced from landfill gas; compared to Germany where agricultural biogas plants dominate. This is because in Germany, most biogas plants use specially grown crops, whereas the UK do not produce the same amount of purpose-grown biogas feedstocks, and purpose-build anaerobic digestion plants are fed with organic wastes. Landfill gas capture is a more productive source of biogas than anaerobic digestion in the UK today.

a. Food waste

7.3 million tonnes of household food waste is collected annually in the UK, and 15% is separated and processed through anaerobic digestion or composted (Bia, 2020). This suggests there is a large potential for further digestion of municipal and commercial food waste, and opportunities for co-digestion with WWTP sludge.

b. Farm waste

On-farm AD offers biggest potential for growth. To capture and recycle all agricultural waste (manures, slurries and other forms of waste), it is predicted that the number of on-farm AD plants in the UK will need to increase from the current 375 to 3200 (an investment of 8.5 billion pounds) (Bia, 2020). UK could feasibly reach levels of animal manure yield and digestion achieved by Denmark given appropriate policy support (see below).

c. Energy crops

In the UK, 96,000 ha of agricultural land was used to grow crops for bioenergy – just over 1.6% of arable land. Of this 96,000 ha, 20% was used for biofuel (biodiesel and bioethanol) in the UK road transport market. The remainder of this land was used for heat and power generation.

- Maize (67,000ha) is produced primarily for digestion into biogas.
- 11,000 ha of wheat was produced for production of biofuel (bioethanol). This is significantly lower than previous years – likely due to intermittent closures of UK cereal bioethanol plants in 2019

2.5.3 Policy and Incentives

a. Green Gas Levy

The Green Gas Levy (GGL) was announced in the March 2020 Budget. It sets out to fund support for biomethane injection into the national grid through the Green Gas Support Scheme. The ‘Consultation on a Green Gas Levy’, released in September 2020, proposes to put a levy on natural gas suppliers to support biomethane injection into the grid (Department for Business Energy and Industrial Strategy, 2020a). This levy will hopefully be used to support schemes like the Green Gas Support Scheme (see below).

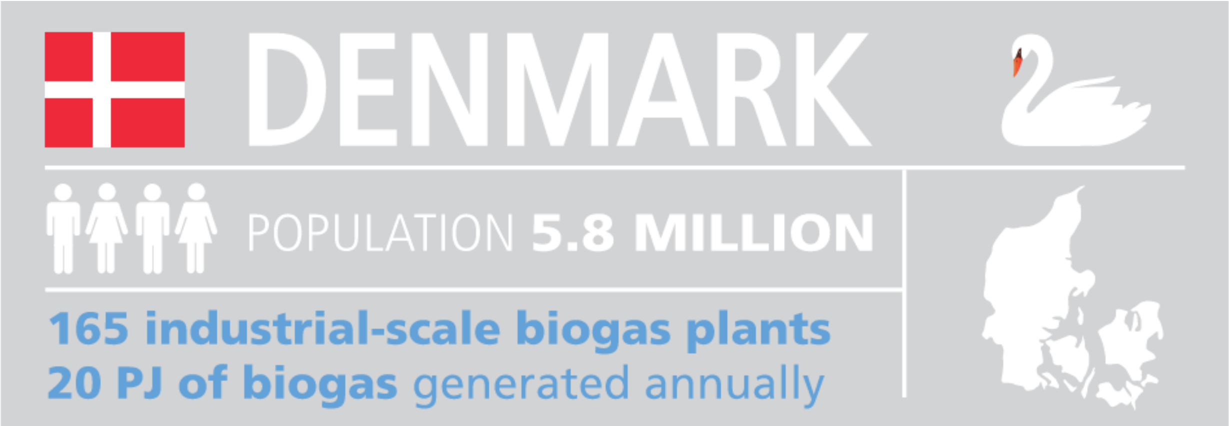
b. Green Gas Support Scheme

This proposed scheme acts to accelerate the decarbonization of the UK gas grid through promoting biomethane injection. Expanded Feed-In Tariffs (FIT) ,funded by the GGL, are the main proposed mechanism to incentivise ongoing production and development of new plants (Department for Business Energy and Industrial Strategy, 2020b). These have worked well in countries like Denmark and Sweden. The UK has run a smaller FIT scheme in the past that incentivises the generation of renewable energy by small scale projects (Bioenergy Insight, 2018). This scheme was introduced in 2010 but ended in 2019. Payments were made to those who produce and export renewable energy (e.g. hydro, solar, biogas, wind) with a capacity of up to 5 MW (or 2 kW for CHP). It will be interesting to see whether this new phase of incentives can re-invigorate the growth of biogas in the UK.

2.6 Denmark

Biogas has been a significant part of Denmark's energy mix since the 1970s. The two main drivers for the uptake of this technology in Denmark were the need to develop independent and secure supplies of energy following the oil crises of the 70's and 80's, and a need to reduce pollution, waste and emissions associated with its agricultural sector (Danish Energy Agency, 2020). The production of biogas in Denmark has been rapidly increasing in recent years, reaching a total annual production of 20 PJ in 2020 (Stockler et al., 2020).

In 2012, Denmark formally committed to biogas when it became a political priority and part of the National Government's strategy for a fossil-free energy supply by 2050. Feed-in tariffs and investment tax credits significantly matured the industry, increased the number of large-scale projects and spurred innovation in areas like CO_2 recovery, Power2Gas, and nutrient recovery. Denmark's largest-ever biogas facility is currently under construction and will produce 75 million m^3 of biogas annually (around 1.5PJ) when operational (ENDS Waste and Bioenergy, 2021).



2.6.1 Sources of Biogas

More than two-thirds of Denmark's renewable energy comes from bioenergy. Agriculture is big business in Denmark, and it indirectly helps provide energy too, with manure, animal fats, and straw used as the basis for biogas and liquid biofuels. Separately from just biogas, many Danish power plants are switching from coal generation to biomass (wood pellets, wood chips, or straw), and there are widespread efforts to swap out traditional fossil fuels with their biofuel equivalents. (Danish Energy Agency, 2020).

The main feedstock utilised for biogas and biomethane production in Denmark is animal manure and other agricultural by-products. Over 20% of Denmark's animal manure from its dairy, poultry, pork and fur industries is collected from barn operations and processed to create biogas, and returned to farmers as processed digestate to support agricultural activity (Hermann et al., 2019).

2.6.2 Uses of Biogas

Unlike most other countries profiled in this section, the majority of Denmark's biogas is not used for electricity generation or CHP. In fact, less than 40% of biogas created from Denmark's many digestion plants is used to generate electricity. The majority of biogas produced in Denmark is refined and scrubbed into biomethane, which is then injected into Denmark's national gas grid (Eyl-Mazzega & Mathieu, 2019).

The Danish gas industry predicts that by 2040, the entirety of gas supplied via the national gas grid will be biomethane (the Danish government however expects this to be by 2050 at the latest). Currently they have passed the milestone of being 20% renewable at the end of 2020.

2.6.3 Biogas and Biomethane Snapshot

As of 2018, there were 165 industrial-scale biogas plants operating in Denmark - this includes 51 WWTPs, four industrial plants, 27 dumpsites, and 83 agricultural plants. That same year, 32 of these plants were processing biogas into upgraded biomethane (Biogas Go Global, 2020).

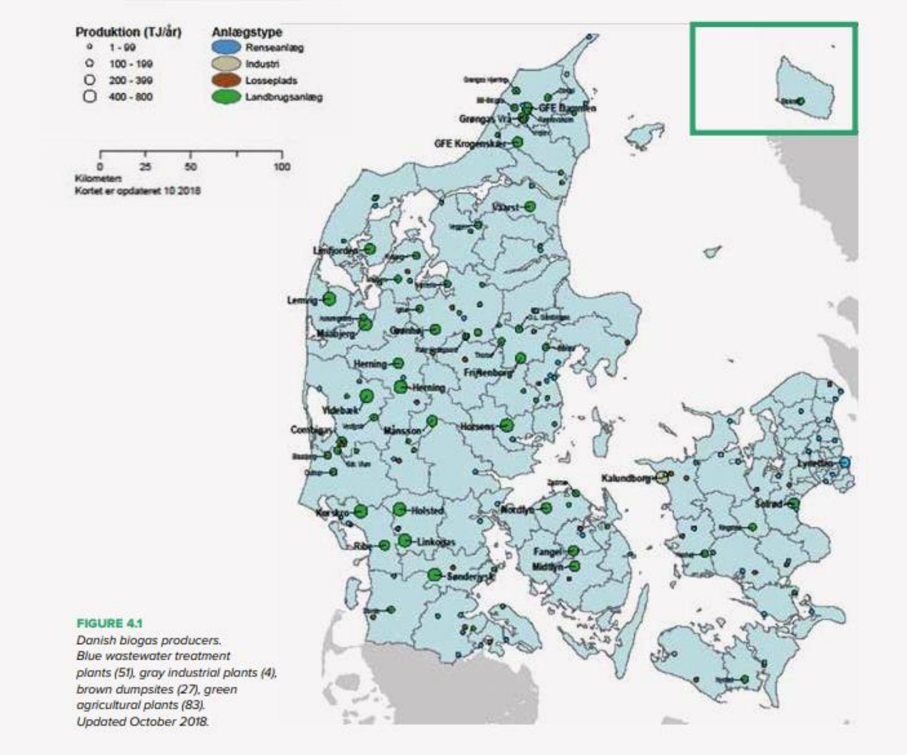


FIGURE 4.1

Danish biogas producers. Blue wastewater treatment plants (51), gray industrial plants (4), brown dumpsites (27), green agricultural plants (83). Updated October 2018.

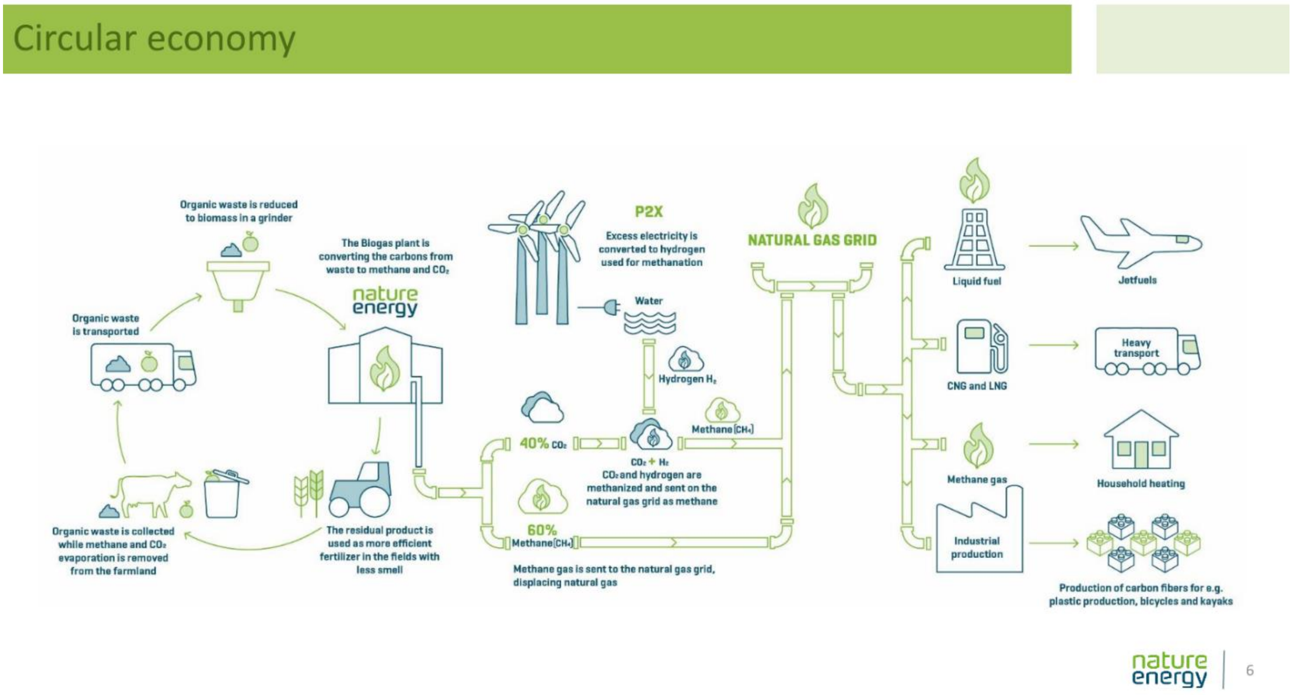
In 2021, 48 biogas upgrading plants are connected to the national gas grid, with 8-10 plants currently under construction (Ministry of Foreign Affairs of Denmark, 2021a).

Figure 1: Biogas Plant in Denmark (Biogas Go Global, 2018)

2.6.4 Danish Case Study: Nature Energy

Nature Energy is a company based in Denmark that constructs, owns and operates biogas and biomethane plants. Nature Energy has over 250 employees split across 13 plants in Denmark (11), France (1) and the United Kingdom (1). 30% of the biogas generated by Nature Energy is refined and injected into Denmark's natural gas network.

In 2020, Nature Energy received and processed 5 million tonnes of organic waste (75-80% animal manure and 20-25% household waste etc.) and produced enough energy to heat 71,000 Danish households or power 10,000 heavy vehicles.



Circular economy

Figure 2: Nature Energy Process Diagram

A typical biomethane plant in their portfolio would be designed to process 600,000t of organic waste annually, and produce 22,000,000 Nm^3 of biomethane for the grid. The plants are around 6-10 acres in size, and vendors + local stakeholders are offered ownership up to 49%.

Through their partnerships with local farmers, Nature Energy also produces digestate/ natural fertilisers which is returned to the farmers in exchange for feed material for the plant. This circular approach produces a range of benefits for the local community and reduces agricultural emissions and pollution.

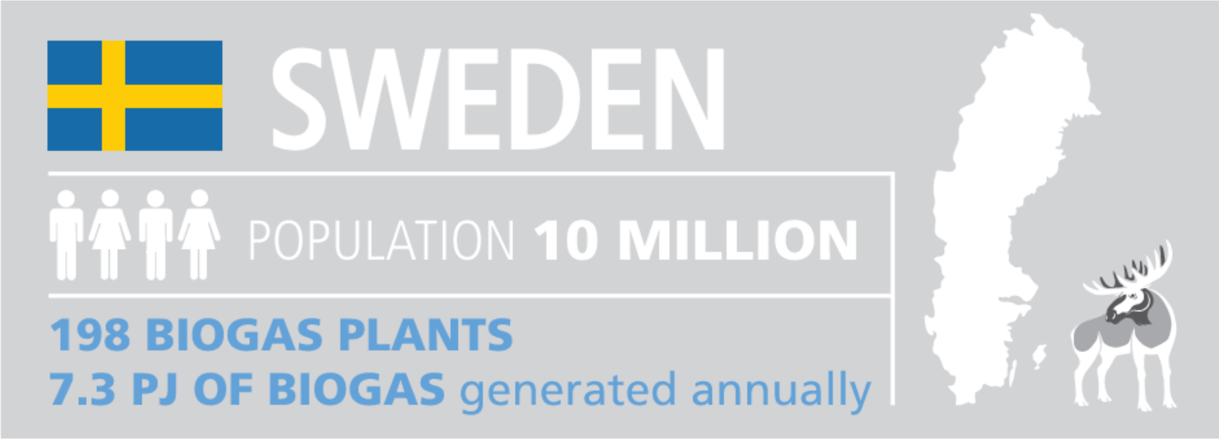
At a pilot level, Nature Energy is trialling biological methanization to turn CO_2 generated in its digesters into additional methane by combining it with green hydrogen produced by renewable energy sources. This represents a way to utilise surplus electrical generation and store energy in the gas grid, balancing out supply and demand of renewable energy.

Nature Energy is rapidly expanding; with ten plants in construction (four in Denmark, six in France) as demand for biomethane grows in Europe.

As well as owning and operating biomethane production facilities, Nature Energy also owns 16 of the 18 biomethane vehicle refuelling stations in Denmark.

2.7 Sweden

Sweden is a unique case study in Europe, being the only country in Europe that consumes more than double the amount of biomethane it produces annually. In 2018, Sweden imported more than 4 PJ of biomethane from Denmark for use within its borders as a transport fuel, which represented about 2/3rds of its overall biomethane imports (Decorte et al., 2020).
Overall, Sweden produces around 7.3 PJ of biogas per year from 198 biogas plants, with the majority of its biogas being produced by WWTPs and co-digestion facilities mostly processing food wastes (Ammenberg & Gustafsson, 2020; European Biogas Association, 2018).



2.7.1 Biogas Feedstocks in Sweden

As far back as the 1930's Sweden's WWTPs generated biogas as a by-product of wastewater treatment, which became a high-value fuel in the 1970's as oil crises threatened energy supplies globally. Through the 1970's and 1980's industrial effluent and farm-scale anaerobic systems became more popular, but it wasn't until 1990 that codigestion plants for food waste took off. Until 2013, WWTPs were still the dominant sources of biogas supported by landfill gas generation, but now 47% of biogas is generated in codigestion facilities (Smart City Sweden, 2020).

2.7.2 Biomethane Use in Sweden

In Sweden, biogas and biomethane make up around 22% of total Energy Gas supply, which overall makes up 3% of Sweden's total energy supply. The majority of Sweden's energy supply comes from Nuclear Power (32%), Oil (24%) and Biofuels (25%).

The majority of Sweden's biomethane is used as a vehicle fuel (63%), thanks to incentives promoting CNG vehicles powered by biomethane. These incentives are the reason that biomethane produced in countries like Denmark ends up being used in Sweden; incentives from production of the product in Country 1 and use in Country 2 mean that the biomethane is double-incentivised (Klackenberg, 2019).

Today, a large portion of Sweden's biomethane production is off-grid, or confined to local or reginal markets. This has led to the creation of many bioenergy hubs, where the end use of the biomethane is often used as a vehicle fuel or transported to customers as CNG.

In 2018, Sweden produced and utilised 2.8 million tonnes of digestate from anaerobic digestion plants as fertiliser in its agriculture industry, around 86% of the total digestate produced. Only 40% of digestate from WWTPs was utilised in this way, given the additional challenges of processing and pasteurising this waste (Ammenberg & Gustafsson, 2020).

2.7.3 Commercial Developments in Sweden

Recently, on the 27th of April 2021 forest and fibre product manufacturer Stora Enso opened a biogas plant at their Nymölla mill in partnership with Gasum, a Nordic gas producer. This new plant will produce 0.3 PJ worth of liquified biogas for use as a heavy vehicle fuel, which represents a 90% reduction in the emissions of fuelled trucks. The plant also returns clean water to the paper mill process (Tenz, 2021).

Gasum has also recently entered into an agreement with Sweden's largest fuel company Preem to supply their tankers with a new fuel blend consisting of liquefied natural gas and liquefied biogas. The liquified biogas is produced in Finland from Industrial effluents and sewage sludge, and locally in Sweden from crop residues (Helmen & Lidén, 2021).

2.7.4 Future Biomethane Predictions

Out to 2030, Sweden predicts that its production of biogas will increase from 7.3 PJ to 25 PJ, mainly from utilisation of new feedstocks including manure and energy crops. Existing production from Food Waste and WWTPs are anticipated to stay static for the near future.
Sweden also anticipates an additional 10 PJ of renewable gas from gasification processes in its grids by 2030.

2.8 Australia

The biogas industry in Australia is not as developed as industries in some of the other countries profiled in this section, but is steadily growing.

In 2019, Australia produced 16 PJ of biogas, of which 75% came from landfill gas capture (Australian Energy Statistics, 2020). In 2017 Australia had 242 biogas plants of which around half were landfill gas capture plants. Half of the gas captured at these plants was not used for energy production and was flared instead.

A report by ENEA Consulting in March 2019 estimated a potential of up to 371 PJ of biogas in Australia, equal to 9% of Australia's total energy consumption in 2017.

2.8.1 Biomethane Developments in Australia

In November of 2020, it was announced that Australia's first biomethane-to-grid plant will be proceeding with support from ARENA (Australian Renewable Energy Agency (ARENA), 2020b). Jemena and Sydney Water are collaborating to upgrade up to 95 TJ of biogas per year into biomethane, which will be injected into Sydney's gas network and displace 5,000 tCO_2e annually (Mavrokefalidis. Dimitris, 2020). This plant will eventually be expanded to supply 200 TJ annually.

2.8.2 The Future of Australian Biomethane

The Australian Renewable Energy Agency (ARENA) is currently preparing a Bioenergy Roadmap for Australia in partnership with ENEA and Deloitte. This will be provided to the Australian Government to inform policy decisions and investment decisions at a central level (Australian Renewable Energy Agency (ARENA), 2020a) .

A previous ENEA Report highlighted obstacles to achieving maximum biomethane uptake in Australia, including:

- Financial viability of biogas and biomethane projects in current conditions; high initial investments and complexity of securing revenue sources are specifically mentioned
- The need for more favourable policy conditions

- The complexity of project development and operation; related to the first point, but inclusive of complex approval processes facing project proponents
- The lack of widespread industry experience in Australia, given the early stage of the industry in Australia.

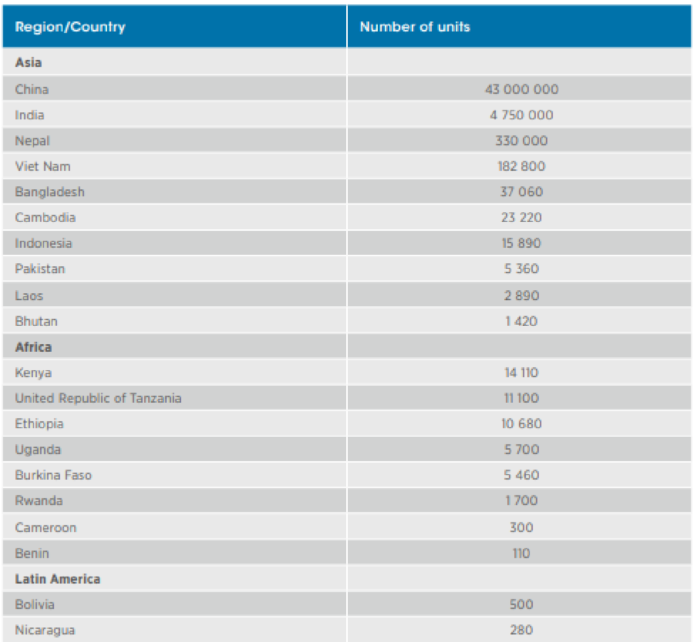
It is promising to see that some of the recommendations of this report, namely creation of a national roadmap and strategy for bioenergy and the use of ARENA finding to support biomethane projects, have already been implemented. It is likely that the next decade will deliver many more biogas and biomethane projects across Australia.

2.9 Rural Biogas in Developing Countries

In developing countries, household biogas plants are a common feature of rural farming communities. Without connections to national or regional gas distribution networks, biogas created by processing agricultural residues and animal manure presents a low-cost method to produce heat and energy for cooking and lighting etc.

In 2016, China had over 42.6 million small-scale biogas digester units installed in rural areas (Renewable Energy Agency, 2017). Between 2003 and 2012, total investments in rural biogas production in China totalled almost $15 billion USD. In 2014, this investment avoided 61 million tonnes of carbon dioxide emissions.
Biogas produced in household biogas units in China accounted for 1.2% of China's total energy supply in 2014.

India produced 2 million cubic metres of biogas in 2016 from rural installations (Mingyu, 2016) from such national programs like the New National Biogas and Organic Manure Programme (NNBOMP) helping establish small scale rural plants.



Region/Country	Number of units
Asia	
China	43 000 000
India	4 750 000
Nepal	330 000
Viet Nam	182 800
Bangladesh	37 060
Cambodia	23 220
Indonesia	15 890
Pakistan	5 360
Laos	2 890
Bhutan	1 420
Africa	
Kenya	14 110
United Republic of Tanzania	11 100
Ethiopia	10 680
Uganda	5 700
Burkina Faso	5 460
Rwanda	1 700
Cameroon	300
Benin	110
Latin America	
Bolivia	500
Nicaragua	280

Figure 3: Household-scale Biogas Units in Developing Countries (Renewable Energy Agency, 2017)

Uptake of rural biogas systems has been rapid in Asia over the last several decades, with China and India alone possessing over 95% of all household agricultural biogas units.

Africa is currently trailing behind Asia, but programmes like the Africa Biogas Partnership Programme (SNV World, 2021) are assisting the uptake of this technology. Between 2014 and 2019, the programme installed 60,000 biogas units across Burkina Faso, Ethiopia, Kenya, Tanzania and Uganda which resulted in:

- Access to clean energy for more than 300,000 people (Hivos, 2016b)
- Digestate for 300,000 ha of land
- A corresponding 20% crop yield increase for this land
- Creation of 4200 jobs supporting biogas unit installation and biogas production
- Improved health outcomes via displacement of wood-fired cooking indoors
- Time savings for residents; "On average, 38,000 women save 2.5 hours daily by no longer collecting firewood or scrubbing soot from pots". (Hivos, 2016a)

From the above, we can see the social, environmental and economic impacts of this technology in developing and isolated rural communities are significant.

As these rural communities continue to develop, it is likely that smaller family-owned farms will be replaced by large-scale commercial farming operations as is the case in China. This will have impacts on the manure supplies for many of these installed small biogas units and larger centralised units will become more commonplace. China, recognising this incoming shift in regional economic development, are modifying their biogas support policies to further incentivise medium and large-scale digestion. Whether there will be a way to utilise the previous investment in small-scale household unit technology in the long-term remains to be seen.

2.10 Key Learnings and Success Factors for New Zealand

It is clear from our profiles of each country above that biogas and biomethane is a mature and rapidly-growing technology. Especially in recent years, countries overseas with significant natural gas consumption have been turning to biomethane as a mechanism to help them decarbonise their primary energy supplies.

Countries like Denmark and France are proving that significant displacement of natural gas by biomethane (in the order of 10-20%) is readily achievable today by utilising available feedstocks, and much further natural gas displacement is achievable with a strategic vision for a decarbonised natural gas network (even up to 100% in Denmark's case). It is promising to see both large and small countries utilising this resource, and it reinforces the idea that New Zealand could be the next country to do so.

Corporate interest in biomethane technology has spiked overseas in recent years; biomethane is becoming a popular mechanism for oil and gas companies to diversify their energy portfolios and develop more sustainable technologies.

A common factor across all countries with significant biogas and biomethane uptake is the presence of strong policy support and financial incentives for renewable energy investment. Policy and financial support can manifest in several ways, including:

- Restrictions (i.e. bans) or levies on disposing of organic materials in traditional landfills,
- Emissions penalties for suppliers and users of fossil fuels,
- Capital funding support for renewable energy investments,
- Tariffs or credits for generators of renewable energy – especially where biogas or biomethane are used to support peaking electrical demand
- Formal recognition & approval of digestate quality standards (PAS110 or equivalent)

In countries that have made the most of biomethane, policy support for biomethane has been backed up by a renewable energy strategy, usually with the aim of achieving energy-independence.

Tariffs and financial incentives without careful directives have sometimes led to inefficient outcomes in the countries we have studied. Where policy hasn't been clearly signalled or policy has been modified/ended prematurely, investment has declined and/or gone to waste:

- In Germany, where incentives were originally applied on a feedstock processing capacity basis, financial benefits led to the construction of many large biogas and biodiesel plants fed by energy crops since this feedstock was the easiest to collect at scale. Now, energy crops take up 17.5% of Germany's arable land and energy crop production competes with food crop production for farmland. The incentives were re-evaluated in 2014 to incentivise processing of waste material streams rather than energy crops and this has significantly slowed development of the sector.

- In developing parts of China, government-incentivised small-scale household units on family-owned farms are being abandoned as rural communities are being transformed into productive conglomerate farms with new centralised biogas plants. To some degree, the original assets are being prematurely retired and the investment in these small-scale units has gone to waste.

The most successful tariffs in terms of investment efficiency are the feed-in tariffs employed by the likes of Denmark and the UK. When funding is given out based on quantity of production, plants are incentivised to be efficient and achieve maximum biogas yield during their full operational life.

To make it easier for developers and investors to acquire funding, these tariffs are usually guaranteed for a set period of time (related to the expected life of the asset). This helps provide confidence that the plant will generate a fixed revenue for its operating life which significantly supports the economic case for investment.

In countries with an electricity grid with a much lower proportion of renewable electricity to New Zealand, biogas was initially utilised as a mechanism to create green power. Then, as technologies like wind and solar became favoured options for renewable energy generation, the digestion plants were reconfigured to produce biomethane instead.

In New Zealand, it is unlikely that we would see the same targeted uptake of biogas production for electricity generation as seen in countries like Germany, given how renewable our electricity supply is currently. The NZ government has expressed interest in achieving 100% renewable electricity by 2030, and biogas or biomethane production could support this by decarbonising gas-fired electricity generation in peak demand periods.

Another more likely scenario is that large users of natural gas in New Zealand would directly consume biogas and biomethane to offset their current natural gas or coal thermal generation, either produced onsite or supplied via a distribution network. Initial targeted uptake would focus on developing anaerobic digestion plants capable of injecting their biomethane into the existing network infrastructure or directly feed a large gas user to achieve this outcome.

New Zealand can learn a lot from countries like Sweden and Italy with significant biomethane utilisation and a geographically-dispersed population. In areas without natural gas distribution infrastructure, Sweden still manages to utilise biomethane as a transport fuel and distribute the biomethane from centralised plants to users via 'virtual pipelines' i.e. CNG trucks. In these countries, a few easily utilised feedstocks were the first to be developed (food wastes, WWTP sludges) and as the demand for biomethane grew harder-to-utilise feedstocks became the next in line (animal manures, industrial wastewaters). This model of targeted biogas and biomethane development could help New Zealand develop its biogas and biomethane capacity at a sustainable rate.

3 Biogas and Biomethane in New Zealand Today

3.1 History of Biogas and Biomethane in New Zealand

New Zealand was an early adopter of biogas, after the oil crisis of the mid-1970's prompted countries around the world to re-evaluate their energy supplies and start looking into ways of achieving local energy security. As the Ministry of Energy established the New Zealand Energy Research and Development Committee (NZERDC), and New Zealand began supporting widespread CNG vehicles fuelled by the gas reserves in Taranaki, another parallel development was the implementation of farm-scale bioenergy plants. Farmers grew rapeseed and canola to produce diesel substitutes, and others digested their crop residues and manure to create refined biogas as a direct CNG substitute. A standardized farm-scale system for producing, purifying and compressing biogas was developed by the Ministry of Agriculture to support the development and implementation of these systems across the country.

By the middle of the following decade, there were sixteen farm-based biogas plants across New Zealand. New Zealand was a world-leader and early-adopter of biogas processing technology. The success of agricultural biogas plants here inspired expeditions of researchers, engineers and technicians from countries like Sweden, Denmark and Germany to visit and examine our plants and try to learn what they could to implement similar systems at home.

However, in 1984 a change in government policy led to the dissolution of the NZERDC and government support for CNG/Compressed Biogas (CBG) was discontinued. Coupled with the return to regularity for oil/petrol prices, New Zealand's agricultural biogas plants gradually closed down (Ministry of Agriculture & Forestry, 2008).

Unlike New Zealand, the countries that sent observers to learn from our technology have continued to develop their biogas technology and have successfully achieved grid-scale biogas generation. Today, those very same countries are leaders in global biogas/biomethane, like New Zealand was in the 1980's.

The experience left in New Zealand after the closure of our agricultural biogas plants helped develop biogas generation as an avenue for wastewater solids and sludge treatment, and in 1986 led to the creation of a world-leading biomethane upgrading technology vendor Greenlane Renewables, which is now based in Vancouver, Canada (Greenlane Renewables, 2021).

3.2 Snapshot of Current Biogas and Biomethane in New Zealand

New Zealand's current production of biogas is dominated by three sources: landfill gas recovery (LFGR), industrial effluent treatment plants and sludge digestion at WWTPs. In 2019, New Zealand produced a total of 3.5 PJ of energy across eight WWTPs, several industrial effluent treatment plants including Fonterra's Tirau and Darfield sites, and thirteen landfills with CHP plants. As context, 3.5 PJ represents half the residential gas demand in New Zealand (Ministry of Business Innovation and Employment, 2020), so our current biogas generation is in no way insignificant at a national level.

Today, this gas is generally burned at its source to generate electricity and heat. In some cases, excess heat and CO_2 can be used by nearby agricultural facilities. For example, Redvale landfill sends a portion of the gas and hot water generated by its gas engines to a local greenhouse.

Recently, New Zealand's first purpose-built biogas plant for source-segregate organic waste was announced in Reporoa. The first of its kind in New Zealand, it will accept food waste from Auckland City and from local municipal collections to create carbon-neutral energy and CO_2 for a local Turners & Growers plant and produce digestate from the waste that will be suitable for local agricultural operations. The plant is expected to be operational in 2022.

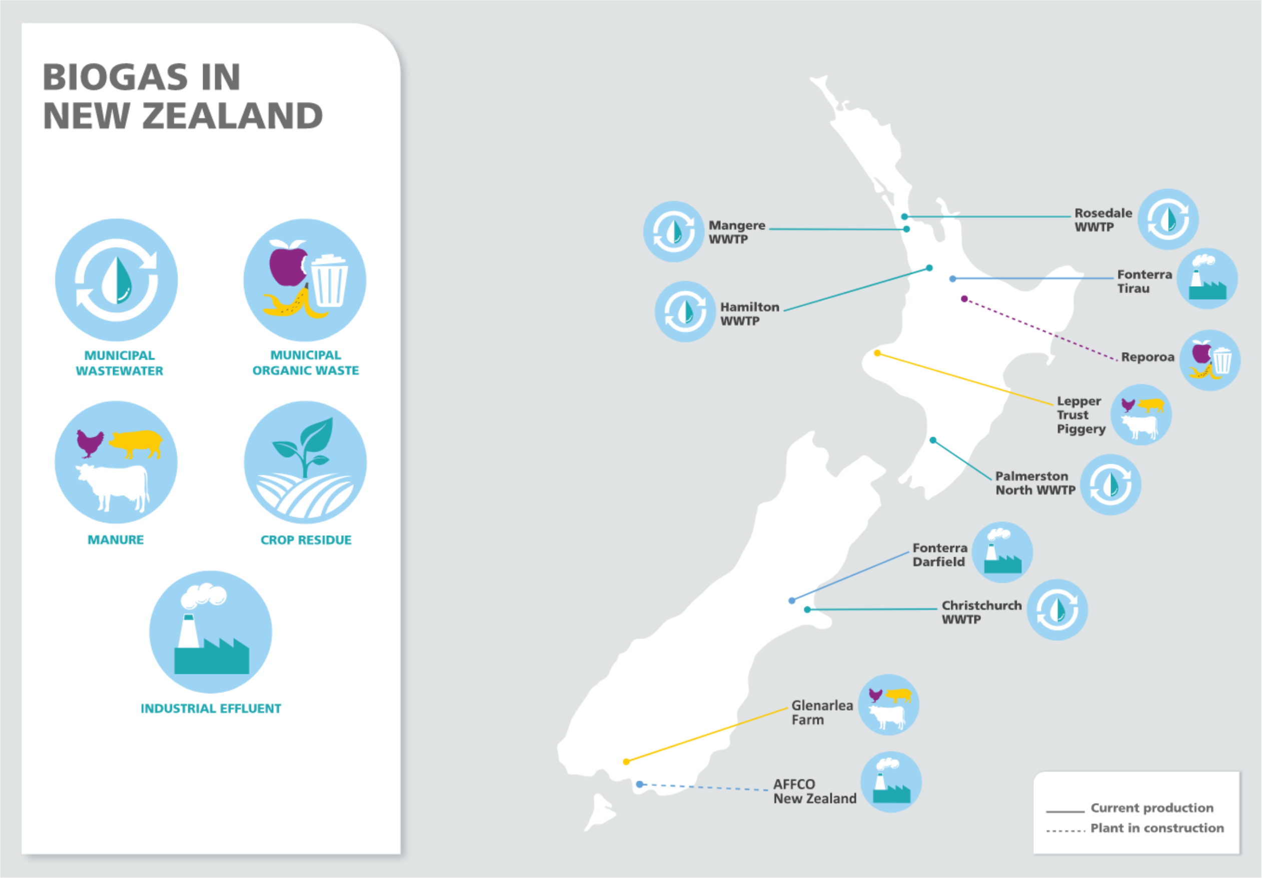


Figure 4: Snapshot of biogas in New Zealand today

3.2.1 Landfill Gas Capture

Currently landfill gas capture is the largest source of biogas in New Zealand (around 3 PJ/year) (Wabnitz et al., 2011). In New Zealand 90% of municipal solid waste ends up 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 (Bioenergy Association New Zealand, 2019).

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).

In the landfills where gas is captured, the biogas is generally utilised in CHP plants to generate electricity and some useful heat.

3.2.2 Municipal Wastewater

The majority of New Zealand is serviced by centralised 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 per year (Water New Zealand, 2021).

The existing biogas production from sludge digestion in WWTPs in New Zealand is approximately 0.6 PJ. Most of the existing biogas produced at WWTPs is currently consumed onsite for electricity generation or combined heat and power units. Grid injection from WWTPs is not feasible unless biogas production surpasses the onsite plant consumption. Plants overseas have been successful in boosting biogas production by co-digesting energy crops and food waste with municipal sludge. This approach is currently being adopted by Palmerston North WWTP

3.2.3 Case Study: Fonterra Tirau Biogas Plant

Fonterra operates one of the largest anaerobic digesters in the southern hemisphere at its Tirau plant. This digestion system generates biogas from whey and other high-Chemical Oxygen Demand (COD) wastewater streams onsite, which is used to offset the natural gas consumption of the utilities plant. The plant has been running for over two decades and produces around 12 TJ of biogas per year.

Figure 5: Fonterra's Tirau Anaerobic Lagoon Digestion Plant

The sludge produced from Tirau’s anaerobic lagoon is harvested and applied to maize cropping land, as a natural fertiliser supplement. The sludge has high quantities of phosphorous and lime which promote plant growth.

Fonterra’s Darfield site has a purpose-built hydraulic digester which treats its effluent stream to produce biogas and remove COD from its wastewater stream.

4 Availability of Feedstocks in New Zealand

Several sectors generate streams of organic wastes which can become part of New Zealand's energy mix, namely the agricultural sector, industrial sector, and municipal sector. Determining the potential for feedstocks for biogas production in New Zealand requires analysis of available quantity, quality, and location of the various feedstock streams. As part of our analysis we have reviewed:

- Factors affecting the quality of feedstock streams include the chemical composition of the feedstock, level of contamination from foreign matter, and seasonality and reliability of the stream.
    - Contamination from foreign matter such as glass and plastic in source segregated organic waste can affect the biological stability of the digester and cause technical issues such as blockage and build-up of inorganic material.
    - Seasonality affects the security of the feedstock stream.
- Location of the feedstock stream, which affects transport costs, the potential for co-digestion with other feedstocks, and the possibility of injection into the North Island gas grid.
- Sites similar to Fonterra Tirau, or the opportunities to co locate business in industrial parks, supporting a more circular economy.

Table 1 summarises the available biogas feedstocks from three key sectors; municipal, industrial, and agriculture, and the total energy these streams could produce assuming 100% of the feedstock is anaerobically digested. This has formed the basis of the uptake scenarios detailed in Section 9.

Table 1: Summary of available biogas feedstocks in New Zealand

Category	Feedstock Type	Feedstock Quantity (wet t/year)	Methane Yield (m^3 CH_4/wet tonne)	Maximum[3] Biogas Potential (PJ/year)
Municipal waste	Source-segregated food waste	354,000	128	1.5
	Municipal wastewater	N/A	N/A	0.60 – 0.87[1]
Industrial wastewater[2]	Dairy	67,400,000	0.50 – 0.84	1.1 – 1.9
	Meat	22,000,000	1.0	0.72
	Pulp and paper	36,100,000	0.49	0.58
Agricultural	Dairy manure	5,320,000	39	5 - 6.8
	Pig manure	281,000	39	0.36
	Poultry manure	825,000	49	1.3
	Crop residue	300,000 – 600,000	145	1.4 – 2.9
Total				12.6 – 16.9

Notes:

1. Based on NZ urban population of 5,107,700 and gross gas production of 18-26 L/PE/day (PE = Population Equivalent)
2. Industrial wastewater quantities have been converted from cubic meters to tonnes at an assumed density of 1.1 t/m^3
3. Maximum assumes 100% of the estimated feedstock size is anaerobically digested to produce biogas

We have not considered the implementation or use of purpose-grown energy crops in our calculations of the total biogas potential in New Zealand. This feedstock has been a large part of the uptake of biogas and biomethane in some overseas countries like Germany. Overseas the growth of energy crops has led to conflicts for land use between biogas producers and agricultural operators. Due to this our analysis has considered repurposing existing organic wastes only.

Types of Feedstocks and Volumes

4.1 Municipal Wastewater Treatment Sludge

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. Table 2 outlines the generation potential from wastewater sludge. Further detail is in Section A1.

Table 2: Summary of Biogas Potential from Municipal Wastewater Solids in New Zealand

Resource	Generation Potential	Existing Biogas Generation	Maximum* Biogas Generation	Key Assumptions
Primary Sludge	315 to 400 Nm^3 CH4/t Organic Dry Matter (ODM)	0.4 to 0.6 PJ/year (consumed onsite)	0.6 to 0.87 PJ/year	• New Zealand's urban population (86.6% of the total population (Trading Economics, 2019)) was used as a basis for potential generation • Gross gas production per capita, assuming the wastewater is processed in a plant with anaerobic sludge digestion ranges from 18 to 26 L per capita per day (Bachmann, 2015)
Secondary Sludge	190 to 240 Nm^3 CH_4/t ODM			

*Maximum assumes 100% of the estimated feedstock size is anaerobically digested to produce biogas

4.2 Source-segregated Food Waste

Table 3 outlines the generation potential from municipal, commercial and industrial food waste. Essential to the uptake of biogas production from this stream is the introduction of segregated food waste collection schemes across New Zealand. Further detail is in Section A1.

Table 3: Summary of Biogas Potential from Organic Waste in New Zealand

Resource	Maximum* Biogas Generation	Key Assumptions
Source-Segregated Food Waste	1.5 PJ/year	• New Zealanders produce 0.07 tonnes of digestible municipal solid waste (food waste) per year per capita (Reynolds et al., 2016) • Biogas generation from Food waste is equal to approximately 128 Nm^3/tonne (Al Seadi et al., 2008; Banks et al., 2018; Jain, 2019)

* Maximum assumes 100% of the estimated feedstock size is anaerobically digested to produce biogas

4.3 Crop Residue and Manure

New Zealand's large agricultural sector provides several sources of biogas feedstock streams, including manures from different livestock and crop residue. Table 4 outlines the biogas generation potential from each of these sources. Further detail is in Section A1.

Table 4: Summary of Biogas Potential from Crop Residue and Manure in New Zealand

Resource	Feedstock Recovery	Maximum* Biogas Generation	Key Assumptions
Crop Residue	5 tonnes per hectare of arable land	1.4 – 2.9 PJ/year	• Based on the region of Canterbury only • 30% - 60% of crop residue can be sustainably recovered (Jain, 2019)
Dairy Manure	10% of total manure produced (Ministry of Agriculture & Forestry, 2008)	5 – 6.8 PJ/year	• 4,900,000 dairy cattle in New Zealand each produce 27 - 35 kg of manure per day (Ministry of Agriculture & Forestry, 2008; Wilcock, 2006) • Only manure from the dairy shed can be recovered
Poultry Manure	100% of total manure produced	1.3 PJ/year	• 22,600,000 chickens in New Zealand produce 0.1 kg of manure per day (Ministry of Agriculture & Forestry, 2008)
Pig Manure	100% of total manure produced	0.36 PJ/year	• 233,000 pigs in New Zealand produce 3.3 kg of manure per day (Ministry of Agriculture & Forestry, 2008)

* Maximum assumes 100% of the estimated feedstock size is anaerobically digested to produce biogas

4.4 Industrial Wastewater

Table 5 outlines the maximum biogas generation available from meat, dairy and pulp and paper wastewater. These values should be evaluated with consideration that most industrial plants will not produce biogas in excess of their process heat demand. Meat and dairy wastewater have substantial biogas potential due to the high COD concentrations of these streams, which can be processed in a purpose-built hydraulic reactor. The COD concentration and subsequent biogas yield of pulp and paper wastewater is too low to make anaerobic digestion of pulp and paper wastewater a feasible option. Other waste streams and by-products are generated by the industrial sector, such as food waste from food manufacturers, trade waste, spent grain and yeast from distilleries and breweries, grease from grease traps and paunch grass from slaughterhouses. These additional streams have not been quantified.

Table 5: Summary of Biogas Potential from Industrial Wastewater in New Zealand

Industry	Existing Generation	Maximum* Biogas Generation	Key Assumptions
Meat Processing	-	0.72 PJ/year	• 20,000,000 m^3/year of wastewater with a COD of approx. 3600 g/m^3 (A. Khan et al., 2014; Wabnitz et al., 2011) • Processed in a purpose-built hydraulic reactor
Dairy Processing	0.12 PJ**	1.1 – 1.9 PJ/year	• Based on Fonterra only • 61,000,000 m^3/year of wastewater with a COD of approximately 1800 to 3000g/m^3

Industry	Existing Generation	Maximum* Biogas Generation	Key Assumptions
			(R. Hamilton et al., 2011; NZ Institute of Chemistry, 2017; Wabnitz et al., 2011) • Processed in a purpose-built hydraulic reactor
Pulp and Paper Processing	-	0.58 PJ/year	• Based on Kinleith mill only • 32,000,000 m^3/year of wastewater (Oji Fibre Solutions, 2019) with a COD of 1760 g/m^3 • Processed in a purpose-built hydraulic reactor • Pre-treatment is required for lignocellulosic material

* Maximum assumes 100% of the estimated feedstock size is anaerobically digested to produce biogas

** Excludes newly commissioned Darfield site

4.5 Forestry Waste

Biogas from forestry waste has not been quantified as rigorous pre-treatment is required to break down the complex structure of lignocellulose found in woody biomass. Established pre-treatment methods do exist, but these are costly and energy-intensive. Refer to Section A1 for more information.

4.6 Conclusions

The variety of biogas feedstock available in New Zealand illustrates that the solution to expanding on biogas (and subsequently biomethane) production entails the utilisation of all feedstock types, namely livestock manure, source segregated food waste, municipal wastewater, industrial wastewater and crop residue. New Zealand is already producing biogas from municipal WWTP sludge, landfill gas recovery, and industrial wastewater. Livestock manure, crop residue and source-segregated organic waste, which are not currently an established source of biogas production in New Zealand, have the potential to produce up to 13 PJ of biogas.

Agriculture, one of New Zealand’s largest sectors, could play a key role in producing scalable biogas and biomethane. While this feedstock is certainly available at scale, there are logistical challenges associated with collection and transportation of the feedstock. Notwithstanding, the distribution of agricultural land is regionally dense. Canterbury has access to approximately 70 percent of New Zealand’s crop residue, while 33 percent of New Zealand’s dairy herds are in the Waikato (Dairy NZ, 2018). Regions like these may be suited for on-site anaerobic digestors for creation of biogas or be suited for focused feedstock collection and transportation to be converted into biomethane in an opportune location. Industrial wastewater tends to be at a scale that constitutes reuse on site, with anaerobic digestion used as part of the treatment process. The dairy and meat industries produce wastewater at scale, with high biological loadings and are therefore highly suited for biogas production. Source segregation of municipal organic waste also presents a considerable opportunity for biogas production such as at the Reporoa plant due to open in 2022, but there is still room to expand on the use of this feedstock with the key being the establishment of a standardised organic waste collection system in New Zealand.

4.7 Limitations and Conflicts of Feedstock Use

4.7.1 Composting or Other uses for Organic Waste

Home composting and vermicomposting (using worms to digest organic materials) turns food waste and plant waste into a product rich in nutrients that are beneficial to soil. Some individual New Zealanders opt to compost their kitchen waste themselves, which could divert a portion of municipal organic waste away from biogas production. However, it is assumed that the uptake of home composting is minimal compared to the total volume of organic waste New Zealander's produce. There are organisations in New Zealand, for example Living Earth and WeCompost, who collect organic waste to be composted, which is a noteworthy means of reducing waste to landfill. There has also been an increased uptake in vermicomposting in recent years. Both of these technologies require much greater areas of land than anaerobic digestion. In 2013, 35,196 tonnes of source segregated organic waste was vermicomposted (Quintern & Morley, 2014). Nonetheless, a vast majority of organic waste still goes to landfill and thus composting and vermicomposting is not anticipated to significantly conflict with the realistic uptake of organic waste as biogas feedstock.

4.7.2 Landfill Gas Capture vs Source Segregated Collection

Some organic waste streams already produce biogas in New Zealand through collection and disposal in landfills with landfill gas capture systems installed. Some landfills in New Zealand use the biogas generated to create heat and power, while others flare the gas to reduce its Global Warming Potential (GWP). Landfill gas capture systems are on average only 60% efficient and many landfills across New Zealand are close to reaching capacity.

The advantages of anaerobic digestion over landfill gas capture is that it enables more complete capture and use of the biogas generated, and allows for the production of digestate which is another valuable by-product of the digestion process. However, landfill gas capture is capable of producing biogas from highly contaminated wastes with only partially digestible contents.

There is already an established roadside waste collection network in New Zealand, whereby waste is transported to landfill via pickup trucks, of which 90% of these landfills are already equipped with gas recovery (Biogas Association of New Zealand, 2019). Establishing a household collection system where organic waste is diverted to a dedicated biogas plant conflicts with these existing practices. Adopting a new collection system for organic waste will no doubt be a challenging mindset change for New Zealanders. Therefore, it should be expected that a portion of organic waste will still go to landfill, thus conflicting with its use as feedstock to biogas plants. Nonetheless, there are strong drivers for making the change.

4.7.3 Manure Fertiliser

While anaerobic digestion has been shown to improve the fertilisation properties of manure (Barłóg et al., 2020; Drosg et al., 2015; Möller & Müller, 2012), its use as a fertiliser via other processes, for example, 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.

4.7.4 Anaerobic Digestion in the Context of the Waste Management Hierarchy

The production of biogas and biomethane relies on the continued creation of organic waste products for collection and processing. While the creation of digestate to be applied back to land from this waste creates a circular economy for this waste, we should keep in mind that a more effective strategy for reducing the impacts of waste to our environment is reducing the amount of waste generated in the first place.

Biogas feedstocks like food waste and industrial wastewater are unlikely to disappear , but changing waste management practices around New Zealand could impact the amount of these feedstocks available.

5 Biogas and Biomethane Processing

5.1 Feedstocks to Biogas

Biogas is created through the decomposition of organic matter. Micro-organisms digest the organic material in the absence of oxygen and as a result methane, carbon dioxide and other compounds are produced. The exact conditions inside the reactor encourage different kinds of bacteria to produce different organic compounds, and in some cases can inhibit these same bacteria. The key to designing a successful anaerobic digestion system is understanding how to optimize the conditions in a reactor for the selected feedstock to enable sustainable, effective, and balanced conversion of organic waste to biogas throughout each of the key stages of conversion.

There are four main steps in the conversion of organic material to biogas, undertaken by three separate kinds of bacteria. Detailed steps are outlined in Section A3. A simplified diagram is shown in Figure 6:

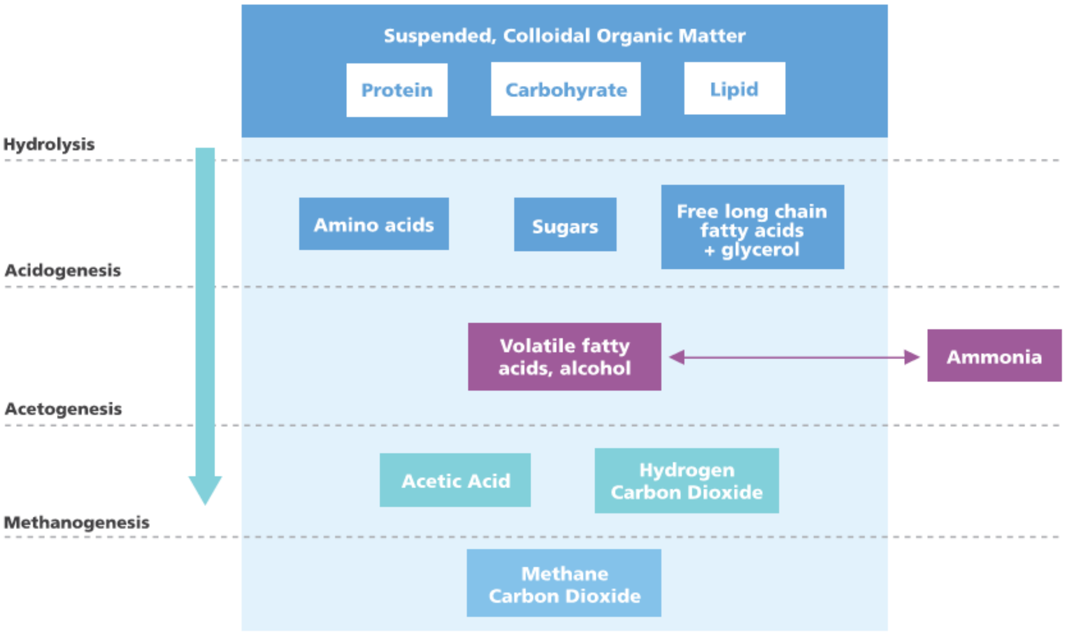


Figure 6: Simplified diagram of the main stages of methane-yielding anaerobic digestion (Mes et al., 2003)

Each of these different bacteria work at different rates and prefer slightly different conditions to grow and convert their food into intermediate products for the next group of bacteria (Achinas et al., 2017). The conditions inside an anaerobic digester are often optimized to try and even out the speed of each reaction and achieve the highest overall conversion speed, but this is a dynamic exercise. The most important group of bacteria in terms of methane production, the methanogens, are often the slowest and most sensitive to changes in digester conditions and commonly deemed the rate limiting step. (Nsair et al., 2020).

Like all biological processes, there are several variables that need to be tightly controlled for these different bacteria to operate effectively and maintain the balance in the digester.

Before we discuss how these conditions can be optimized in the design of a reactor, let’s review which conditions and variables affect the digestion process the most (Table 6).

5.1.1 Process Variables and Additives

Table 6: Feedstocks to Biogas Process Variables and Additives

Variable	Conditions
Temperature	Methane bacteria can be either: • Psychrophilic (10-20°C) • Mesophilic (20-40°C, or 30-38°C with the latter more common) • Thermophilic (50-60°C) Reaction to produce biogas is exothermic however external heat is usually still required.
pH	Most microorganisms grow best in neutral pH conditions. pH control can be done in the following ways dependent on reactor design: • Extra buffer capacity • Adjusting or stopping the feed into the reactor • Direct dosing of the reactor with chemicals
Organic Loading Rate and Feedstock Control	The Organic Loading Rate (OLR) for a digester system is a measure of the digestible material feed rate, or the feed rate of volatile solid materials Generally, systems are designed for a set OLR and it is not easy to implement process changes to boost this figure after an operating scheme has been selected High C/N (carbon to nitrogen) ratios mean good biogas yields from feeds, and lower C/N rations mean reduced biogas yields.
Nutrients	Sulphur: • There is a minimum level of sulfur compounds required for the reaction pathway from organic waste to biogas to proceed • High concentrations of sulfur compounds in solution interfere with the methanogenesis stage of the reaction, preventing maximum conversion Ammonia • Optimum ammonia levels can keep the reaction chain stable and buffer the methanogenic stage of the reaction • Too much ammonia, especially at pH below 7, can be toxic to bacteria

Further detail on the process variables is in Section A3.

5.1.2 How to Choose a Plant for your Feedstock

At scale, there are only a handful of different processing arrangements widely used to create biogas from organic waste. This is because these designs have proven to be the most efficient and the most cost-effective after years of operation in overseas markets. Over the past 30 years, plant designs have been continually refined and developed to provide the most effective biogas conversion for every dollar spent.

Consideration of the most desirable processing arrangement, includes the following factors:

- Types of feedstocks available
- Available land or cost of land
- Access to markets for energy products and digestion by-products
- Acceptable level of technical complexity.

Types of feedstock include:

- Industrial effluent
- Energy crops
- Animal manure
- Energy crops

The factors that influence the way the processing scheme is designed, and the decisions that investors and operators of anaerobic digestion facilities make at the start of any project to ensure that a best-fit installation is achieved will be reviewed.

5.1.3 Pre-treatment Methods for Feedstocks

Wet digestion systems will often require extensive pre-treatment of feedstocks to prepare them for mixing and processing in the anaerobic digester (Ariunbaatar et al., 2014). Table 7 outlines the broad categories of feedstock pre-treatment. Further detail on the pre-treatments is in Section A3.

Table 7: Pre-Treatment Methods for Feedstocks

Treatment	Objective/Process
Preparing Feedstocks for Digestion	Pre-treatment to make organic wastes suitable for biological digestion – removing impurities and processibility
a. 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
a. 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
b. Chemical or Biological Pre-Treatment	• Use of chemical reagents to break up cellular structures and reduce the downstream work for the anaerobic digester
c. Electrical Pre-Treatment	Two main types: • Microwave treatment (where feedstocks are exposed to microwave radiation) • Ultrasound treatment (where feedstocks are exposed to high-frequency vibrations)
d. 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).

5.1.4 Designing the Best Digestion Process

Conversion of organic material into biogas can be done in a number of ways, and there are many ways to configure a biogas plant to process organic materials. For maximum yield and plant utilization, the key is to design the biogas plant around the type of organic waste it will be processing. Then, depending on scale required and acceptable operational complexity, the plant can be tweaked and adjusted to be economically and practically successful.

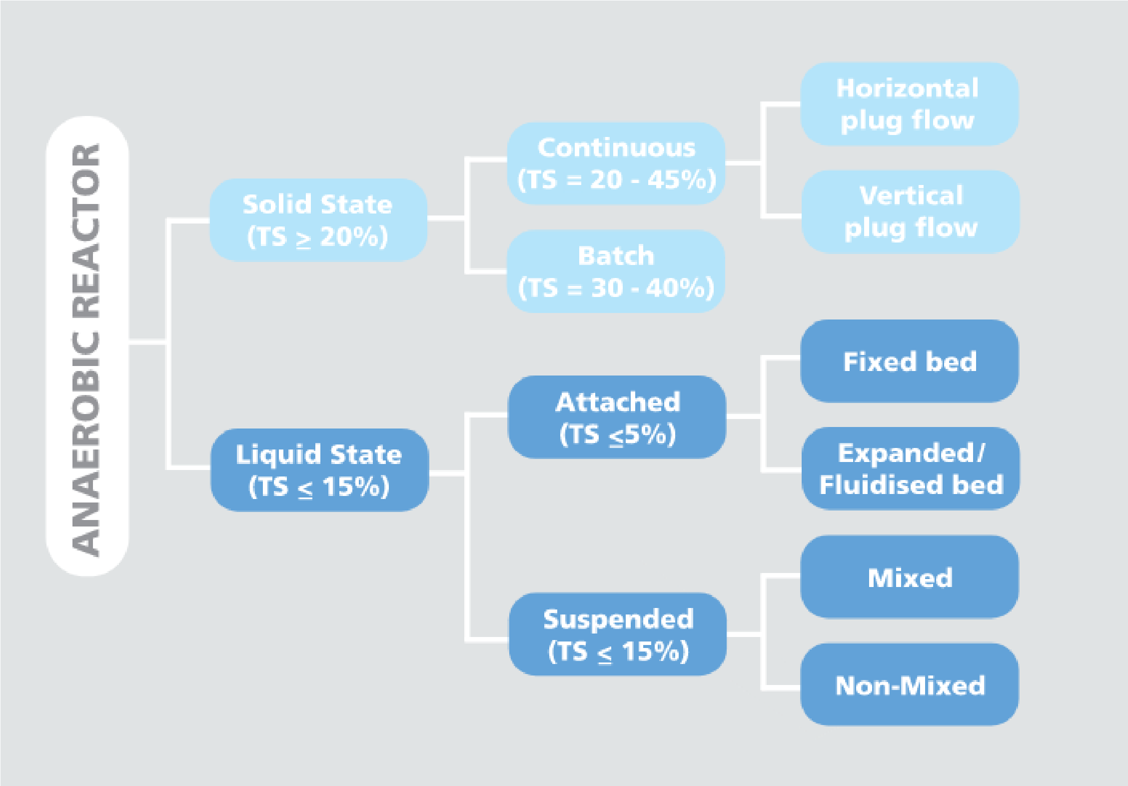


Figure 7: Digester Classifications by Total Solids % (Van et al., 2020)

Table 8 briefly compares the different digestion processes. Further detail is in Section A3.

Table 8: Comparison of Digestion Processes

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 easily pumped and are often manually moved usually via front end loader
Wet AD Technologies	• Three categories; ○ Suspended Solid digestion (where 15% > TS >5%) (common for wastewater treatment sludge and food waste where there is a lot of suspended organic matter) or ○ Attached Medium digestion (TS <5%) (predominantly liquid organics streams) ○ High-rate Hydraulic digestion (TS <1%) used when organic material is mostly in dissolved state • Involves a much higher amount of fluid entering and leaving digester (compared with dry) • Feedstock can be treated like a liquid allowing for more autonomous control and processing
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	• When feedstock is low in solids content (TS <15%) • Suspended organic matter is circulated and mixed with bacteria to achieve a more-or-less homogenous solution • Continual supply or organic material into reactor

Process	
	• Biogas/digestate is continually harvested from the reactor • Always maintains a level of the required bacteria
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	• Lower yields of biogas than thermophilic • Can't process as much organic material as thermophilic digesters • Less susceptible to temperature swing upsets than thermophilic digesters
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.

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5.2 Typical Anaerobic Digestion Processes + Costs

Table 9 summarises the best-fit standardised processing configuration for all feedstock sources. Further detail on the sources and their properties is in Section A4.

Table 9: Standard Digester Technology/Configuration by Feedstock Source Type and Volume

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

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

5.2.1 Capital Costs

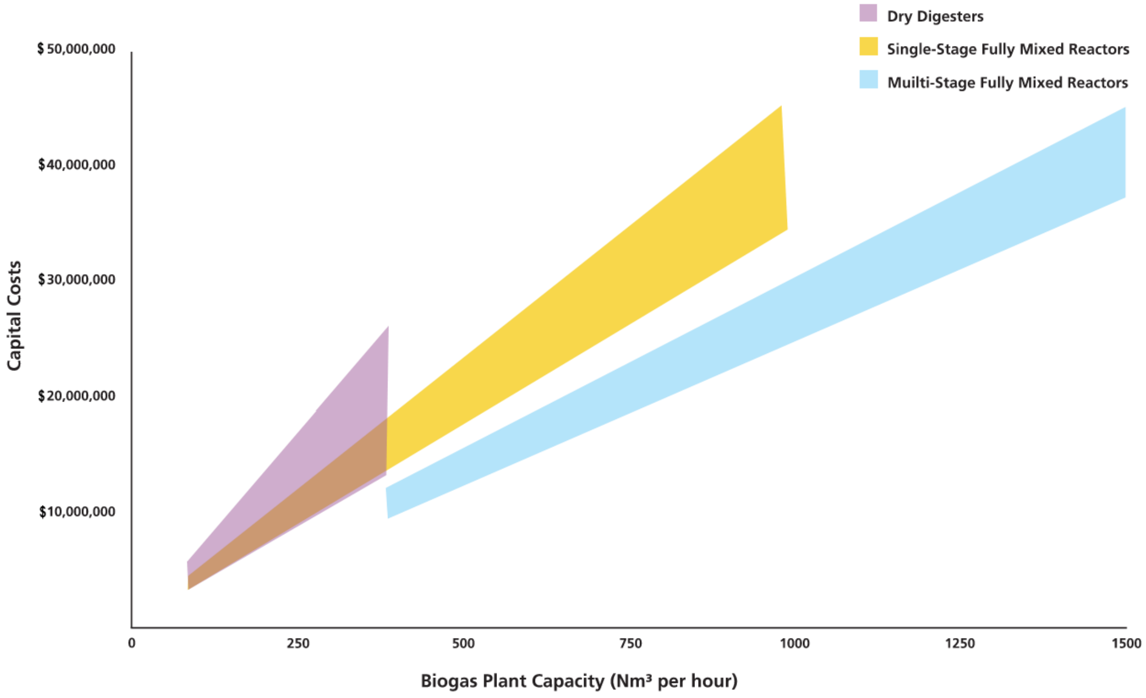

Figure 8: Capital cost ($NZD) vs biogas plant capacity (Nm^3/h) for dry digestors, single-stage fully mixed reactors and multi-stage fully mixed reactors

Figure 8 shows the magnitude of capital costs associated with each main type of digester for solid organic wastes (Cleanleap, 2013; Moriarty, 2013; SAMCO, 2019; Scion, 2013; Spencer, 2010; Truong et al., 2019). Please see Section A4 for more information on these estimate ranges.

5.2.2 Operating Costs and Revenue Streams of Biogas Generation

There are many different costs and revenue streams associated with the operation of a biogas production plant. These can positively or negatively affect the economics of operating the facility and all contribute to the financial feasibility of a biogas installation. Below we have identified the main ongoing costs and sources of revenue for a biogas installation, and a commentary on how these would be quantified in a New Zealand context.

a. Gate Fees and/or Purchasing Feedstocks

Gate fees and similar revenue models are the driving force behind a large number of alternative waste disposal technologies like Waste to Energy plants in the UK. Collecting payment for accepting and processing biogas feedstocks is a great way to generate revenue for some biogas feedstocks, as disposal of most feedstocks will incur a cost to dispose of via other means e.g. landfilling. Currently in New Zealand, gate fees for landfills can be in the range of $100-$150/ tonne of waste which includes a waste disposal levy.

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[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.

New Zealand’s waste disposal levy is being increased gradually from $10 /t to $60 /t by July 2024 (Ministry for the Environment, 2021).

This revenue stream will not feature as prominently for some feedstocks e.g. manure or crop residue which are currently left in fields or burned as a waste product. To collect these feedstocks, the biogas plant would either have to pay for the feedstocks to be supplied or exchange processed digestate for raw biomaterials as is done in Denmark (Ministry of Foreign Affairs of Denmark, 2021b).

b. Sale of Biogas or Biomethane

The biogas generated by the plant is the primary product of the digester plant. The biogas generated can either be sold as-is or refined into biomethane for gas grid injection and use.

The average wholesale price for natural gas in New Zealand during 2020 was 2.38 ¢/kWh (excluding GST), or $6.60 /GJ (Ministry of Business Innovation & Employment, 2021), not including an extra $3 /GJ including current ETS changes and transmission costs. In future years, it is expected that the realistic sale price for gas could increase well beyond $15-20 /GJ which would help the economics of these installations (Silk et al., 2021).

c. Sale of CHP

In other plants, the biogas generated can be burned for direct generation of electricity and power. In most modern biogas CHP engines, around 45% of the energy in the fuel can be converted into electricity (Clarke Energy, 2021). This can then be supplied to the grid and sold on the spot market, or used to power onsite equipment like in most of New Zealand’s WWTPs.

The average wholesale spot price for electricity in 2020 was around $0.14/kWh, which after accounting for efficiency generates $15 per GJ of gas generated. In recent months, average monthly wholesale spot prices have reached $0.25 /kWh, which would provide $27 per GJ of gas generated (Electricity Authority (Te Mana Hiko), 2021). The waste heat generated by the engines can also be used for other purposes e.g. hot water heating for greenhouses.

In New Zealand’s current energy market, electricity generation is currently more profitable than biomethane production per GJ. However, the electricity spot price market is subject to frequent change and this elevated price is unlikely to continue indefinitely, and long term predictions suggest prices of around $80 /MWh are more realistic, which would equate to a sell price of $8.5 per GJ of gas generated.

d. Sale of Digestate

In some countries with legislation to support the uptake of standards like Publicly Available Standard (PAS) 110, digestate produced from an anaerobic digestion facility can be certified and sold as a value-adding product (Waste & Resources Action Programme (WRAP), 2014). If the digestate is being used to supply specific nutrients or high-quality material is required, additional processing of the digestate may necessary. In New Zealand, no such legislation or support for equivalent standards exists currently and the use of digestate as a fertiliser will likely be dependent on individual supply agreements (Tinholt, 2019). Biosolids generated from WWTPs in New Zealand can be used for land rehabilitation after secondary treatment (NPDC use a drying step and sell their biosolids as Bioboost (Bioboost, 2017), HCC supply vermicomposted digestate from their WWTP for land rehabilitation (Murray, 2017)), but likely there would be no financial compensation for untreated anaerobic digestate supply given its classification as a waste product currently, but would avoid the operation paying landfill disposal costs.

Achievable digestate revenues in New Zealand for source-segregated digestion operations are around $20 /t including transport and spreading costs (Bouskova, 2021). Revenues of $10-$30 /t would generate large revenue streams for these operations. Sale of certified digestate supported by specifications like TG8 in New Zealand would enable higher prices to be charged for the material, depending on its composition. Further analysis should be done to determine achievable premiums for this material.

e. Sale of Carbon Dioxide

If the decision is made to install an additional CO_2 recovery plant to extract food-grade carbon dioxide for sale, this can add an additional revenue stream to the operation of the plant. Generally, the yield of carbon dioxide from biogas is around 25-35%.

Food-grade CO_2 can be sold for between $200 and $500/tonne based on current industry trends and allowing for distribution costs.

In New Zealand, the majority of our CO_2 supply is generated at Refining NZ, located at Marsden Point, and the domestic market for CO_2 is expected to grow in coming years (Underhill, 2018). As Marsden Point plans to transition towards a smaller operation in coming years, biogenic sources of CO_2 could become valuable.

f. Operations and Maintenance Costs

Operating the anaerobic digestion process and keeping the plant equipment maintained will be an ongoing cost to the plant. Depending on the degree of process automation, operators may be required to handle and transport feedstocks, adjust digester conditions and handle digestate as well. In a fully automated plant, only a handful of operators and technicians will be required to control the digestion process and fix any equipment faults. For most industrial plants of this scale, operational and maintenance costs are equal to 4-6% of the original capital cost per annum (Cleanleap, 2013).

g. Electricity Costs

In general, we would expect most biogas plants to be self-sufficient for electricity and utilise some of the biogas produced (generally 7-15% (Cleanleap, 2013)) to supply the plant with heat and electrical power, so electrical costs should be minimal over a year of operation. However, an electrical connection would still be required for non-production periods and for start-up etc when the plant cannot produce its own energy. Plants should consider the relative costs of CHP engines and reduction in biogas yields for self-sufficiency vs purchasing grid electricity in a detailed economic analysis.

5.2.3 Other Operational Costs

Some operational costs vary massively across individual installations and can either enable or prohibit economic operations. These include:

- Energy Requirements – as more automated and efficient processes are pursued to maximise biogas yield from feedstocks, the amount of energy consumed by the process (heating, electrical power, mechanical or thermal pre-treatment) compared to the amount of energy generated by biogas can start to decrease energy yields of the plant.

- Labour costs – smaller-scale systems with minimum automation require higher degrees of manual intervention to keep the process running successfully. Relatively dry feedstocks rule out the use of pipes and pumps as transport equipment, in which case bucket loaders/front end loaders will be needed to move organic material between stockpiles and digesters, which means additional operators and staff. In this way, upfront capital spend can be the inversely proportional to ongoing operational costs.

- Chemical Costs – dosing chemicals or enzymes into the process to increase yields of biogas can be a significant drain on bottom line profit from the sale of biogas products, but some feedstocks may not be able to be processed without them. When assessing a feedstock as an input to a biogas plant, the chemical requirements should be well understood to give an honest reflection of plant profitability. This can also be addressed by mixing feedstocks with complementary properties.

- Logistical Costs – because the majority of biogas plants utilize waste organic materials, it is necessary to understand how/where these waste materials are generated. For feedstocks generated over a wide area e.g. manure or municipal food waste, understanding how easily these can be collected and transported to a central processing location is vital. Additionally, once the biogas is generated, consideration of how this energy can be transported and sold is crucial, as connecting poorly-placed plants to local or national energy infrastructure can be prohibitively expensive (Chen & Liu, 2017; Hengeveld et al., 2020).

5.3 Biogas to Biomethane Processing

Biogas produced from the breakdown of organic materials will contain a variety of components that can be beneficial or detrimental to further uses. Raw biogas will typically contain methane (CH_4) concentrations greater than 50mol%, with the remainder being comprised mostly of carbon dioxide (CO_2). The CH_4 and CO_2 content of raw biogas can be considered as potential value streams for biogas upgrading schemes.

Table 10: Methane and carbon dioxide content (% by volume) of landfill gas and biogas from anaerobic digestion

Component	Landfill Gas (Nyamukamba et al., 2020; Sun et al., 2015)	Biogas from AD % by mol at standard conditions (Al Seadi et al., 2008; Nyamukamba et al., 2020; Sun et al., 2015)
Methane	30-60 mol%	50-90 mol%
Carbon dioxide	15-40 mol%	10-45 mol%

For biogas to be utilised as fuel in reticulated natural gas networks, the calorific value (CV) requires upgrading to meet the appropriate gas specification. In New Zealand, all reticulated natural gas is required to meet constituent and Wobbe specifications according to NZS 5442-2008.

5.3.1 Gas Quality

The New Zealand standard “Specification for Reticulated Natural Gas” is NZS 5442: 2008. This specification states the requirements for the safety and suitability of methane-based gas transported and supplied for use in natural gas burning appliances and equipment. NZS 5442 Section 1.2.1 states that this specification applies to biogas production sources that are blended into open access gas systems.

The key requirements for biogas in this specification is the Wobbe Index, which must be between 46 and 52 MJ/m^3, with a maximum relative density of 0.8. This corresponds to a CV range of 35.2 to 46.5 MJ/m^3. The hydrogen sulphide content must not exceed 5 mg/m3 and the water content must not exceed 100 mg/m^3. The oxygen limit is 0.1 mol% with an exception for low and medium pressure networks where the oxygen limit is 1.0 mol%. Gas must also be free from other contaminants such as particles, heavy metals and gum forming constituents. Biomethane processing plants are likely to have additional equipment requirements to maintain oxygen levels below 0.1mol%. Most biomethane processing can typically provide less than 1mol% oxygen without additional equipment.

Typical biogas sources produce gas which has a CO_2 content of approximately 30-45 mol% and depending on the biogas feedstock can include a variety of other contaminants. The NZS 5442 specification requires biogas to biomethane processing to produce a dry gas, where the majority of CO_2 has been removed and any other contaminants such as hydrogen sulphide or Siloxanes have also been thoroughly removed.

The gas distribution or transmission network owner will insist on gas quality monitoring technology as part of the biogas processing plant to ensure that the gas specification is constantly met. The equipment design will need to allow for any “off specification” biomethane to be rejected back to the anaerobic digestion plant or a flare (generally unacceptable).

Biomethane may only be injected into a reticulated gas network if it constantly meets the New Zealand gas quality standard. This is a legal requirement for the network owner to supply gas to consumers. If the gas does not meet the specification requirements at any time, then the biomethane injection plant must be designed to reject and/or recycle the non-compliant gas.

5.3.2 Gas Treatment

There are three steps when upgrading biogas to biomethane and exporting, detailed in Figure 9:

- Pre-treatment (cleaning)
- Biogas to biomethane processing (upgrading)
- Network injection

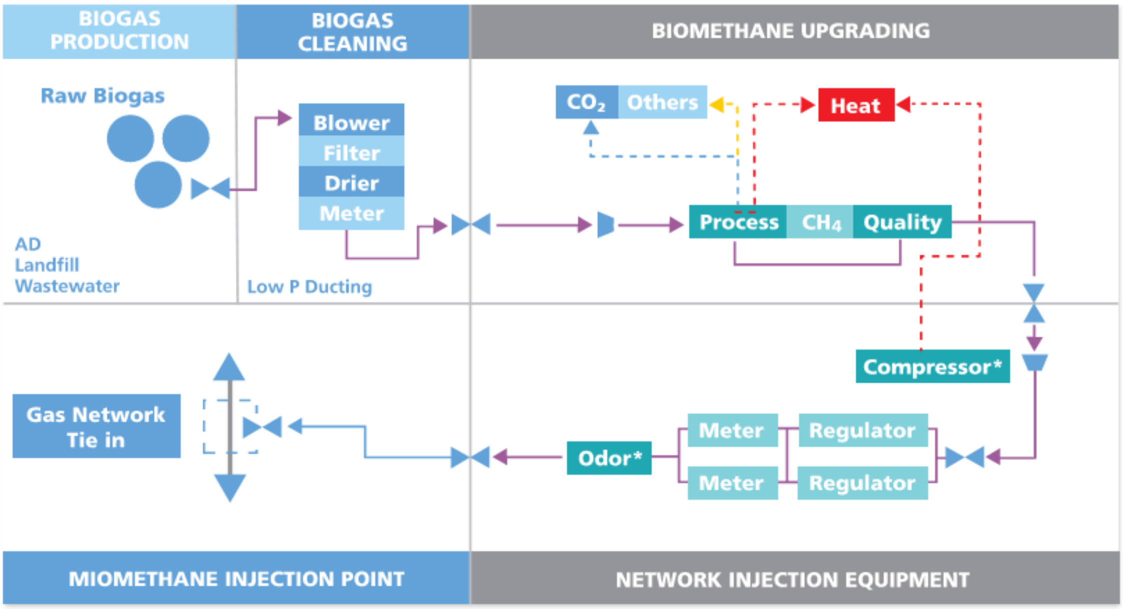

Figure 9: Typical biomethane upgrading process

Depending on the type of feedstock the biogas is produced from, there can be smaller concentrations of components such as hydrogen sulphide (H_2S), silicon organic compounds (siloxanes), oxygen (O_2), water (H_2O), ammonia (NH_3), Nitrogen (N_2) and particulates that are viewed as contaminants to the raw biogas (Sun et al., 2015b). The actual concentration of these contaminants varies depending on the feedstock quality but are typically viewed as detrimental to downstream equipment.

Table 11: Contaminants in raw landfill gas, biogas from AD, and limits for reticulated gas in NZ

Contaminant	Landfill Gas % by volume at standard conditions	Biogas from AD % by volume at standard conditions	Reticulated NG % by volume at standard conditions
Nitrogen – atmospheric N_2 is introduced during AD feeding or landfill gas extraction	0-15 mol%	0-1 mol%	Not specified
Water vapour – AD process is saturated & reactor temps are	1-5 mol%[1]	1-5 mol%[1]	<0.00001 mol%[2]

Contaminant	Landfill Gas % by volume at standard conditions	Biogas from AD % by volume at standard conditions	Reticulated NG % by volume at standard conditions
typically higher than ambient			
Oxygen – atmospheric O_2 is introduced during AD feeding, H_2S control or landfill gas extraction	<2 mol%	<2 mol%	<1% (low and medium pressure grids) <0.1% (all other cases)
Ammonia – AD treatment of feedstocks with high levels of nitrogen	0-5 mg/m^3	0-100 mg/m^3	Not specified
Siloxanes – caused by the digestion of silicone compounds in landfills or WWTP sludge	0-50 mg/m^3	0-20 mg/m^3 (WWTP sludge can produce high levels of Siloxanes)	Not specified
Hydrogen sulphide – caused by the digestion of sulfide/protein containing feedstocks	100-10,000 mg/m^3	0-1000 mg/m^3	<5 mg/m^3
Hydrogen – from the digestion of sugars & VFA's	0-3 mol%	<1 mol%	<0.1 mol%
Total Cl	0-100 mg/m^3	0-100 mg/m^3	<25 mg/m^3
Volatile Organic Compounds – typically found in landfill gases	<2,000 mg/m3	-	Not Specified
Sources	(ATSDR, 2001; Nyamukamba et al., 2020; Sun et al., 2015(Soleilhavoup & DESOTEC, 2020))	(Al Seadi et al., 2008; Nyamukamba et al., 2020; Sun et al., 2015)	(Standards New Zealand, 2008)

[1] Temperature dependent

[2] At standard conditions

5.3.3 Pre-Treatment

A summary of the different pre-treatment options for contaminants is included in Table 12. Further detail of pre-treatment options is described in Section A5.

Table 12: Pre-treatment Summary

Impurity	Technology	Outlet levels	Comment
H_2S	Biological desulphurisation	< 50 ppm	Most common
	Iron Chloride	100 - 150 ppm	Used for high quantities
	Impregnated Activated Carbon	< 0.1 ppm	Common prior to PSA
	Iron Hydroxide or oxide	< 1 ppm	Finite regeneration cycles
	Sodium hydroxide Scrubbing	< 1 ppm	Regeneration not possible
Siloxanes	Activated carbon	< 0.87 ppm	Carbon unable to regenerate. Sensitive to humidity
	Cooling	26% - 99% removal	-27°C to -70°C
O_2/N_2	Activated carbon		
	Molecular sieves	<1000 ppm	Outlet levels will be dependent on internal surface area of the desiccant and process parameters
	Membranes		
H_2O	Adsorption with Silica Gel or Aluminium Oxide	Dew Point -10C to -20C	At atmospheric pressure
	Absorption with Triethylene glycol or glycol	Dew Point -5C to -15C	At atmospheric pressure, Regeneration required to 200C

. (Sun et al., 2015a)

5.3.4 Biogas to Biomethane Processing / Upgrading

Table 13 gives a brief overview of the major commercial processing technologies used to upgrade raw biogas to biomethane. The best choice is generally determined by the composition of the raw biogas and the specific end use requirements for the biomethane. Further detail on these processes is in Section A5.

Table 13: Biogas to Biomethane Processing Technologies

Process	Key Points
Pressure Swing Adsorption (PSA)	• Different sized gas molecules selectively adsorbed to a solid surface at high pressure then released using a reduction in pressure. • Used to upgrade raw biogas by adsorbing other gas molecules like CO_2, N_2, and O_2 from the larger methane molecule
Water Scrubbing	• 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 • Operating pressure for the process is between 4 – 10 barg • Process takes place in a scrubbing column where water is sprayed downwards while raw biogas is directed upward
Chemical Scrubbing	• Similar principle as water scrubbing except the solvent is a chemical mixture which reacts to absorb components from the gas with the solvent

Process	Key Points
Membrane Scrubbing	• 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).
Physical Scrubbing	• Same as pressurised water scrubbing but using organic solvents such as “Selexol” for enhanced selective absorption of CO_2

There are other methods to process impurities from biogas such as cryogenic separation, in-situ removal, biological methods and hydrate separation that have yet to be made readily available to the commercial market (Sun et al., 2015b). 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 available.

5.3.5 Network Injection Equipment

Once the biogas has had the majority of CO_2 and other contaminants removed to upgrade the CV, the biomethane can be injected into the natural gas network. Like other natural gas producers, the biomethane producer is required to ensure the biomethane adheres to NZS 5442 prior to network injection. Certain equipment is required by the network operator to enable biomethane injection into the network. This injection equipment can be located at the biomethane production facility or at the biomethane injection point (BIP) to the network. The potential ownership models for this equipment is outlined in Section 3.C.iii.

Table 14 outlines the different types of network injection equipment. Further detail on these processes is in Section A5.

Table 14: Network Injection Equipment Summary

Network Injection Equipment	Summary
Gas Chromatograph (GC)	• Measures the components of the biomethane and ensures the gas meets the specification essential for reticulated customer use • Provides an online measurement of gas quality
Gas Enrichment	• Based on composition and Wobbe Index, biomethane can be dosed with propane to improve energy content for compliance with NZS 5442
Pressure Compression or Regulation	• Compressors can be controlled to ensure that the maximum allowable operating pressure (MAOP) of the network is not exceeded • A second stage of pressure regulation such as a pressure relief valve will be required according to either AS/NZS 2885 or AS/NZS 4645
Gas Metering	• Accurate metering allows network operators to measure the quantity of gas entering the network and allocate gas sales to specific producers
Gas Odorisation	• As part of the requirements of NZS 5442 for reticulated gas networks, natural gas must be odorised to be able to identify gas leakage • The recognisable smell is the odorant added to natural gas
Network Isolation Valve and Interconnection	• To connect a biomethane production facility to an existing network, a BIP will require interconnection equipment • Depending on the chosen location of the BIP, the equipment required to connect to the existing network could include modifications to an existing delivery point

5.3.6 Capital Cost of Biogas Upgrading and Key Cost Drivers

Every biomethane processing scheme will be slightly different; however, most will fit into three categories according to the source of the biogas feedstock:

- WWTP

- Landfill
- Anaerobic Digestion

Table 15 outlines the capital cost for biogas upgrading. Further detail is in Section A5.

Table 15: Biogas Upgrading Cost Matrix ($NZD)

Biogas Processing Plant Costs					Biomethane Injection Costs			
	Raw Biogas source					Components		
Biogas (Nm^3/hr)	**AD**	**Landfill**	**WWTP**	**Food Grade CO$_2$**	**Biomethane (Nm^3/hr)**	**Compression**	**Metering & Regulation**	**Injection Point**
40-400	1.9M	~2M	~2M	0.7M – 1.4M	20-240	0.5M - 2M	0.3-0.5M	0.5M - 1M
400-1000	2.4M - 2.9M	2.49M-3.13M	2.47M-3.07M		200-600			
1000-1500	3M-4.2M	3.22M-4.54M	3.17M-4.46M		500-900			

Table 16: Additional Costs

Additional Requirements	$/unit	Unit	Range
Odorisation	$ 100k	ea.	± 10%
Distribution Pipeline	$ 300k	km	± 20%
Transmission Pipeline	$ 750k	km	± 30%
Gas Chromatograph	$ 80k	ea.	± 10%
Land use	$ 300	m2	± 30%
Telemetry Connection	$ 45k	ea.	± 10%
Compression to IP pressure (19.6barg)	$ 0.5M – 2M	ea.	± 50%

References: (Sun et al., 2015a) , (Pentair Haffmans, 2021), (Galileo Technologies, 2020), (Sauer Haug Compressors, 2021), (Xebec, 2020), (Firstgas Ltd, 2020a)

5.3.7 Operational Costs for Biomethane Production and CO$_2$ Production

Aside from regular operations and maintenance costs which annually total around 4-6% of the plant's capital value (citation needed), electrical consumption for biogas upgrading and CO$_2$ separation requires around 0.4 kWh/Nm^3 of biomethane produced. At 15c per kWh, this costs 6c per Nm^3 of biomethane produced. Additionally, electrical consumption for CO$_2$ upgrading comes to around 420 kWh per tonne CO$_2$ produced (Jackson & Brodal, 2019). At 15c per kWh, this costs an additional $63 per tonne of CO$_2$ produced.

5.4 Transporting and Using the Gas

During the conceptual phase of a biogas project, the location of the biogas production source needs to be considered based on feedstock, but additional consideration for proximity to existing natural gas reticulation networks is also required. The gas transmission or distribution network operator in the vicinity of a proposed biogas production site should be consulted early in the conceptual phase of designs. The network operator can help provide network details to be used by a biogas project developer to consider opportunities and obstacles of a site location. Below are some factors to be considered when locating a BIP:

5.4.1 Network Pressure

The New Zealand gas transmission and distribution systems are operated at very different pressures. Gas distribution networks are typically lower pressure networks which supply most gas customers. There are several operating pressure ranges for distribution networks across the country, the highest pressures for distribution networks are 19.6 barg, while most networks operate below 10 barg. Distribution network pressures are location specific and can vary even within a single town. New Zealand gas transmission pipelines typically operate at pressures from 20 barg up to 86 barg. Each location specific gas network operating pressure will define the required biomethane injection pressure.

Raw biogas typically leaves the production process at pressures up to 10 mbarg (Lemmer et al., 2017). Biogas processing equipment needs to boost the raw biogas to pressures between 4- 20 barg depending on the biomethane processing elements (UNIDO & German Biogas Association, 2017). Biomethane processing technologies should achieve outlet pressures suitable for injection into most distribution systems without additional compression.

Across the country, pressures in gas transmission pipelines vary across different regions. For example, a transmission pipeline near Auckland can operate at pressures between 66 barg and 86 barg, but most gas producers around Taranaki inject into transmission pipelines that operate between 42 and 48 barg (Firstgas Ltd, 2020b). If biomethane is to be injected into the transmission system a second stage of gas compression is required which will add complexity and cost to the biomethane scheme.

5.4.2 Biomethane volume to be injected and Network Capacity

The amount of gas consumed within transmission and distribution networks is metered and understood through annual network analysis to ensure that minimum pressures are consistently exceeded (Firstgas Ltd, 2020b). The amount of biomethane generated by any proposed scheme and the potential hourly variability of this volume is essential when considering potential injection locations for the gas network owners' system.

Most gas transmission pipelines experience large gas throughput on an hourly basis and most biomethane plant outputs should be able to be accommodated without the risk of oversupply. However, when connecting a biomethane plant to a local distribution system, the risk of oversupply can be material. Some distribution networks may only supply gas to a few customers or there may be defined times when even large numbers of gas consumers have little or no demand for gas (Firstgas Ltd, 2020a). In situations where consistent volumes of biomethane are injected into a network with little demand, the system pressure may increase to the point where no further gas can be injected and the biogas plant would be backed out, shut off or diverted to flare or put into storage at additional cost (but with a better environmental outcome).

It is important to understand the biogas volumes being generated at an hourly level and match this against the gas being consumed within the gas network system being supplied, to ensure that the gas may be constantly injected without interruption. Gas transmission networks are typically able to accommodate large biomethane quantities. Gas distribution networks will require network capacity analysis to prove that an injection point can accommodate the supply of biomethane.

5.5 Carbon Emissions from Biogas and Biomethane vs Regular Material Disposal Pathways

The overall emissions impacts of diverting organic waste from landfill or other disposal pathways for the purpose of biomethane generation is made up of several connected areas, illustrated in Figure 10:

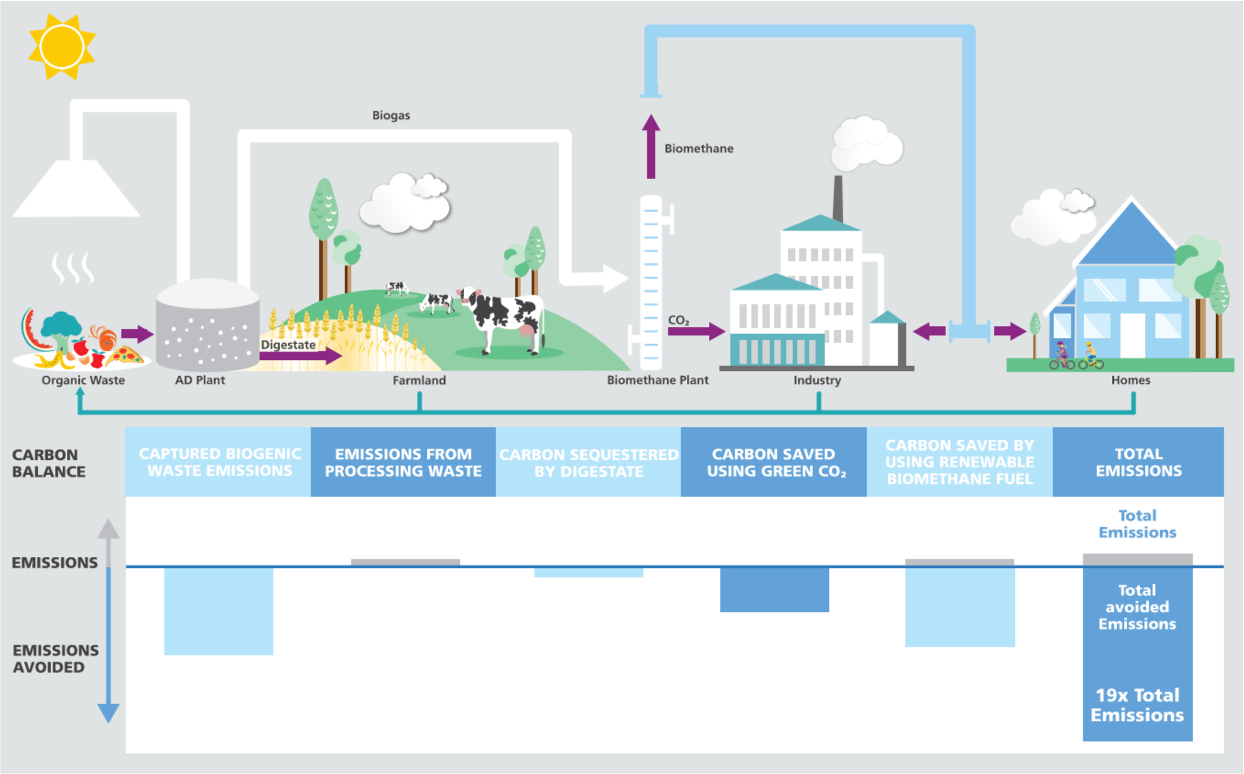

Figure 10: Emissions impacts of diverting organic waste from landfill or other disposal pathways

5.5.1 Emissions from Processing of Feedstocks

In the processing of feedstocks to biogas in an anaerobic digester a percentage of the biogas generated is assumed to escape to atmosphere, similar to the way that composting operations are treated from an emissions perspective. In MfE's 2020 emission factor guidance document, there is an emissions factor given for anaerobic digestion (0.02 kgCO$_2$e/kg) and composting (0.172 kgCO$_2$e/kg) of waste. The factor for anaerobic digestion assumes an 80% reduction in fugitive methane emissions compared to composting and none of the nitrate emissions associated with composting.

5.5.2 Emissions from Use of Biogas or Biomethane

In New Zealand, biofuel use is given a blanket emissions factor of 3.42 kgCO$_2$e /GJ. However, the only biofuels included in MfE's current guidance document are biodiesel and bioethanol. CO$_2$ emissions from the combustion of biofuels are not counted when calculating their emissions factors under the guidance of IPCC, so these factors only consider other GHG produced via combustion.

In other overseas emissions reporting guidelines e.g. the United States (via EPA guidelines) or the UK (via the Department of Business, Energy & Industrial Strategy) biogas and biomethane are given a significantly lower emissions factor (0.106 kgCO$_2$e /GJ per UK guidelines) than liquid biofuels (Department for Business Energy & Industrial Strategy, 2020). The exclusion of a more specific emissions factor for biogas or biomethane in New Zealand's emissions factor guidance documentation is likely because the use of these fuels at present is limited.

5.5.3 Transport Emissions from Biogas Feedstock Collection

If the feedstocks for the biogas processing operation are not already being collected and transported to a disposal location, the additional emissions generated by feedstock collection should be considered.

Depending on the type of vehicle, emissions factors can vary between 0.986 $kgCO_2e$ per km for a new diesel truck with capacity of <20 t, to 0.088 $kgCO_2e$ per km for an electric truck with a capacity of <15 t.

5.5.4 Emissions Avoided by Displacing Fossil Fuels/Grid Electricity

If the biogas or biomethane generated is used to offset natural gas or electricity, then we can calculate an emissions abatement by comparing the energy displaced and the relative emissions factors. Natural gas has an emissions factor of 54 $kgCO_2e$ /GJ, and electricity has an emissions factor of 28.2 $kgCO_2e$ /GJ which are both considerably higher than the emissions factor for biomethane. Swapping to biomethane from natural gas can help reduce stationary energy emissions for a gas user by up to 99.8%.

5.5.5 Emissions Avoided by Capturing Biogenic Methane from Organic Wastes

In New Zealand, most landfills have LFGR installed which means the majority of biogenic methane generated is destroyed before it escapes to atmosphere. In landfills with LFGR, organic wastes like food waste and garden waste have emissions factors of 0.299 $kgCO_2e$/kg and 0.398 $kgCO_2e$/kg respectively. Without landfill gas capture, these factors increase to 1.125 $kgCO_2e$/kg and 1.5 $kgCO_2e$/kg respectively. These emissions factors are very high compared to the emissions factor for AD treatment of waste; diverting organic waste from landfill has a large impact on waste emissions.

The breakdown of captured and spread dairy cattle manure results in 212.6 $kgCO_2e$/head produced per annum (Ministry for the Environment, 2020). Treating and managing this waste via anaerobic digestion would prevent the release of this carbon.

5.5.6 Emissions Avoided by Displacing Chemical Fertilisers

If the digestate from the digestion process can be used to displace chemical fertilisers, the avoided emissions should be considered in the overall emissions calculations.

For example, non-urea nitrogen fertilisers produce 5.4 $kgCO_2e$/kg used. Urea fertilisers with urease inhibitors can decrease the total GHG emissions to 4.86 $kgCO_2e$/kg used. If digestate can be used to reduce the total amount of chemical fertilisers applied to land, this creates a large net emissions benefit assuming biodigestate has zero or near-zero emissions. The EPA states that bio fertiliser use can abate up to 30 $kgCO_2e$/tonne used, with an additional 80 $kgCO_2e$/tonne of carbon becoming sequestered in the soil (EPA USA & Change Division, 2020).

Depending on the ratio of chemical fertiliser displaced vs bio-fertiliser required, the GHG reduction will vary for a given digestate production volume.

5.6 Biomethane in areas without a Reticulated Gas Network

For instances where raw feedstock and biogas production facilities are located away from existing pipeline infrastructure there are still opportunities to use these bioenergy resources. Biogas production facilities away from pipeline infrastructure are found in many countries worldwide. In the case where a direct user of the energy generated is located nearby and is able to accept untreated biogas as a fuel, it may make sense to not pursue biomethane generation. However, the flexibility provided by converting the biogas into biomethane is still worth considering. There are many options to effectively use biomethane in these cases, this study summarises options that could be valuable opportunities in New Zealand. A summary of the opportunities for biomethane producers includes:

- Construction of dedicated pipelines to connect to existing infrastructure or industrial sites
- Compression or liquefaction of biomethane to be transported by tube trailer
- Creation of a bioenergy hub to connect multiple biogas producers to a central upgrading plant
- Local combined heat and power (CHP) electricity generation
- Conversion to hydrogen for transportation

These opportunities are explored in Section A6.

6 Digestate Production

6.1 Introduction

Digestate is the organic matter remaining after anaerobic digestion, which has demonstrated to be an effective plant fertiliser, rich in both organic matter and nutrients (Aso, 2019; Drosg et al., 2015). Digestate presents not only a secondary revenue source of biogas production, but also enables the recirculation of nutrients back to the land, effectively closing the carbon cycle (Figure 11).

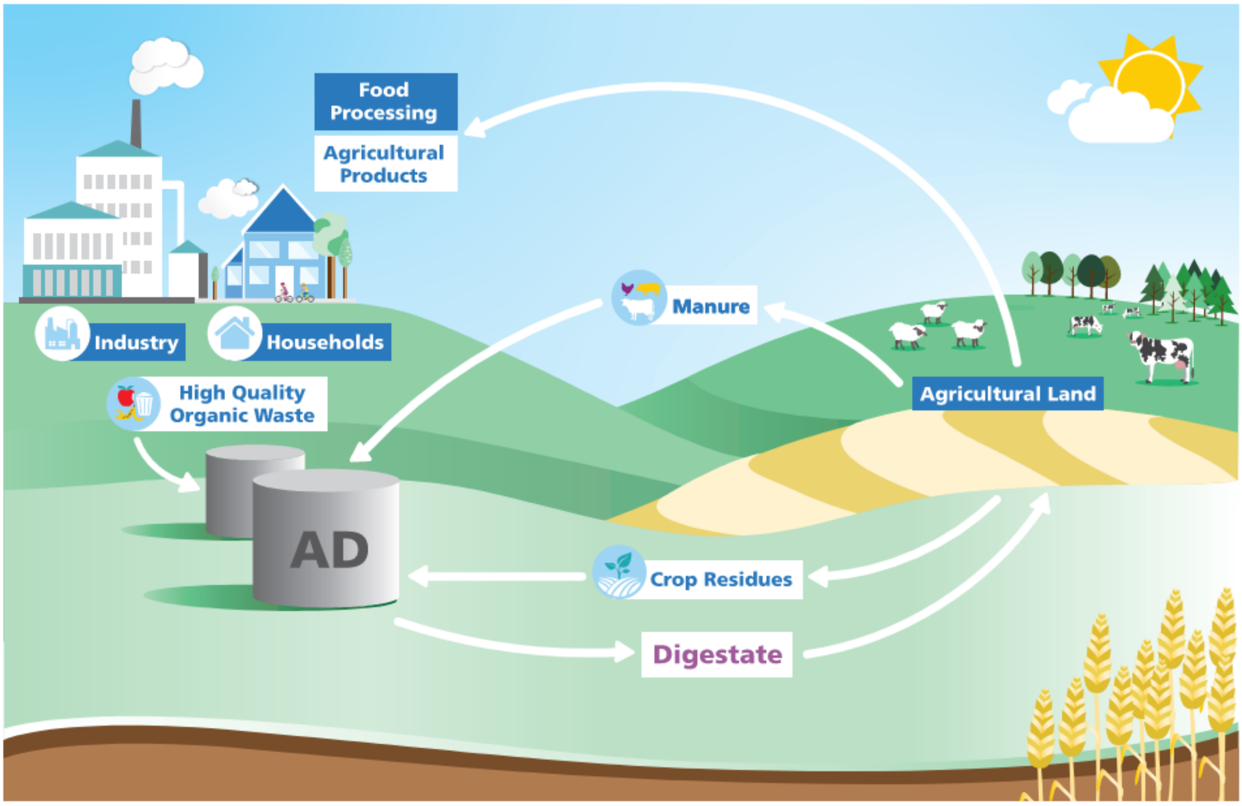

Figure 11: The role of digestate in closing the carbon cycle

Digestate is produced from anaerobic digestion of solid material, including animal manure, crop residue, wastewater sludge and organic household waste. Therefore, the production of digestate will be proportional to the uptake of solids digestion, primarily manure, crop residue and organic municipal waste. Advantages of digestate include the reduced the risk of nitrogen leaching compared to other fertilisers, and an increased nutrient profile in comparison to untreated manure and crop. Additional technical detail on digestate properties, processing, application to soil and relevant legislation is in Section A2.

6.2 Digestate Potential in New Zealand

Based on available quantities of agricultural and municipal organic waste feedstock in New Zealand, a maximum of approximately 6 million tonnes of digestate could be produced if all available feedstock is digested (Table 17). In addition to the feedstocks presented in Table 17, WWTPs produce around 300,000 wet tonnes of biosolids (stabilised sludge) annually, of which 68% is productively used either for quarry rehabilitation, landfill cover, agricultural land or forestry. Approximately 192,000 wet tonnes (64%) is produced via anaerobic digestion, which neutralises the pathogens contained in the unprocessed sludge, allowing for agricultural land application in some instances (Tinholt, 2019). In New Zealand only the highest grade of biosolids can be used to grow crops for human consumption (Bioenergy Association New Zealand, 2021; Ministry for the Environment, 2003).

Table 17: Maximum theoretical production of digestate from available agricultural feedstocks in New Zealand

Feedstock Type	Feedstock Quantity (t/year)	Digestate Quantity (t/year)
Dairy manure	5,320,000	4,470,000
Pig manure	281,000	236,000
Poultry manure	825,000	693,000
Crop residue	450,000	378,000
Source-segregated food waste	354,000	297,000
Total	**7,230,000**	**6,070,000**

Notes
1. Numbers are rounded to 3 s.f.
2. Manure feedstock quantities refer to fresh tonnes (no additional water added)
3. Digestate quantities are calculated based on the assumption that 0.84 tonnes of digestate can be produced per **tonne** of input (feedstock) material

Whole (unprocessed) digestate is weak in nutrient concentration compared to synthetic fertiliser. To give a sense of scale, 430,000 tonnes of nitrogen was applied to New Zealand soils as fertiliser in 2015 (Stats NZ, 2015). Available agricultural and municipal organic waste feedstock in New Zealand could produce 6 million tonnes of whole digestate containing 30,000 tonnes of nitrogen. It is therefore not anticipated nor suggested that digestate could replace chemical synthetic fertiliser. Digestate could, however, be used concurrently with synthetic fertiliser in ratios specific to the soils' physical and chemical properties.

6.3 Processing of Digestate

Direct application of whole (unprocessed) digestate to soil is an inexpensive means of disposing of the product remaining after anaerobic digestion (Barłóg et al., 2020), while still returning the nutrients to soil. However, whole digestate can be refined further to significantly increase both nutritional and economic value. Digestate processing is primarily aimed at volume reduction, which reduces the transport costs, and nutrient recovery, which diversifies the digestate fertiliser product and ensures adherence to quality obligations, thus making it a marketable product (Drosg et al., 2015).

Processing implemented must take into consideration whether the value added by decreasing volume and increasing nutrient density validates the additional energy input and processing costs associated. Figure 12 gives a basic overview of the options for digestate processing. Further detail on solid-liquid separation, liquid processing and solid processing is described in Section A2.

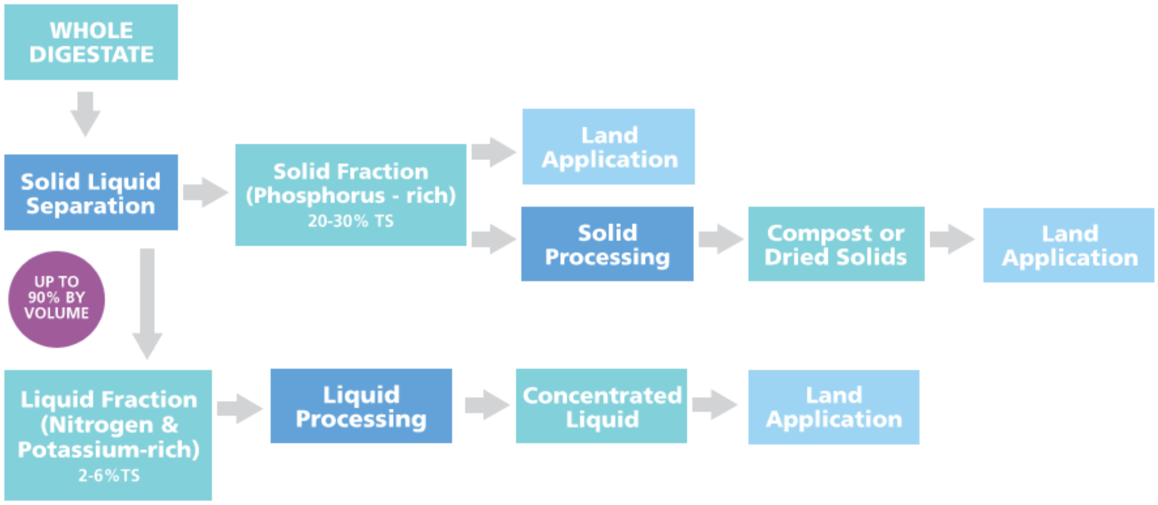

Figure 12: Simplified overviewed of digestate processing steps

Source: (Drosg et al., 2015)

6.4 Digestate Use in New Zealand

The lack of a clear regulatory framework for the application of digestate on land means there is scarce utilisation of anaerobic digestion in New Zealand. This presents a barrier to the use of digestate in New Zealand. A standardised approach across New Zealand and associated quality assurance program would increase the confidence with which this resource is utilised. Guidelines and standards relating to the use of digestate in New Zealand and overseas include:

- **Guidelines for safe application of biosolids to land 2003 (Biosolids Guidelines)**
  - The intent of the Biosolids Guidelines is to provide national guidance to producers, dischargers and regulators for managing the application of biosolids to land. In the context of these guidelines, biosolids refers to sewage sludge that have been treated and/or stabilised so that they are able to be safely and beneficially applied to land (Ministry for the Environment, 2003). Currently, these guidelines classify digestate as a waste regardless of its source, which means rigorous testing and permitting is required for high-quality digestate to be used effectively.
- **Bioenergy Association: The Production and Use as Bio-fertiliser of Digestate Derived from Source Segregated Organic Waste (Technical Guide 8)**
  - The intent of the BANZ Technical Guide 8 (TG8) is to encourage the production of high and consistent quality digestate in New Zealand so that the value of digestate can be realised via sale as certified bio-fertiliser. It focuses on the use of digestate produced from source segregated organic waste.
  - TG8 provides a framework for AD plant operators to consistently produce quality digestate suitable for certification and sale as bio-fertiliser. This is an important milestone as if regional councils choose to recognise TG8 as a certification framework, digestate produced at an AD facility can be applied on land without the need for the extensive environmental permitting set out in the Biosolids Guidelines. (Bioenergy Association New Zealand, 2021).
  - TG8 specifically excludes digestate from municipal sludge, which is governed by the Biosolids Guidelines, and animal waste due to risk of disease (Bioenergy Association New Zealand, 2021).
  - Sale of certified digestate supported by specifications like TG8 in New Zealand would enable higher prices to be charged for the material, depending on its composition. Further analysis should be done to determine achievable premiums for this material.
- **PAS110: Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials**
  - PAS110 is an industry specification, published under license from The British Standards Institution, for which producers can use to ensure digestate is produced in such a way that odours, toxic emissions and variance in quality are minimised, and that the digestate produced is safe and fit for purpose. PAS110 is not in itself a British Standard, but it aims to provide a framework that will enable a specification to be rapidly developed (Waste & Resources Action Programme (WRAP), 2014). United Kingdom producers can boost the credibility of their digestate by applying for PAS110 certification (Bioenergy Association New Zealand, 2021).

7 Case Studies: Biogas and Biomethane in the Waikato

The Waikato region of New Zealand is a great area to examine the potential use cases and implementation options for biomethane plants. There are several reasons for this:

- The Waikato is New Zealand's fourth most populous region, with the city of Hamilton being the home to more than 176,000 residents
- The region is home to many dairy farms, so produces lots of animal manure as a potential feedstock
- There are a large number of industrial plants that use natural gas as a fuel for process heat
- These same industrial plants often produce high energy effluent streams, which can also be used for biogas generation
- The region is well-connected via the natural gas network and there are many potential locations for injection.

Below we have examined two possible case studies for biomethane plant implementation. We have reviewed the expected capital costs, operational costs, revenue streams and the impact of plant operation on carbon emissions.

7.1 Case Study 1: Municipal Food Waste Processing Plant

The city of Hamilton has a population of 176,000 residents. As of 2020, Hamilton City Council has begun a source-segregated food waste collection service through its contractor Envirowaste which collects and transports a portion of this material for composting at the Hampton Downs landfill. Based on the feedstocks analysis food waste collection in Hamilton could generate up to 12,300 t of food waste per year alone.

While composting is a better use of this material than landfilling, there are a number of additional advantages that anaerobic digestion could provide if employed instead:

- Reduced biogenic emissions from processing of this waste
- Creation of biogas/biomethane as an additional revenue stream
- Less land required for processing of food waste (up to ten times less land requirement).
- Less manual handling challenges compared to composting

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Table 18: Case Study 1 Summary

Case Study 1: Municipal Food Waste Processing Plant	
Feedstock	12,300 t of source-segregated food waste
Biomethane Generation	1.9 million Nm^3 per year (57,000GJ)
Other Products Generated	1,800 t of Carbon Dioxide 10,500 t of digestate material
Capital Cost	$22M NZD
Emissions Avoided	7,000 t CO$_2$e per year
LCOE for breakeven NPV	$5 / GJ
LCOE for 10-year payback	$21 /GJ

7.1.1 Biogas Generation and Plant Sizing

Processing 12,300 t of food waste per year would produce 360 Nm^3 of biogas per hour, so this would be considered a medium sized installation. At this size, the capital costs can vary based on the requirement for particular processing requirements e.g. depending on the quality of the food waste it may be more expensive to pre-screen for a continuous fully mixed digester, and it may make sense to use a dry batch digester system.

The cost of a standard fully-mixed digester would range between $12 million and $16 million while a dry digestion facility could cost between $12 million and $23 million. The best choice would depend on operational complexity of the plant and appetite for manual handling.

7.1.2 Biomethane Processing, Grid Connection and CO_2 Generation Costs

The capital cost to take the raw biogas from this digester and upgrade it into biomethane ready for injection into the transmission pipeline would come to around $4.5 million (including $2.4M for biomethane processing and $2.1M for injection infrastructure). Assuming this plant can be positioned close to the transmission pipeline no costs are included for additional pipework.

A food grade CO_2 recovery plant would cost an additional $1 million.

7.1.3 Operational Costs

Based on a total capital cost of $16.2M + $4.5M + $1M = $22 million dollars, the annual operations and maintenance costs for this plant are assumed to be $1M.

As this waste is currently collected and transported to Hampton Downs for disposal, we can assume that any extra costs associated with collecting and transporting this waste to a new digestion facility are negligible.

Electrical consumption for biogas upgrading requires around 0.4 kWh/Nm^3 of biomethane produced, or 600,000 kWh per year. At 15c per kWh, this costs an additional $90,000 per year.
Additionally, electrical consumption for CO_2 upgrading comes to around 420 kWh per tonne CO_2 produced (Jackson & Brodal, 2019), or 760,000 kWh per year. At 15c per kWh, this costs an additional $113,000 per year.

Table 19: Case Study 1 - Annual Operational Costs

Case Study 1: Annual Operational Costs		Basis
Operations and Maintenance	$1M	Section 5.2.2
Electricity – biogas upgrading	$90,000	Refer above
Electricity – CO_2 upgrading	$113,000	Refer above
Total	$1,203,000	

7.1.4 Revenue Streams

Because this plant is accepting material that would otherwise be landfilled or sent to some other kind of waste treatment centre, the plant will be able to charge a gate fee for acceptance of food waste. Assuming $120/t can be charged based on general industry practise, this generates the plant $1,480,000 per year. If this project can successfully redirect material from landfill, the plant may be eligible for a portion of revenue that the local council would have needed to pay due to the ETS scheme. Based on the current ETS price, this could generate up to an additional $10 /t of waste diverted, or an additional $123,000.

Annually the plant would produce around 3.1 million Nm^3 of biogas, including 1.9 million Nm^3 of biomethane after processing and 900,000 Nm^3 of carbon dioxide.
Generally plants of this size will consume about 20% of the total energy generated via the digestion process for onsite use for powering equipment and controlling process temperatures. This leaves us with 1.5

million Nm³/year of biomethane, or 59,000GJ. At a current wholesale price of $10 /GJ, this generates $590,000. However, new commercial arrangements are seeing gas prices of $15-$20 /GJ. Assuming that gas prices will reach upwards of $15 /GJ in coming years this would generate $885,000. The carbon dioxide generated is equal to 1800 t, which could be sold for around $500,000.

Assuming the incoming food waste is around 20% TS the plant would produce around 5,000 t/yr of solid digestate material with a similar moisture quantity, as well as 5800 t/yr of liquid digestate. Although current legislation does not make the sale of this product viable in current markets, we should assume that these value-add products (solid and liquid) can be sold for around $20 /t which would generate $216,000.

Table 20: Case Study 1 - Annual Revenue Streams

Case Study 1: Annual Revenue		Basis
Gate fees	$1,480,000	Section 5.2.2
Council – ETS	$123,000	Section 5.2.2
Biomethane sale	$885,000	Section 5.2.2
CO_2 sale	$500,000	Section 5.2.2
Digestate sale	$216,000	Section 5.2.2
Total	$3,204,000	

7.1.5 Carbon Emissions Savings

a. Emissions from Waste Capture and Processing

If the entirety of this feed material is being diverted from landfill for digestion, the net carbon saving (including avoided emissions from landfilling – emissions from digestion of the same material) is equal to 3,430 tCO_2e per year. If the material is being diverted from composting instead, the total avoided emissions are equal to 1,870 tCO_2e per year. The residual emissions from digestion are 246 tCO_2e per year.

b. Emissions from Use of Gas Products

When the biomethane is used after being transported through the natural gas network, it displaces regular natural gas so there is a net emissions saving. If we use the default emissions factor for biofuels in New Zealand's emissions guidance document the carbon abated is equal to 3,000 tCO_2e per year. Residual emissions from use of this fuel is equal to 205 tCO_2e per year, but this could be lower if a proper biomethane emissions factor is introduced. Producing 1,800 t of green CO_2 for use instead of petrochemical carbon dioxide saves an additional 1,800 tCO_2e per year.

c. Emissions Savings from Use of Digestate

The EPA states that bio-fertilisers can abate 30 kg of CO_2 emissions per tonne used, so if we also include the emissions potential of the digestate produced we can abate an additional 324 tCO_2e per year.

d. Emissions Summary

The total emissions produced by the operation come to 451 tCO_2e per year (not including feedstock transport emissions), but the use of anaerobic digestion can directly abate 7000-8600 tCO_2e per year.

Table 21: Case Study 2 - Emissions Summary

Case Study 1	Emissions (tCO_2e/year)	Basis
Emissions from digestion	246	Section 5.5.1
Emissions from burning biomethane	205	5.5.2
Total emissions produced	**451**	
Avoided emissions from landfilling	3,430 – 1,870	5.5.5

Displacement of natural gas	3,000	5.5.4
Emissions abated from digestate	324	5.5.6
Emissions abated from green CO_2	1,800	
Total emissions abated	**6,694 – 8,554**	

7.1.6 Financial Summary: NPV and LCOE

We have assumed the following metrics for the project:

- Economic life of 30 years
- Weighted Average Cost of Capital (WACC) is 5%
- Tax Rate: 28%
- Depreciation rate: 16%

Considering the total Capital Cost of the facility ($21.7 million) and the overall Operational Revenue ($1,997,000), the project has the following financial results:

- Net Present Value (NPV): $5.1 million – with the combined sales of biomethane, CO_2, digestate and charging a gate fee for processing the food waste, the project achieves a payback period of 12 years.
- Levelised Cost of Energy (LCOE): $5 /GJ – at this price for biomethane, the facility breaks even over its lifetime, and for $21 /GJ the project achieves a 10-year payback.
- Marginal Abatement Cost (MAC): $-32 /t$CO_2$e – over the lifetime of the project, the total cost of abating each tonne of carbon saved in the operations of this facility is far less than the current cost of carbon, demonstrating that this plant is an effective mechanism for reducing emissions.
  For a buyer of biomethane produced by this facility via the grid, based on the breakeven LCOE of $5 /GJ and the carbon abated by substitution of fossil gas alone, switching from fossil gas to biomethane has a MAC of $-14 /t$CO_2$e. To achieve 10-year payback with a biomethane sale price of $21 /GJ, switching to biomethane has a MAC of $77 /t$CO_2$e.

The above figures demonstrate that by maximising the value of all revenue streams (including gate fees), these facilities can become profitable and competitive economically, as well as being extremely effective mechanisms for reducing carbon emissions.

7.1.7 Sensitivity Analysis – Digestate Costs, Operational Costs, Gate Fees, Capital Costs

a. Gate Fees

The gate fees are by far the largest revenue stream for the project, providing 50% of the revenue generation. If gate fees are unable to be charged for the incoming material, the project has an NPV of -$12.1M and doesn't not pay itself back over its lifetime. The biomethane would have to be sold for $48 /GJ to achieve a 10-year payback without generating revenue from this source.

As the landfill levy increases out to 2026, an additional $40/t could be charged for reception of this waste. A gate fee of $160/t would make the facility achieve a 10-year payback with an NPV of $10.4M.

b. Digestate Pricing

If the digestate is unable to be sold, the facility has an NPV of $2.8M and a payback period of 13 years. The biomethane would have to be sold for $27 /GJ to achieve a 10-year payback.
At a cost of $40 /t, the facility has an NPV of $7.5M and achieves an 11-year payback. The biomethane would have to be sold for $17 /GJ to achieve a 10-year payback.

c. Operational Costs

If the operational costs of the plant increase by 50%, assuming all other factors stay the same, the NPV of the facility goes to -$1.4M and the facility achieves a 16 year payback. Gas would have to be sold for

$31 /GJ to achieve a 10-year payback. This could be a result of high screening requirements etc. Increasing operational costs by 25%, the NPV becomes $1.9M and the facility pays itself off in 14 years.

d. Capital Cost

If the Capital Cost for the plant increased by 25%, the NPV would become $1M and the payback period would increase to 14 years. A gas price of $30 /GJ would generate a 10-year payback.

7.2 Case Study 2: Dairy Manure Processing Plant

Hamilton is one of New Zealand's most productive dairy regions, with a large number of dairy farms and cattle. There are over 3700 dairy herds, with a median size of 365 cows. In total, there are over 1.37 million milking cows in the Waikato region. The average farm size of 127 ha means there are around 2.9 cows per hectare used for dairy land.

A medium-sized manure-fed anaerobic digester requires around 50,000 t/y of manure. Each dairy cow produces around 978 kg of collectible manure (from the milking shed) per year, which means feedstock from around 140 herds would need to be collected to achieve the scale needed. These farms would be likely to be spread over 17,780 ha, or a 13km x 14km area.

Collection and processing this manure would result in positive outcomes for farmers and communities in the region, including:

- Reduced agricultural emissions from manure breakdown
- Creation of biogas/biomethane as an additional revenue stream
- Upgraded and processed manure digestate being returned to farms in the area, for use in agricultural operations.

Table 22: Case Study 2 Summary

Case Study 2: Dairy Manure Processing Plant	
Feedstock	50,000 t of dairy cattle manure
Biomethane Generation	2.4 million Nm^3 per year (72,000 GJ)
Other Products Generated	2,300 t of Carbon Dioxide 45,000 t of digestate material
Capital Cost	$26M NZD
Emissions Avoided	18,300 t CO_2e per year
LCOE for breakeven NPV	$27 / GJ
LCOE for 10-year payback	$50 /GJ

7.2.1 Biogas Generation and Plant Sizing

Processing 50,000 t of animal manure per year would produce 450 Nm^3 of biogas per hour, so this would be considered a small-to-medium sized installation. At this size, a fully mixed digester is the best choice.

The cost of a standard fully-mixed digester would range between $15 million and $20 million. Depending on land availability, an anaerobic pond/lagoon could also be considered and would cost a similar amount based on UK case studies.

7.2.2 Biomethane Processing, Grid Connection and CO_2 Generation Costs

The capital cost to take the raw biogas from this digester and upgrade it into biomethane ready for injection into the transmission pipeline would come to around $4.2 million (including $2.4M for biomethane processing and $1.8M for injection infrastructure). Assuming this plant can be positioned close to the transmission pipeline no costs are included for additional pipework.

A CO_2 recovery plant would cost an additional $1 million.

7.2.3 Operational Costs

Based on a total capital cost of $20.3M + $4.2M + $1M = $26 million dollars, the annual operations and maintenance costs for this plant are assumed to be $1.2 million.

Collection of 50,000 t of waste annually would involve transporting around 140 t of manure per day. Assuming each delivery would consist of around 20 t of material and involve travelling around 20 km (both ways), the total daily logistics operation would involve travel of 140km. Assuming an average speed of 20 km/h allowing for pickup and delivery of material, this requires 14 h of truck operation per day. Over the course of the year, this adds up to 5,110 h of transportation effort. At an assumed cost of $120 /h including labour, equipment, fuel and all other externalities, this logistics operation would cost $610,000 per year. These truck movements can also be used to return digestate to the farms so we will assume there are no extra truck movements needed for this.

Electrical consumption for biogas upgrading and CO_2 separation requires around 0.4 kWh/Nm^3 of biomethane produced, or 760,000 kWh per year. At 15c per kWh, this costs an additional $114,000 per year. Additionally, electrical consumption for CO_2 upgrading comes to around 420 kWh per tonne CO_2 produced (Jackson & Brodal, 2019), or 970,000 kWh per year. At 15c per kWh, this costs an additional $145,000 per year.

Table 23: Case Study 2 - Operational Costs

Case Study 2: Annual Operational Costs		Basis
Operations and Maintenance	$1,200,000	Section 5.2.2
Transport and Logistics	$610,000	Refer above
Electricity – biogas upgrading	$114,000	Refer above
Electricity – CO_2 upgrading	$145,000	Refer above
Total	$2,069,000	

7.2.4 Revenue Streams

Because this material is not currently being collected and disposed of, there is no additional revenue from gate fees. We should assume that the farmers will not charge a fee for collection.

Annually the plant would produce around 3.9 million Nm^3 of biogas, including 2.4 million Nm^3 of biomethane after processing and 1.2 million Nm^3 of carbon dioxide.
Generally, plants of this size will consume about 20% of the total energy generated via the digestion process for onsite use for powering equipment and controlling process temperatures. This leaves us with 1.9 million Nm^3/year of sellable biomethane or 74,000 GJ. At a current wholesale price of $10 /GJ, this generates $740,000. However, new commercial arrangements are seeing gas prices of $15-$20 /GJ. Assuming that gas prices will reach upwards of $15 /GJ in coming years this would generate $1.1M per year. The carbon dioxide generated is equal to 2300 t, which could be sold for around $580,000.

Assuming the incoming manure is around 15% TS the plant would produce around 15,000 t/yr of solid digestate material with a similar moisture quantity, as well as 30,000 t/yr of liquid digestate. Since the processed manure is being returned to farmers that supplied the material for use as value-added products we could assume a small fee is charged for processing and upgrading this material, around $10 /t. This would generate $450,000 annually for the plant. This will depend on the specific installation.

Table 24: Case Study 2 - Revenue Streams

Case Study 2: Annual Revenue Streams		Basis
Biomethane sale	$1.1M	Section 5.2.2
CO_2 sale	$585,000	Section 5.2.2
Digestate sale	$450,000	Section 5.2.2
Total	$2,135,000	

7.2.5 Carbon Emissions Savings

a. Emissions from Waste Capture and Processing

The net carbon saving from preventing the release of emissions from manure on land is equal to 10,900 tCO_2e per year. The residual emissions from digestion of the material is equal to 1,000 tCO_2e per year. However, since biogenic emissions are not currently included in the ETS there is no revenue stream associated with this emissions avoidance. This may change in future years.
Assuming a conservative price of $10/ tCO_2e for on-farm emissions, in the future this could add a new $109K revenue stream for the plant (not included in financial analysis).

b. Emissions from Additional Transportation

Emissions from collection of the feedstock come to 50 tCO_2e per year, based on 51,100 km of transit in a 20 t diesel truck.

c. Emissions from Use of Gas Products

When the biomethane is used after being transported through the natural gas network, it displaces regular natural gas so there is a net emissions saving. If we use the default emissions factor for biofuels in New Zealand's emissions guidance document the carbon abated is equal to 3,750 tCO_2e per year. Residual emissions from use of this fuel is equal to 250 tCO_2e per year, but this could be lower if a proper biomethane emissions factor is introduced. The emissions abated by capturing and selling an additional 2,300 t of green carbon dioxide saves an additional 2,300 tCO_2e per year.

d. Emissions Savings from Use of Digestate

The EPA states that bio-fertilisers can abate 30 kg of CO_2 emissions per tonne used, so if we also include the emissions potential of the digestate produced we can abate an additional 1350 tCO_2e per year.

e. Emissions Summary

The total emissions produced by the operation come to 1,300 tCO_2e per year, but the use of anaerobic digestion can directly abate 18,300 tCO_2e per year. The total lifecycle emissions abated by this project would be equal 550,000 tCO_2e.

Table 25: Case Study 2 - Emissions Summary

Case Study 2	Emissions (tCO_2e/year)	Source
Emissions from digestion	1,000	Section 5.5.1
Emissions from transport	50	Section 5.5.3
Emissions from burning biomethane	250	Section 5.5.2
Total emissions produced	**1,300**	
Avoided emissions from manure	10,900	Section 5.5.5
Displacement of natural gas	3,750	Section 5.5.4
Emissions abated from digestate	1,350	Section 5.5.6
Emissions abated from green CO_2	2,300	

Total emissions abated	**18,300**	

7.2.6 Financial Summary: NPV, LCOE

We have assumed the following metrics for the project:

- Economic life of 30 years
- Weighted Average Cost of Capital (WACC) is 5%
- Tax Rate: 28%
- Depreciation rate: 16%

Considering the total Capital Cost of the facility ($26 million) and the overall Operational Revenue ($120,000), the project has the following financial results:

- Net Present Value (NPV): -$18 million – the facility does not generate enough revenue from the combination of biomethane, CO_2 and digestate sale to become profitable over its lifetime. The lack of any gate fee or profit from feedstock collection and requirement for additional logistical effort means that the facility does not make a large enough profit to become financially beneficial.
- Levelised cost of Energy (LCOE): $27 /GJ – for this price of energy, the facility breaks even over its lifetime assisted by the sale of CO_2 and digestate. For $50 /GJ, the project achieves a ten-year payback with all other costs the same.
- Marginal Abatement Cost (MAC): $33 /t$CO_2$e – over the lifetime of the project, the total cost of abating each tonne of carbon saved in the operations of this facility is less than the expected price of carbon in coming years.
  For a buyer of biomethane produced by this facility via the grid, based on the breakeven LCOE of $27 /GJ and the carbon abated by substitution of fossil gas alone, switching from fossil gas to biomethane has a MAC of $120 /t$CO_2$e. To achieve 10-year payback with a biomethane sale price of $50 /GJ, switching to biomethane has a MAC of $284 /t$CO_2$e.

7.2.7 Sensitivity Analysis – Digestate Costs, Operational Costs, Gate Fees, Capital Costs

a. Digestate Pricing

If the digestate is unable to be sold, the facility has an NPV of -$22.9M and also does not generate a profit. The biomethane would have to be sold for $56 /GJ to achieve a 10-year payback.
At a cost of $40 /t, the facility has an NPV of -$3.4M and achieves an 18-year payback. To achieve a ten-year payback, a gas price of $32 /GJ is required.

b. Operational Costs

If the operational costs of the plant increase by 25%, assuming all other factors stay the same, the NPV of the facility goes to -$23.5M and the facility does not pay itself back over its lifetime. Gas would have to be sold for $57 /GJ to achieve a 10-year payback.
Decreasing operational costs by 25% the NPV remains negative (-$12.6M) but the project does still not pay itself back over its lifetime. Gas would have to be sold for $43 /GJ to achieve a 10-year payback.

c. Capital Cost

If the Capital Cost for the plant increased by 25%, the NPV would become -$22.8M and the facility does not pay itself back over its lifetime. A gas price of $59 /GJ would generate a 10-year payback.

7.3 Case Study Conclusions

The types of biomethane installations we have explored in our case studies present quite different results. While the Waikato Food Waste plant (Case Study 1) presents some promising financial indicators, utilisation

of animal manures (Case Study 2) appears to be much more challenging.
A few factors that have contributed to the outcomes above worth discussing in more detail are below.

Biomethane: The primary product of these plants. On its own, achievable revenues from biomethane production cannot provide enough revenue to justify initial investment.

CO_2: A secondary product from biomethane production. In the plants we have reviewed, CO_2 production can increase revenue by around 50% and abate 60% the carbon emissions abated by biomethane. For a small amount of additional capital investment, CO_2 production can greatly improve the operational feasibility of the plant.

Digestate: As discussed in Section 6, digestate is a valuable by-product of anaerobic digestion, and operators should aim to maximise the value of this revenue stream when constructing a biogas/biomethane plant. Revenues from this stream can add an additional 40% of the revenue generated by biomethane and improve operational profitability.

Gate Fees: Only some types of feedstocks will allow generation of a gate fee for the reception and processing of organic wastes. Gate fees can greatly improve the financial viability of the plant. For feedstocks not actively collected and disposed of for a fee (i.e. animal manures, crop residues), it is harder to justify this revenue stream.

Waste Collection & Logistics: In our examples, the process of collecting and transporting biogas feedstock materials varies significantly in terms of additional complexity from the base case scenario. While Case Study 1 re-purposed organic wastes already being collected for centralised processing, Case Study 2 was based on a feedstock that otherwise had no real drivers for collection and processing which provided additional complications. Case Study 2 was much more of a deviation from current organic waste management strategies than Case Study 1, and the financial indicators reflected this.

7.3.1 Review of LCOE and MAC Figures

Case Study 1 breaks even over its lifetime with a green gas price of $5 /GJ, and a 10-year payback with a green gas price of $21 /GJ. Based on this pricing, the project is financially viable to implement in the near future.

Case Study 2 only breaks even over its lifetime with a green gas price of $27/GJ, and a 10-year payback with a gas price of $50 /GJ. Based on this pricing, the project is not financially viable in current conditions but could become viable with green gas certification providing a cost premium, and increasing prices of natural gas out towards 2050.

At breakeven biomethane sale prices, users of fossil gas could purchase biomethane through the natural gas grid to greatly reduce the carbon emissions associated with their use of fossil fuels, without requiring them to invest in onsite capital upgrades. The MACs associated with this kind of conversion for Case Studies 1 and 2 respectively are \$-14 /tCO_2e and \$120 /tCO_2e, which even for Case Study is comparable to MACs for alternative fuel switching opportunities e.g. biomass boiler upgrades or electric boilers.

The numbers above stress that while not all potential biomethane projects in New Zealand may make sense strictly financially today, in terms of a decarbonisation strategy for high-to-medium temperature process heat especially biomethane can be an effective investment opportunity.

7.3.2 Producing Biogas instead of Biomethane

If the biomethane plant in Case Study 1 was able to be constructed near a connection point to the electricity grid, or near a large heat user, then using the generated biogas directly should be a consideration.

A biogas plant of the same size, without the biomethane upgrading equipment and CO_2 recovery plant, would cost $16.2M instead of $21.7M. Some initial investment would be required to purchase biogas engines and provide a HV connection, or retrofit local natural gas boilers to accept biogas, which would need to be considered in upfront costs.

Depending on the quality and energy content of the biogas produced, the acceptable price for biogas as a product may be lower than the achievable sale price for biomethane. Electricity generation could potentially be scheduled to take advantage of market sport prices and could generate similar revenues to biomethane (upwards of $15 /GJ of biogas generated), especially if a use could be found nearby for the heat generated. See Section 5.2.2 for more details.

The absence of a biomethane/CO_2 recovery plant would decrease electrical and operational requirements for the plant, but also not allow carbon dioxide to be sold which would have a negative impact on ongoing operational costs.

All of the above should be factored into decisions when designing the facility.

8 What is the Realistic Potential of Biomethane in New Zealand?

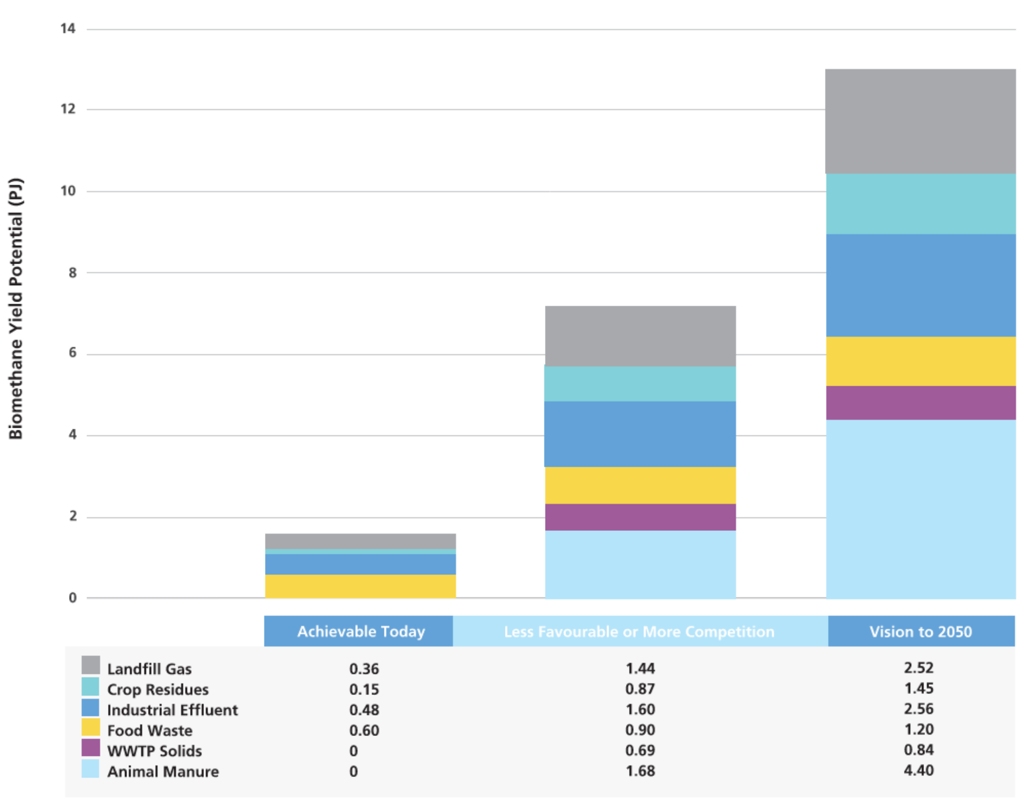
When considering the learnings from previous sections, including:

- Available feedstocks and the ways they can be collected and processed,
- Available technologies best suited to processing different kinds of materials,
- The interactions between different uses of organic material, and other barriers to achieving 100% yield of the identified biomethane,

What can we expect New Zealand’s biomethane future to look like with different levels of uptake based on current feasibility and economics and future drivers for change, and what are benefits associated with different levels of uptake?

Table 26: Summary of three scenarios: achievable today, achievable tomorrow, achievable by 2050

Scenario	Biomethane Potential (PJ)	% of 2020 Natural Gas Consumption	Total CO_2 Emission Reductions	CO_2 Emission Reductions as % of NZ 2020 emissions	Indicative Biomethane Price Required ($/GJ)
Achievable Today	1.6	1%	184 ktCO_2e	0.2%	$20
Achievable Tomorrow	7.2	4%	848 ktCO_2e	1%	$35-40
Achievable by 2050	13	7.2%	1,540 ktCO_2e	2%	$50-$60



	Achievable Today	Less Favourable or More Competition	Vision to 2050
Landfill Gas	0.36	1.44	2.52
Crop Residues	0.15	0.87	1.45
Industrial Effluent	0.48	1.60	2.56
Food Waste	0.60	0.90	1.20
WWTP Solids	0	0.69	0.84
Animal Manure	0	1.68	4.40

Figure 13: 2050 Biomethane Potential in New Zealand across three scenarios

8.1 Scenario 1: Biomethane Injection Achievable Today

Based on the analysis in this report, New Zealand is ready to realise some of its biomethane potential today, and plant can become economic with gas prices we are currently observing/ are predicted to occur in the next ten years.

The base building blocks for this case study are:

- Source-segregated organic wastes in the North Island,
- High-energy industrial effluent streams at plants with existing WWTPs
- A portion of New Zealand's existing landfill gas generation.

Table 27: Summary of Scenario 1

Scenario	Biomethane Potential (PJ)	% of Natural Gas Consumption	Total CO_2 Emissions	Total CO_2 Emission Reductions	Indicative $/GJ Required
Achievable Today	1.6	1%	10 $ktCO_2e$	184 $ktCO_2e$	$20

Refer to Table 28 for a full description of the assumption made for the creation of this Scenario:

Table 28: Quantification of Scenario 1 and Assumptions

Biomethane Potential Achievable Today			
Feedstock	**Scenario Assumptions**	**Scenario Notes**	**Biomethane Potential (2030)**
Animal Manure	Assume none collected for biomethane processing, and are better utilised for CHP or non-AD use if collected.	Feedstocks are not economical to collect and process in current market.	0
WWTP Solids	0%; assume biogas is better used onsite for electricity generation	Current systems better used to continue generating electricity until premium for biomethane increases and grid electricity becomes 100% renewable	0
Food Waste	40% of maximum value; food waste and processing operations make sense economically in the NI today. Boosted by sale of CO_2 and digestate and gate fees	Councils generally moving in the direction of source-segregated food waste collections, so reasonable to assume that all of this collected material could be used for biomethane production.	0.6
Industrial Effluent	Only for high-quality waste streams with existing natural gas connections (assume 15%)	Waste streams identified have processable COD content, biogas and biomethane could become an important method for industrial plants to decarbonise. Most of this gas would be consumed onsite.	0.5

Biomethane Potential Achievable Today			
Feedstock	Scenario Assumptions	Scenario Notes	Biomethane Potential (2030)
Crop Residues	5%; use small portion of crop residues in NI to boost biogas yields in codigestion plants e.g. WWTPs and food digesters	Likely that source-specific biomethane conversion of Canterbury crop residues is possible either locally or via transport to NI grid, rest of feedstock may have to be co-digested	0.1
Landfill Gas	Assume 10% of LFG is generated near a natural gas grid + could be turned into biomethane instead of burned for electricity.	LFGR systems are expensive to maintain and capturing + selling biomethane + trading green gas credits are good ways to offset emissions.	0.4
Total Biomethane Potential:			1.6 PJ

According to our predictions, almost 2 PJ of biomethane are able to be generated and used with relative ease in New Zealand today. This biomethane would reduce New Zealand's gross emission by 184 kt of carbon, around 0.2% of our annual emissions (Ministry for the Environment, 2020).

The other benefits of this case include:

- the creation of 48,400 tonnes of green CO_2, which could supply the majority of New Zealand's current market for high-quality CO_2, which is expected to grow significantly (Underhill, 2018)
- production of 110,000 tonnes of high-quality digestate from food waste digestion

The key challenges/enablers to achieving this scenario include:

- Generating buy-in from industry, farmers, local councils, and waste management/treatment to support the development of this technology across the country and support collaborative projects between stakeholders
- Promoting anaerobic digestion as a frontrunner in alternative disposal mechanisms for organic wastes.

Without these assumptions, it is unlikely that this scenario could be achieved:

- Policy support is implemented for biomethane upgrading installations, focusing on using existing biogas generation installations for the production of the more valuable refined product.
- Biomethane becomes distinguishable as a premium product from fossil methane, as an emissions-free process heat fuel and a renewable source of baseload electricity generation via a green gas certification scheme
- Digestate becomes an additional revenue stream for biogas plants which help cover initial investment costs.

8.2 Scenario 2: Biomethane Potential Achievable Tomorrow (2040)

Over and above the immediately available biomethane in New Zealand, there is a second portion of the available biomethane that we believe will be able to be utilised as gas prices rise due to the combined effects of rising ETS prices and increasing scarcity of natural gas.

According to the Climate Change Commission's predictions for New Zealand's carbon price, the ETS could increase in value to over $200 per tonne by 2035 (Silk et al., 2021). This will almost double the current cost of natural gas for consumers without taking into account the effect of reduced production as predicted by MBIE (Ministry of Business Innovation and Employment, 2020).

At these elevated prices, the use of additional organic waste streams for biomethane production is a valuable proposition to support gas users as they transition to low carbon operations.

The base building blocks for this case study are:

- Source-segregated organic wastes in the South Island,
- WWTPs selling biomethane to the grid and using renewable grid electricity instead of consuming their own biogas
- A portion of isolated diary manure and crop residue used for biomethane generation in large farms with easy grid access.

Table 29: Summary of Scenario 2

Scenario	Biomethane Potential (PJ)	% of Natural Gas Consumption	Total CO_2 Emissions	Total CO_2 Emission Reduction	Indicative $/GJ Required
Achievable Tomorrow	7.2	4%	50 $ktCO_2e$	848 $ktCO_2e$	$35-40

Refer to Table 30 for a full description of the assumption made for the creation of this Scenario:

Table 30: Quantification of Scenario 2 and Assumptions

Biomethane Potential Achievable Tomorrow			
Feedstock	**Scenario Assumptions**	**Scenario Notes**	**Biomethane Potential (2040) (PJ)**
Animal Manure	5% of dairy scoped (from dairy clusters only), 10% of chicken manure (all still collected), 10% of piggery waste (some processed, rest spread on fields as is currently practised)	Best use of most manures would still be onsite use of biogas, and only particular installations on large farms would make sense supported by higher prices of gas.	1.7
WWTP Solids	30%; with higher gas prices, plants can export their biomethane and purchase electricity to run their plants instead	Highly dependent on connection costs and relative electricity supplies. However, as grid becomes more renewable the carbon offsetting potential of biomethane sale would become more favourable.	0.7
Food Waste	60% of max value, allowing for majority of NI municipal collections integrated with biomethane operations and some strategically placed SI digestion plants able to supply biomethane to industrial users	This approach in the SI copies successes of Swedish model, where biomethane can be generated and used without large grid infrastructure. Building plants make economic sense if buyers for biomethane can be found.	0.9
Industrial Effluent	Only plants with existing natural gas connections implement technology (50%) - 50% of dairy, 60% of meatworks, all P&P plants use gas	Plants without gas connections may find it hard to sell back the gas to the grid.	1.6

Biomethane Potential Achievable Tomorrow			
Feedstock	**Scenario Assumptions**	**Scenario Notes**	**Biomethane Potential (2040) (PJ)**
Crop Residues	30%; partial collection of NI and SI residues for biomethane generation in areas of process heat demand e.g. dairy plants in Canterbury.	Enabled by strong need for decarbonisation for gas/LPG users in SI. Majority of material still hard to utilise. Possible to co-digest this feedstock with other sources as a booster	0.9
Landfill Gas	Assume 40% could be utilised with higher gas prices and conversion of truck fleets to run on biomethane etc., or other council infrastructures being supplied with biomethane as a green fuel.	As incentives/gas prices increase, this existing resource can be better utilised. Likely that the majority of landfills with gas capture remain not available, due to either spatial location to grid or low gas production.	1.4
Total			7.2 PJ

According to our predictions, more than 7 PJ of biomethane becomes achievable as economic factors change and low emissions fuels become priced as preferred alternatives. This biomethane would reduce New Zealand's gross emission by 850 kt of carbon, around 1% of our annual emissions (Ministry for the Environment, 2020).

The other benefits of this case include:

- the creation of 220,000 tonnes of green CO_2, enough to provide New Zealand's predicted requirements and potentially allow for extra CO_2 for export or CCS
- production of 330,000 tonnes of high-quality digestate from food waste and crop residue, and 1 million tonnes from manure digestion

The key challenges/enablers to achieving this scenario include:

- Generating buy-in from industry, farmers, local councils and waste management/treatment to support the development of this technology across the country
- Convincing dairy farmers and crop farmers in particular to recover manure and crop silage for processing, given that these materials are generally viewed as low-value waste streams. Focus can be put on farmers where recovery operations can be implemented with relative ease, and farms where exercise would be too difficult can be excluded
- Promoting anaerobic digestion as a frontrunner in alternative disposal mechanisms for organic wastes.

Without these assumptions, it is unlikely that this scenario could be achieved:

- Policy support is implemented for anaerobic digestion and other kinds of organic waste treatment, guided by additional advantage of biomethane production from AD becoming a valuable differentiator
- Policy support is implemented for biomethane upgrading installations, focusing on using existing biogas generation installations for the production of the more valuable refined product.
- Biomethane becomes a highly valued commodity in the near future and distinguishable as a premium product from fossil methane, as an emissions-free process heat fuel and a renewable source of baseload electricity generation as the ETS price increases
- Digestate becomes an additional revenue stream for biogas plants which help cover initial investment costs

8.3 Scenario 3: Biomethane Injection Achievable by 2050

Out as far as 2050, it is hard to predict the sort of market changes that will occur in the energy market. Based on our feedstock quantification and case studies, large-scale digestion of animal manures is the largest single available biogas/biomethane feedstock in the country and it requires a biomethane price of \$50-60 /GJ to become economically viable.

At gas prices in this range, it is likely that other sources of biogas used predominantly for electrical generation or heat (e.g. landfill gases) or non-utilised sources of biogas (e.g. industrial effluent producers in areas without natural gas infrastructure) will be incentivised to convert to biomethane production as energy prices reach this height.

Reaching this point would put New Zealand on par with countries like Sweden and the United Kingdom which have already capitalised on easily attainable biomethane feedstocks and are looking to more challenging feedstocks to reach higher yields.

Table 31: Summary of Scenario 3

Scenario	Biomethane Potential (PJ)	% of Natural Gas Consumption	Total CO_2 Emissions	Total CO_2 Emission Reduction	Indicative \$/GJ Required
Achievable by 2050	13	7.2%	90 ktCO_2e	1,540 ktCO_2e	\$50-\$60

Refer to Table 32 for a full description of the assumption made for the creation of this Scenario:

Table 32: Quantification of Scenario 3 and Assumptions

	Vision to 2050		
Feedstock	Scenario Assumptions	Scenario Notes	Biomethane Potential (2050) (PJ)
Animal Manure	50% of dairy waste (from dairy clusters in the NI), 60% of chicken manure (allowing for non-biomethane alternate end uses), 60% of piggery waste.	More limited collection and centralised processing of dairy and pig wastes; portion of chicken waste retained for existing fertiliser market	4.4
WWTP Solids	80% of un-utilised potential realised by conversion of plants with AD to produce grid-injected biomethane in the NI and biomethane as a vehicle fuel/process heat fuel in the SI	Conversion to AD still makes economic sense for most plants, but some particular installations may be limited by upstream processes.	0.9
Food Waste	80% of max value; assume an even larger portion of SI food waste can be utilised to produce green fuel	This approach in the SI copies successes of Swedish model, where biomethane can be generated and used without large grid infrastructure. Building plants make economic sense if buyers for biomethane can be found.	1.2

Feedstock	Scenario Assumptions	Vision to 2050 Scenario Notes	Biomethane Potential (2050) (PJ)
Industrial Effluent	80% of high energy effluent streams can be utilised to help industrial plants produce their own process heat and sell excess fuels to the grid in times of low use.	With larger push for industry to decarbonise out to 2050, and limit of available fuels for process heat, high energy effluents represent a readily-available path for decarbonisation.	2.6
Crop Residues	50%; larger collection of NI and SI residues for biomethane generation in areas of process heat demand e.g. dairy plants in Canterbury driven by requirement for green fuels	Enabled by strong need for decarbonisation for gas/LPG users in SI. Possible to co-digest this feedstock with other sources as a booster, or generated in bioenergy hubs.	1.5
Landfill Gas	Assume 70% of this gas can be captured, allowing for high utilisation of this gas but taking into account decreased landfill gas generation due to diversion of organic waste from landfill	Uptake of food waste digestion and more circular organic waste handling strategies will limit this source of biogas/biomethane going forward	2.5
Total:			13 PJ

According to our predictions, more than 13 PJ of biomethane could become achievable in the long term as ETS prices and natural gas scarcity combine to produce high biomethane prices. This quantity of biomethane would reduce New Zealand's gross emission by 1,540 kt of carbon, around 2% of our annual emissions (Ministry for the Environment, 2020).

The other benefits of this case include:

- the creation of 400,000 tonnes of green CO_2, which opens up the possibility of large-scale CO_2 exporting or sequestration as well as fulfilling New Zealand's domestic demand
- production of 490,000 tonnes of high-quality digestate from food waste and crop residue, and 2.7 million tonnes from manure digestion

The key challenges/enablers to achieving this scenario include:

- Generating buy-in from industry, farmers, local councils, and waste management/treatment to support the development of this technology across the country
- Convincing dairy farmers and crop farmers in particular to recover manure and crop silage for processing, given that these materials are generally viewed as low-value waste streams
- Promoting adoption of anaerobic digestion processing over other kinds of equivalent waste treatment options e.g. landfilling, composting, waste incineration, cheaper methods of wastewater treatment. Need overwhelming favouring of anaerobic digestion to achieve specified yields.

Without these assumptions, it is unlikely that this scenario could be achieved:

- Strong policy support is implemented for anaerobic digestion over other kinds of organic waste treatment, guided by additional advantage of biomethane production from AD becoming a valuable differentiator
- Biomethane becomes a highly valued commodity in the near future and distinguishable as a premium product from fossil methane, as an emissions-free process heat fuel and a renewable source of baseload electricity generation, as an emissions-free process heat fuel and a renewable source of baseload electricity generation as the ETS price increases
- Digestate becomes an additional revenue stream for biogas plants which help cover initial investment costs.

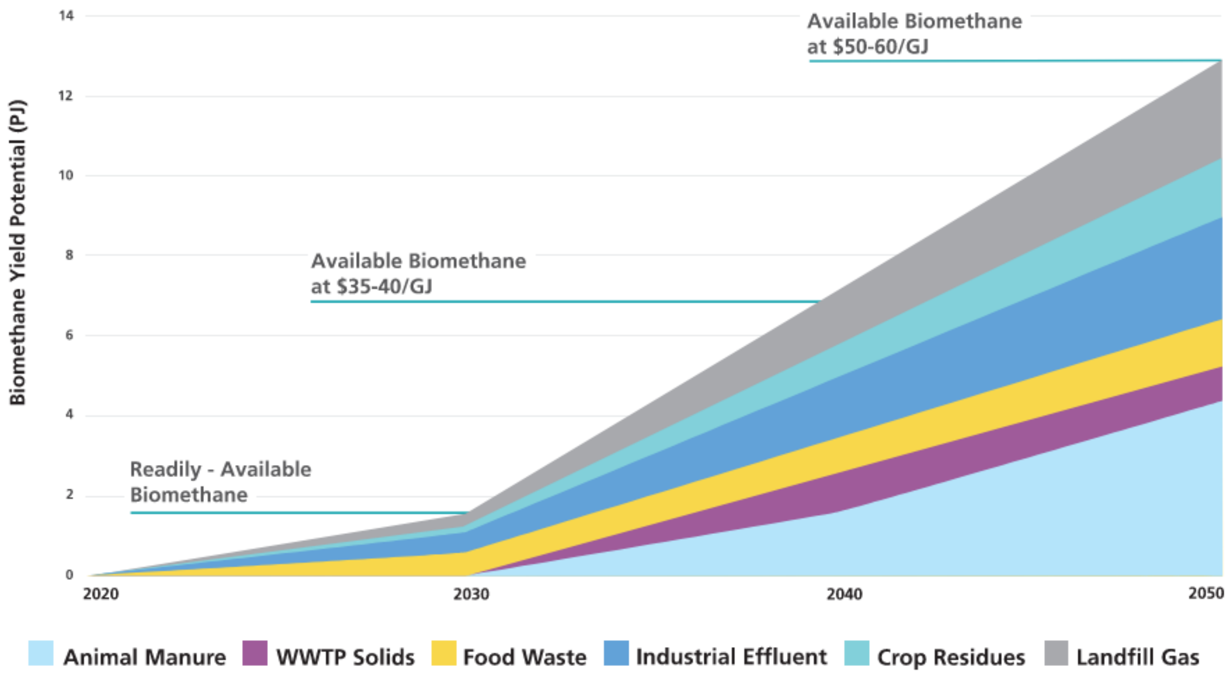


Figure 14: Biomethane Generation Prediction out to 2050

8.4 Notes on All Scenarios

8.4.1 Particularly Challenging Feedstocks to Utilise for Grid Injection

Because of its geographical location, crop residue is a particularly challenging feedstock to utilise effectively as feedstock for grid injection. In New Zealand, 70% of all crop residue is generated in the Canterbury region, far from the HP reticulated gas network in the North Island.

In our uptake scenarios, we have assumed only a maximum of 50% of the identified feedstock can be utilised, which consists of a portion of residues generated in the South Island and most of the available residue generated in the North Island.
Residues generated in the South Island could be used for grid injection by digesting and processing the crops in Canterbury, and transporting compressed biomethane to the North Island for injection by CNG trucks or ships via “virtual pipelines”. That being said, it is likely that costs and associated transport emissions generated from moving gaseous biomethane between islands would erode the possible benefits without additional processing to convert it into liquified-biomethane (bio-LNG).

Another pathway would be for bioenergy plants to be co-located with large users of process heat in the South Island e.g. dairy plants or abattoirs, helping them offset their fossil fuel consumption. Crop residues from the North Island can of course be used just as easily as animal manure from the North Island.

8.4.2 Other Uses of Biogas and Biomethane

The figures presented in our Uptake Scenarios are estimates of the biomethane generation and/or grid injection potential in each scenario only, and does not provide estimates for biogas generation and local use.

In situations where centralised collection and processing of organic wastes at the scale needed to achieve required economic scale for biomethane production is not possible, other options include:

- Using the biogas onsite directly for heat
- Using biogas CHP units to generate electricity

The advantages of these two systems are that they can be employed at much smaller scale and with relatively low capital investment, especially in the case that the gas is already being collected at a landfill or anaerobic lagoon. The disadvantages are that the CO_2 revenue stream cannot be realised, and that without additional scrubbing and processing the biogas can only be used in specialised equipment and is more difficult to transport. However, in smaller operations and in situations where heat or electricity is more valuable than gas these may be the favoured options.

It is worth noting that the use of CHP engines to create electricity needs to consider additional costs of connecting to electrical networks if the electricity cannot be used locally, as this cost can be prohibitive.

Biomethane can also be compressed and bottled for use as a vehicle fuel or as an LPG substitute (note: this would involve asset retrofitting to correct for differences in energy density) in areas without a natural gas reticulation network, in a similar fashion to the bioenergy facilities dotted around Sweden.

8.4.3 Key Conflict in Biomethane Sources – Landfill Gas vs Biogas

One of the main conflicts we note in terms of feedstock use is the commercial conflict between landfill gas generators, and developers looking to install anaerobic digestion plants for processing of Source-Segregated Municipal Food Wastes.

As food waste collections begin diverting food wastes from landfills, the landfill gas generation capacity of our landfills will begin to decrease over time. Residual food wastes and other kinds of organic wastes not suited for anaerobic digestion facilities will still end up in landfills, so their gas generation potential will not disappear entirely, but this represents a loss in electrical generation capacity for incumbent waste management firms.

The advantages of anaerobic digestion over landfill gas generation are:

- Creation of digestate by-product
- More complete biogenic methane recovery
- Less land use required

However, landfill gas generation has advantages of its own:

- Able to accept highly contaminated wastes
- Less operational complexity.

Because landfill cells take 3-4 years to start producing landfill gas and remain productive for 6-10 years, the drop-off in landfill gas generation will trail the increase food waste digestion gas production by roughly a decade. This has been factored into our projections for landfill gas generation in all scenarios.

8.4.4 Co-digestion: Advantages and Disadvantages

Co-digestion (the digestion of different kinds of feedstock sources at the same time) is a technique commonly used at large-scale digesters that require a large amount of incoming feed material to keep the plant operating. Designing a large plant to process a mix of feedstocks is advantageous if the plant is too big for a single dedicated source of organic materials. When high-energy feedstocks (e.g. crop silage or food waste) are combined in small quantities with low-energy feedstocks (e.g. WWTP sludge or animal manure), the biogas generation can speed up significantly and some studies have shown this can lead to improved yields too!

There are two main disadvantages of a codigestion system. Firstly, having to design a digester to handle feed with variable make-up and changing nutrient content is that the digester cannot be optimised based on tight material specifications. Digesters processing very consistent incoming feeds can be finely tuned and can operate for long periods of time without intervention. Feed composition changes can affect operating yields as the biological cultures adjust to their new environment.
Secondly, if feedstock like crop silage or food waste are co-digested with WWTP sludge the presence of pathogens and human waste materials in the sludge means the digestate from the plant is considered lower quality and cannot be used as a fertiliser. Co-digestion of small quantities of food waste or crop silage with WWTP sludge could be considered to boost biomethane yields from existing biogas plants, but separate digestion is preferable if a reasonable quantity of the high energy feedstock is preferable.

For this reason, in our scenarios we have elected to nominate the majority of feedstock use will be in purpose-build digesters, and unless grid-scale use of a particular feedstock is not deemed reasonable we have avoided building up scenarios based on assuming a portion of the feedstock is available for co-digestion.

In this way, the biomethane figures in the tables above represent the portion of available energy we think could be utilised as a renewable methane substitute, rather than the total energy contribution of biogas and biomethane towards New Zealand's zero-carbon energy future.

8.5 What are the Benefits?

There are a number of benefits associated with maximising the production of biomethane in New Zealand, across environmental, social and economic dimensions. We touched on some of these benefits in the Introduction section, but let's expand on how a maximised biomethane uptake between now and 2050 would impact different groups:

8.5.1 Benefits of Biomethane to Natural Gas Users

Biomethane or Renewable Natural gas production allows a simple decarbonisation roadmap for gas-fuelled operations. By switching to a chemically-identical, biologically-sourced substitute for natural gas the emissions associated with this gas use are dramatically decreased. It is also possible to decrease emission gradually over time as the percentage of renewable gases feeding chemical or heating infrastructure increases over time.
In addition, the emissions associated with gas use are decreased without high abatement costs for the users. The same assets and equipment can be used if natural gas users switch to biomethane instead of switching to alternative fuels like biomass or electric element boilers.

As an example of this, biomass boiler fuel switching installations for gas users generally cost around $2M in initial capital per MW installed capacity, with Marginal Abatement Costs of around $80-110 /tonne of CO_2 abated due to their high operational and maintenance costs. Based on our first case study, biomethane plants generally have much higher upfront capital costs than this (around $10M /MW installed capacity), but have much lower Marginal Abatement Costs (around $-14 /tonne of CO_2 abated) because of the additional revenue streams the anaerobic digestion and biomethane processing operations create, which allow more competitive energy prices. Biomethane plants charging gate fees and selling CO_2 and digestate as by-products can end up generating revenue in contrast to biomass boilers which generate a loss over time.

As well as users that need gas for heat and power generation, there are industries in New Zealand that use methane as an input to their chemical manufacturing processes. Biomethane and other RNG sources could support the continuation and decarbonisation strategies of existing industries that have the most future uncertainty around continuation of New Zealand natural gas supplies.

8.5.2 Benefits of Biomethane to Biomethane Generators

While individual generators of biogas may not have a natural use for the energy they generate, a biomethane economy integrated into existing natural gas networks would provide a larger, more flexible market for production allowing more consistent production and a steadier demand. Biomethane is a more flexible resource than regular biogas, and less specialised equipment is needed to handle the gas which means a larger potential customer base for producers.

Biogas and biomethane generation from a company or council's organic waste is a powerful mechanism to help them reduce emissions, as well as turn waste products into additional revenue streams.

8.5.3 Benefits of Biomethane to Distributors

New Zealand (especially the North Island) has considerable transmission and distribution infrastructure used to transport natural gas from the Taranaki to gas users all over the North Island. Current natural gas production in New Zealand is expected to decrease yearly until 2050 when it is expected to reach close to zero. As a result, these assets will need to be retired much earlier than intended. Tied to this, there are still gas users that will need to continue using natural gas right up until 2050 as they figure out how to transition away from fossil fuels, and as users drop off the network operational and maintenance costs will become more and more expensive for remaining operators and users. Biogas could continue to be transported through the natural gas network if it is modified to transport hydrogen in the future.

In addition, the development of a biomethane economy will create opportunities for the transition of workers experienced in New Zealand's oil and gas sector to new roles in bioenergy.

8.5.4 Benefits of Diverting Organic Wastes to Anaerobic Digestion/Biomethane Plants

Capacity for alternate organic waste disposal created by a thriving biomethane industry diverts material from landfills and slows demand for additional landfilling space. Additionally, the GHG emissions generated by the process of converting organic material into biogas and biomethane are much lower than the emissions produced by the eventual degradation of organic material in a landfill.

The creation of an industry that uses a waste product to generate energy and valuable by-products is much more sustainable and circular in nature than traditional waste management strategies in use around New Zealand.

8.5.5 Benefits of Other Biomethane Products

Of the by-products produced from biomethane production, the two most valuable are carbon dioxide (CO_2) and bio fertiliser.

Most CO_2 consumed as a product in New Zealand is generated by petrochemical processing e.g. the refining of crude oils into petroleum fuels. Carbon dioxide captured and refined from biogas presents a sustainable alternative to fossil fuel-based CO_2. Additionally, biomethane producers in Europe are developing processing technology to combine green hydrogen with CO_2 from biogas plants to create additional renewable methane. This is easier to store, transport and use than pure hydrogen.

Bio-fertiliser and digestate have been successfully used to supplement or altogether replace synthetic nitrogen fertilisers overseas and help restore soil health. New Zealand's large agricultural sector is highly dependent on imported phosphorous/nitrates to sustain agricultural yields which:

- Are responsible for a large quantity of emissions due to overseas transport and fugitive nitrate emissions after application
- Contribute to soil degradation and release of stored soil carbon if over-applied, as well as degradation of fresh water via fertiliser runoff and soil destabilisation.

Bio-fertilisers and other organic fertiliser products could be an important tool for balancing New Zealand's carbon emissions and reducing our dependence on imported synthetic fertiliser products.

9 Unlocking New Zealand's Biogas/ Biomethane Potential

9.1 Regulatory and Policy Barriers

9.1.1 Policies and Certification Schemes missing to promote and incentivise use of bioenergy and bio-fertilisers

In our overseas research we mentioned that Germany is a net exporter of biomethane, and most of this biomethane ends up in Sweden where it is used as a vehicle fuel. This biomethane is exported to Sweden is transported down the same pipeline connecting Germany and Sweden that contains regular natural gas, and the attribution of production and use of biomethane between different parties connected by the pipeline is facilitated by issuing of credits and certificates for this renewable gas.

Companies buying biomethane in Sweden can claim benefits by demonstrating certified biomethane purchases, which allows German biomethane producers to compete with cheaper petrochemical natural gas suppliers. It is anticipated that a similar system of certifying biomethane as its own product will be required for organisations to claim potential benefits. Certified Energy, who administers the New Zealand Energy Certificate System, has recently announced public consultation on establishing a green gas certification scheme. This will elevate biomethane as a low/no-carbon gas option for sale via the existing natural gas grid.

In a similar way, the production and selling of biodigestate or bio fertiliser in New Zealand is unlikely to become feasible without its own certification schemes or other method for buyers to have guarantees on quality of material supplied. New Zealand's current regulations concerning the possible end uses for biosolids produced from anaerobic digestion processes will not allow digestate to be certified, marketed and sold as a fertiliser supplement on most agricultural land, and prohibit the use of biosolids on land without rigorous testing. 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 biodigestate from biowaste and other biosolids as per existing legislative classifications, and therefore market and sell this valuable by-product from anaerobic digestion.

The Bioenergy Association has produced a guidance document on this standard, adapting the regulations to a New Zealand context (see Section 6.4). This may allow easier uptake of a similar standard to PAS 110 locally.

9.1.2 Missing coordination of municipal solid waste collections promoting diversion of organic waste from landfills.

Countries such as Norway and Denmark have implemented aggressive policies to prevent the disposal of degradable organic waste in landfills, including partial or total bans. In New Zealand, the vast majority of all food waste from municipal collections (as well as commercial and industrial food waste) is disposed of in landfill. The majority of this gas is captured, but a large portion of biogenic methane emissions from the decomposition of this material still escapes to atmosphere.

Some councils are beginning to promote alternative waste disposal pathways for organic material including Auckland Council, who have awarded EcoGas the contract for collection and processing of Auckland's food waste in the coming years. However, there is a lack of clear policy governing the disposal of this waste at a regional and national level in New Zealand, and it is up to councils to set their own targets and timelines for organic waste strategies.

As the waste sector is such a large contributor to New Zealand's overall GHG emissions (4% in 2019) (Ministry for the Environment, 2019), a strategy to mitigate and reduce these emissions will be crucial for New Zealand to reach its 2050 net zero ambitions. The repurposing of source-segregated waste towards alternative disposal routes e.g. composting and anaerobic digestion would enable better emissions capture, a reduction in volume sent to landfill per year, and create circular markets for waste streams.

9.1.3 Lack of support to promote wide range of sustainable energy technologies.

New Zealand's emergence as a world leader in biogas technology in the 1970's was driven by strong government support for alternative fuels technology in the wake of a developing economic crisis. Biogas was put forward as one of many mechanisms to provide security against overseas oil prices and protect local farmers and rural communities from the effects of market collapse.
However, as the threat passed so did the government support for alternative fuel technologies.

We have demonstrated that biogas and biomethane uptake in European and North American countries has been supported in almost all cases by local and central government policy. These policies (including feed-in tariffs, investment grants, organic waste disposal restrictions) are most successful in developing lasting change when underpinned by a National Energy Strategy with clear long-term objectives. In the absence of this in overseas countries, policy can lead to unintended outcomes or sub-optimal results e.g. Germany's land use conflicts.
With New Zealand needing to create substantial changes to its energy mix and emissions profile to achieve zero-carbon by 2050, we expect that New Zealand will need to take advantage of all available technologies, including biogas and biomethane..

9.2 Technical Barriers

9.2.1 The lack of technical expertise

Despite New-Zealand being an early leader in the production of biogas, anaerobic digestion and biomethane processing is currently not a widely established technology in the New Zealand, which creates a gap in current local experience.

As a result, expertise in this field will in turn have to be gained from overseas to re-establish this technology and supporting amenities such as gas scrubbers and distribution systems. Expertise is required both at the initial instalment of an anaerobic digestion system, but also over the course of operation of digester, for maintenance and operational support. This could be supported by research and development with tertiary education organisations and/or other technical research services.

9.2.2 The lack of local equipment vendors and supporting services

Following from the above, the lack of installed and operating biogas plants and biomethane refining facilities in New Zealand means there will be heavy reliance on overseas equipment vendors and specialists to support construction and operation of these facilities. In the first instance, the few operating biogas/biomethane plants will depend heavily on European and American suppliers to design, construct, commission and maintain specialist equipment, and over time this will lead to a local presence as the industry develops and matures. However, until this critical mass is reached, and key suppliers/contractors/consultants establish a New Zealand presence, it will be difficult and expensive to engage with these crucial participants in New Zealand's biogas/biomethane development.

One potential opportunity is the cross-over between biogas and natural gas handling that would enable New Zealand's oil and gas industry workforce to help support the development and operation of biomethane upgrading plants. These technicians and engineers familiar with fossil fuel methane processing and transportation technology could easily apply their skills to support bioenergy projects.

In the early 2000's New Zealand was the home to one of the leading global biogas upgrading equipment suppliers (Greenlane Biogas) which now operates predominantly in the US and EU markets. However, many of the key engineers and technicians from this company have stayed in New Zealand operating in different areas of practise. If the industry was to re-establish itself in New Zealand, Greenlane Biogas' history in New Zealand could help accelerate the re-establishment process.

9.2.3 The lack of one-size fits all solutions

The anaerobic digestion system, from pre-treatment to gas conditioning, is dictated by the characteristics of the feedstock stream(s). In New-Zealand, there is a wide variety of feedstocks available in a range of different volumes. Co-digestion further diversifies feedstock options. Case by case evaluation of the feed stream is needed for the design of the digestion system, and this makes adoption of the technology more expensive.

The lack of one-size fits all solutions slows the adoption of the technology in New-Zealand, however, it can also be viewed as an advantage, as the process is adaptable to many scales and feedstocks increasing the opportunities available.

9.2.4 The lack of supporting infrastructure and logistics networks

The dispersion of feedstock sources and energy users in New Zealand poses logistical challenges.

A significant number of feedstocks are generated by the agricultural sector; however, these feedstocks require transport over long distances if not processed on farm. Subsequently, digestate requires transport to accepting agricultural land. The financial cost and environmental cost arising from transport of feedstocks and digestate should not compromise the economic viability and sustainability of an AD operation. Sufficient storage of substrate and digestate at the AD site, and well-managed logistics are important to ensure continued operation. For feedstocks and biogas production too difficult to connect to natural gas distribution infrastructure, farm or community-based bioenergy hubs could be incentivised to provide both a method of disposing of feedstocks, a supply of clean energy (for transport, heating, electricity etc.) and digestate by-products.

The installation of the required infrastructure also affects the rate of adoption in New Zealand

Biomethane having comparable properties to natural gas, much of the natural gas infrastructure such as pipelines has the potential to be recommissioned for the transport of biomethane. Nonetheless, additional infrastructure is needed to support a biogas and biomethane network in New-Zealand, including gas scrubbing and compression sites, grid injection sites, possible bottling sites, storage facilities and waste segregation and collection sites.

More established biogas/biomethane markets overseas also experience difficulties due to a lack of infrastructure to support the growth and diversification of their market. This primarily affects the use of CBG as a transport fuel, which requires a distribution system. A limited number of refuelling stations inhibits the widespread use of biogas vehicles, especially civilian cars, which has been the case in countries such as Sweden and Denmark (Eyl-Mazzega & Mathieu, 2019).

9.2.5 Challenges connecting to & injecting biomethane into existing gas grid infrastructure

The Specification for Reticulated Natural Gas (NZS 5442:2008) states the requirements for methane-based gas that is transported and supplied for use in natural gas burning appliances. The specification will need to be reviewed, specifically in regard to the upper oxygen content for biomethane injected into the transmission grid. AD process and landfill gas typically do contain unavoidable, albeit trace, levels of atmospheric oxygen and nitrogen that require extra gas polishing processes to remove. The additional cost required for gas polishing should be contrasted against the concerns around pipeline corrosion, modification of Wobbe Index, and a practical oxygen limit established for biomethane injected into the transmission grid. Biomethane injected into the local distribution grid has an upper limit of 1%-mol Oxygen, which will not typically require any further gas polishing process.

9.3 Economic Factors

9.3.1 Perception of Waste as a Low Value Material

In New Zealand, waste management strategies and plans have traditionally not recognised the value of waste, and as a result landfilling of waste is the default approach taken for most waste streams. This is true of both contaminated/inert construction wastes as well as high energy wastes and other kinds of wastes that can be processed and regenerated i.e. organic wastes and green wastes.

Currently, the levy for sending waste to landfill in New Zealand is $10 NZD/tonne (Ministry for the Environment, 2021). This is very conservative when compared to other countries overseas. For example, in the UK it costs £94.15 ($185.75 NZD) /tonne for standard waste disposal with discounted rates for more inert materials (UK Government, 2020).

Some developed countries overseas including Denmark, Norway, and Sweden have even gone as far as to ban the landfilling of combustible waste. This waste is instead sent to incineration plants to generate heat and electricity. While the levy, introduced in NZ in 2008, is currently used to fund wase minimisation activities and is confirmed to increase to $60 NZD/tonne by 2024 (Ministry for the Environment, 2021), additional policy, such as the ban of landfilling combustible waste and higher penalties for landfilling of organic materials could be considered to further aid decarbonisation.

9.3.2 Low Carbon Price and Carbon Tax as part of ETS (Emissions Trading Scheme)

The NZ ETS puts a price on greenhouse gases and by doing so creates financial incentive for businesses to reduce their emissions and for landowners to plant forests. However, this cost is significantly lower than that of those globally, and as such, the low-cost nature of the units means that it is not appropriately disincentivising New Zealand businesses to lower their emissions at present.

The price for the units is based on a supply and demand basis, with the government reducing the number of available units each year. This creates an incentive for emitters to reduce their carbon production as the price for units increases with demand.

The cost of one unit in NZ is currently $39.20 as of February 2021 (CarbonNews, 2021). This is significantly lower that the price of carbon in Europe of €40.63 EUR ($68.23 NZD) as of March 2021 (Ember Climate, 2021). Furthermore, in order to half their 1990 emissions by 2030 Norway has introduced an additional carbon tax on top of the EU ETS, raising their costs of emissions per unit to 2,000 Norwegian Crown ($333.71 NZD) (Buli & Adomaitis, 2021).

As the ETS price increases in New Zealand, biofuels like biomethane will become more competitive when compared with fossil fuels like natural gas since biomethane would not require an ETS unit to be paid associated with its use. This will create more demand for sustainable energy. As reviewed in our Scenarios, expected ETS price increases will make different kinds of biomethane installations more appealing financially in coming decades.

9.3.3 High Upfront Investment Costs of Biogas/Biomethane Plants

Lack of funding opportunities for new renewable energy investment is one of the key economic barriers preventing businesses from creating and utilising sustainable energy in New Zealand. The high capital costs of these installations can reduce the appeal of these projects to investors without partnering with other organisations for capital funding, as observed in overseas examples. Additionally, guaranteed revenue streams can boost investor confidence which manifest overseas as Feed-In Tariffs, or green gas supply contracts.

Feed in Tariff (FIT) schemes and subsidies are used overseas to incentivise the generation of renewable energy. These provide a guaranteed revenue stream for renewable energy investment which helps companies commit to investing in renewable energy projects.

FITs, like those used in the UK, incentivise the generation of renewable energy through the implementation of small-scale projects. Payments are made to those who export renewable energy, created through the use of solar, wind, or micro CHP, back into the grid (Energy Saving Trust, 2021). Additionally, these tariffs are locked in for a set time period after project implementation so that project investors can have confidence in ongoing revenue generated by their investments. Denmark employs the use of public subsidies to encourage the production of biogas for electricity, industrial use, transport fuel, and heating (Danish Energy Agency, 2021).

The EU has multiple funding options aimed at promoting the development of sustainable energy sources. These include funding to develop suitable energy, transport and digital infrastructure required for renewable sources, grants for energy research and innovation projects, additional funding to support 'low carbon projects', and policies that make it easier for renewable energy projects to get loans approved. Furthermore, there is additional support to and grants to help coal-intensive regions transition to a greener economy (European Commission, 2021).

10 Conclusions and Closing Remarks

This study has demonstrated that biogas and biomethane are robust, well-developed technologies that can be readily deployed and utilised in New Zealand. This technology has a wide range of benefits; aside from providing low-emissions renewable energy, it reduces emissions from organic waste disposal and produces many valuable by-products.

Based on our findings, enough readily-available organic waste exists in New Zealand today to produce as much as 19 PJ of biogas. Some of this material is easier than other types of material to utilise effectively, but by 2050 we expect that as much as 13 PJ of biogas from anaerobic digestion could be converted into biomethane per year. This would replace over 7% of our national natural gas consumption and reduce New Zealand's gross greenhouse gas emissions by 2% over the total biomethane value chain. These figures are positive, however there are still many steps to realising this biomethane potential.

Realising this potential will require continued efforts from a number of stakeholders across industry and government to address and remove the key barriers highlighted by this study, as well as further detailed technical and financial analysis to determine the best installations on a case-by-case basis. As highlighted in this report, each individual biogas/biomethane installation has its own specific benefits and challenges which need to be carefully understood to ensure project success.

Another important next step for the implementation of this technology is an assessment of how the opportunity presented by biogas and biomethane fits into New Zealand's energy transition to Zero Carbon by 2050. Biogas and biomethane, like many other alternative fuels and energy sources, cannot provide all of the answers to the challenge faced by New Zealand to adopt low emissions fuel sources. But by playing a role alongside other fuels, biogas and biomethane can provide part of the overall solution.
The recent Climate Change Commission Advice Report highlights the need for an energy strategy including the range of low-emissions gases available for use in New Zealand. This will be a great opportunity to assess and define the role of biogas and biomethane in our future energy transition.

We look forward to engaging with partners across industry, government, iwi and community stakeholders to continue developing and realising the potential of biogas and biomethane in New Zealand.

A

Appendix A – Additional Technical Material

A1. Types of Feedstocks and Volumes

Municipal Wastewater Treatment Sludge

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. Anaerobic digestion is used to treat primary sludge, which has a high content of organic matter and is easily degradable, yielding 315 to 400 Nm³ CH_4/t ODM, or secondary sludge which has a lower degradable fraction, yielding 190 to 240 Nm³ CH_4/t ODM (Bachmann, 2015). In the absence of accurate municipal wastewater sludge volumes in New Zealand, to capture the maximum quantity of biogas production obtainable from the municipal population connected to WWTP, New Zealand's urban population (86.6% of the total population (Trading Economics, 2019)) was used as a basis. Gross gas production per capita, assuming the wastewater is processed in a plant with anaerobic sludge digestion ranges from 18 to 26 L per capita per day (Bachmann, 2015). This could yield an estimated total **0.60 to 0.87 PJ** of biogas, including current generation. It should be noted that this is the theoretical maximum production. It may not be economical for small WWTPs, especially in remote locations, to anaerobically digest their sludge for biogas production.

Both the quality and the location (in proximity to urban centres) of municipal wastewater sludge lends itself to co-digestion with food or industrial waste (Biogas Association of New Zealand, 2019), which has been shown to increase the biogas yield. Substantial additional biogas production through use of co-digestion would create excess of the heat and power requirements on-site, creating potential for revenue by resale to the national gas grid.

The Mangere, Rosedale, Christchurch and Palmerston North WWTP already use anaerobic digestion to generate biogas for combined heat and power on-site. The Mangere WWTP, New Zealand's largest WWTP treating wastewater from about 1 million New Zealanders, has seven mesophilic sludge digestors capable of producing 49,000 m³ per day of biogas (the equivalent of about 0.3 PJ of biogas per year). The Rosedale WWTP produces 10,000 to 12,000 m³/day of biogas (the equivalent of about 0.1 PJ of biogas per year) (Watercare Services Ltd, 2019).

In New Zealand, WWTPs with anaerobic digesters are rarely designed with significant extra capacity but implementation of recuperative thickening systems and digester optimisation studies have allowed the yields of biogas at these plants to increase and free up room for additional feedstocks e.g. Palmerston North City Council's WWTP (J. Thiele, 2018). This can also free up room for codigestion of other organic wastes e.g. food wastes, which would need to be assessed against separate digestion of food wastes only to also produce a high quality digestate.

Source-Segregated Food Waste

A study conducted in 2011 estimated New Zealanders produce and dispose of 0.07 tonnes of digestible municipal solid waste (food waste) to landfill per year per capita (Reynolds et al., 2016). This includes Residential, Commercial and Industrial food wastes, and only captures food that is not home-composted, used as animal feed, or disposed of in other ways. Based on this figure, it is anticipated that New Zealanders will produce approximately 354,000 tonnes of digestible waste in 2021, which could yield an estimated **1.5 PJ** of biogas. Accessing this feedstock stream is dependent on the disposal method: roadside collection, home composting or to sewage via sink waste disposers and if collected, whether it is source segregated or not. In New Zealand, 71 source-segregated organic waste disposal sites exist (Ministry for the Environment, 2011).

Currently, 90% of organic waste goes to landfills that are already equipped with gas capture systems (Biogas Association of New Zealand, 2019). However, biogas captured from these managed landfills can achieve on average only 68% capture, and many of these sites do not use their gas for power generation or heating; it is instead flared (Biogas Association of New Zealand, 2019).

It is foreseeable that the quantity of organic waste reaching landfill will decrease in the coming years as source-segregated waste collection increases. Currently, landfill emissions make up 4% of New Zealand's total GHG emissions (Biogas Association of New Zealand, 2019). While this proportion is not large, there is an opportunity to divert more organic waste from landfill to purpose-built anaerobic digestion facilities as the Reporoa biogas plant will soon demonstrate, or for co-digestion with wastewater sludge. As collection of source segregated food waste is already occurring, such as in Christchurch for composting, the accessibility of this stream is high and has prospect to be maximised if source segregated collection increases. This would require normalisation of organic collection methods across New Zealand and education of the public on organic and food waste disposal; such has been done with recyclable plastic, metal and glass.

Large quantities of pre-consumer industrial food waste would be easier to utilise in the first instance than post-consumer commercial and residential food waste, as this is generally less contaminated and easier to process without additional screening equipment (J. Thiele, 2018).

Agricultural Waste

New Zealand's large agricultural sector provides several opportunities for biogas feedstock streams, including manures from different livestock and crop residue. Additionally, because the agricultural sector contributes 48% of the national GHG emissions (Ministry for the Environment, 2019), improvements in agricultural waste management are primarily to meet international targets, providing a driver for the implementation of anaerobic digesters as a waste management method. While New Zealand's agricultural practices do not necessarily lend themselves to the production of biogas, there are nonetheless sizeable feedstocks streams which are currently not only going unutilized but also cause issues with disposal. For example, crop residue is often burnt on field which disperses absorbed nutrients in the biomass, and manure disposal can lead to odour, runoff, groundwater & freshwater eutrophication problems.

Crop Residue

In New Zealand, 70% of arable crops are grown in Canterbury and include a wide range of seed crops and cereal grains. It is common to burn stubble (post-harvest residue not commonly used as food), which is viewed as an effective way to clear straw and other plant material prior to the next crop rotation. Stubble burning, however, releases 60 to 70% of the carbon, 30 to 90% of the nitrogen and 65 to 81% of the sulphur contained in the crop residue to the atmosphere (Williams et al., 2013). Burning of crop residue produced 23.4 kt CO_2e in 2017 (Ministry for the Environment, 2019). While this is not a significant contributor of GHG emissions (0.1% of total emissions from the agriculture sector), retrieval of this plant material would constitute a viable feedstock for biogas production, and an alternative to current stubble burning for clearing plant material and returning nutrients to the soil via application of the digestate.

The Canterbury region produces approximately 1 million tonnes of crop residue each year (Williams et al., 2013) on approximately 90,000 hectares of arable land (Foundation for Arable Research, 2013). It is not possible, nor desirable, to remove all crop residue, as the roots of the plants help to maintain soil structure and carbon content. According to the World Biogas Association (Jain, 2019), 30 to 60% of crop residue can be sustainably recovered, amounting to an estimated 5 tonnes of recoverable crop residue per hectare of arable land. In Canterbury, this would yield **1.4 to 2.9 PJ** of biogas per year.

Only the region of Canterbury is considered as a primary source of biogas potential; other regions do not have the same significant, concentrated crop production, although use of crop residue in other areas could be considered to complement other feedstocks in co-digestion systems. Obstacles to accessibility are geographical dispersion and ownership of the feedstock being divided between many owners. Crop residue achieves a high biogas yield; however, lignocellulose requires longer to breakdown, requiring more rigorous pre-treatment or a longer retention time within the digester. Seasonality is also an issue to be considered, as the majority of crop residues are produced during harvest seasons. Storage of crop residues will need to be considered to allow effective use of this resource.

Manure

In New Zealand, accessible manures with significant volumes available are dairy cattle, poultry, and piggery manure. Beef and sheep livestock numbers are high but retrieval of the manure from these farms is not feasible due to New Zealand’s high use of pastoral agricultural practices, where manure generation occurs over a much larger area compared with more common feedlot methods used overseas. Table 33 summarises the key inputs used in determining the biogas production from diary, pig and poultry manure.

Table 33: Animal Manure Figures by Livestock Type

	Population	Manure (kg/day/head)	Manure recovery	Total solids % of fresh
Dairy manure	4,900,000	35	8.5%	25%
Pig manure	233,000	3.3	100%	25%
Poultry manure	22,615,000	0.1	100%	21%

In 2017, emissions from manure management systems totalled approximately 1,597 kt CO_2-e (NZ Greenhouse Gas Inventory, 2019). Most of these emissions come from methane being produced during the storage and treatment of manure, as well as manure deposited on pasture. Anaerobic lagoons are used for approximately 7.3% of dairy cattle excrement (Ministry for the Environment, 2019). Gas collected from these lagoons is normally flared, but in a few cases is used in modified diesel generators to produce electricity.

Dairy cattle

Dairy cattle in New Zealand are predominantly pasture-grazed, however there is opportunity for manure collection from the milking shed, which is estimated to be 10% of the total manure produced by dairy cattle (Ministry of Agriculture & Forestry, 2008). Dairy cattle produce an estimated 27 - 35 kg of manure per day, although this varies depending on the type and quantity of feed consumption (Ministry of Agriculture & Forestry, 2008; Wilcock, 2006). With a milking cattle population in New Zealand of 4.9 million in 2019/20, this represents a sizeable feedstock stream of 5.3 million fresh tonnes per year, equating to **5 - 6.8 PJ** per year of biogas. A range has been provided to encompass the variance in biogas yields reported by the World Biogas Association and the Ministry for Primary Industries (Jain, 2019; Pratt et al., 2012). Work should be undertaken to develop a New Zealand-specific biogas yield to better reflect current New Zealand farming practices.

Digestors are economically viable for herds with over 1000 cattle (Rowarth et al., 2015). In New Zealand, the average herd size is 440 cattle (*New Zealand Dairy Statistics*, 2020), which suggests that a centralised anaerobic digestion plant would be more cost effective for smaller operators. However, geographic dispersal of farms and the nature of manure makes transport difficult. A study conducted in 2006 found that it was still more economic to transport manure from a 7500-herd size to a centralised anaerobic digestion plant than it was for the herd to have its own anaerobic digestion unit (Ghafoori & Flynn, 2006). In the North Island, clusters of dairy farms occur in the Taranaki and Waikato regions, which could enable the injection of biogas from a regional digester into New-Zealand’s gas grid. In the South Island, biomethane could be used directly to replace coal for process heat in industry or transported via converted LPG networks.

Use of off-paddock infrastructure has increased from an estimated <1% of dairy farms in the 1990s to an estimated 30% of dairy farms using feed-pads and 25% using stand-off pads in 2017 (Rollo et al., 2017), which is positive from a manure recovery perspective. With 2022 heralding the inclusion of agricultural emissions in the Emissions Trading Scheme, New Zealand farms may see an increased incentive to recover manure from existing off-paddock infrastructure (feed-pads, stand-off pads and milking sheds). The calculated biogas potential has not assumed an increase in off-paddock infrastructure.

Pigs and poultry

Pigs and poultry are mostly farmed in shelters or barns, which allows for a higher fraction of waste to be collected (Ministry of Agriculture & Forestry, 2008). Because waste collection is already occurring, this resource is relatively accessible, but there is little industry experience using anaerobic digestion, with only one out of the 93 piggeries in New Zealand, the Lepper Trust Piggery in Taranaki, currently capturing biogas (Taranaki Regional Council, 2016). Poultry farms are clustered around urban centres, increasing local biogas demand and potential for co-digestion (Ministry of Agriculture & Forestry, 2008).

Broiler chicken manure has a biogas yield of 50 to 100 m³/wet tonne and pig manure has a biogas yield of 40 to 80 m³/wet tonne (Jain, 2019). Assuming all pig and poultry (broiler and laying hens) manure is collected for digestion, this could yield 1.3 PJ of biogas per year from poultry manure and 0.36 PJ of biogas per year from pig manure. The collection of animal manure and subsequent uptake in biogas production is dependent on farming practices. With more pig and poultry farmers making the shift to free-range farming practices, the potential biogas production is expected to decrease.

Variability in quality of feedstock – livestock diet, livestock digestive system, solid content, antibiotic residue

It should be noted that cows have highly effective digestive systems, resulting in a lower fraction of biodegradable organic matter available in their manures. Poultry and pigs have a higher biogas yield in comparison due to their poorer digestive systems (Ministry of Agriculture & Forestry, 2008). Poultry manure also has a favourable carbon to nitrogen ratio. Due to the varied diet of pigs, the manure can be quite susceptible to changes in composition and result in varied gas composition.

Animal manure is favourable for the growth of anaerobic bacteria with a neutral pH, high buffering capacity and a wide range of nutrients. Antibiotic residue can reduce the biogas yield by inhibiting the methanogenic bacteria (D. Hamilton, 2017). Pig and poultry farming tend to use more antibiotics compared to cattle farming, which is a factor that needs to be considered when designing an anaerobic digestion system. The presence of inert wood shavings used as bedding in poultry cages and barns also makes digestion less effective (Ministry of Agriculture & Forestry, 2008)

Low solid content can inhibit digestion due to the biodegradable components of the animal feed having a higher presence in the solids of the manure, compared to the water fraction. This can be overcome by good management or co-digestion with another feedstock. Percentage of dry matter is influenced both by the type of manure, and the collection method. For example, cow manure is usually hosed down into a sump which reduces the solid content of the manure (Ministry of Agriculture & Forestry, 2008).

Industrial Wastewater

Overview

The industrial sector uses 6% of New Zealand’s weekly water consumption (MFE, 2010). If wastewater does not meet local discharge standards, it must undergo treatment, creating the opportunity for anaerobic digestion on-site. 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 industrial wastewater treatment is aerobic, releasing emissions, and the few treatment plants using hydraulic or pond anaerobic treatment systems do not all have gas capture systems for biogas reuse. Only 8 industrial WWTPs flare or utilise captured biogas, leaving an untapped resource of approximately **2.4 to 3.2 PJ per year.**

Meat and Dairy

Chemical oxygen demand (COD) is a measure of the amount of oxygen available for consumption in anaerobic conditions, which in turn determines biogas yield. Dairy plants produce wastewater streams from raw milk, butter, milk powder, cheese and various whey products, which all have varying COD values. Generally, COD values range from 1,700 g/m³ for milk powder wastewater to 5,000 g/m³ for cheese wastewater (NZ Institute of Chemistry, 2017). Best conversion and treatment of dissolved COD in wastewater occurs in streams with a COD of >2,000 g/m3. The streams from both meat and dairy processing plants are subject to seasonality, and variation in volatile solids, pH and chemical composition, dependent on production regime and processes such as CIP (Beca et al., 2016). This means careful management of the digester is required.

Meat processing and dairy processing plants commonly employ dissolved air flotation (DAF) tanks to reduce the volatile solid content of wastewater, up to 70% removal (Heubeck & Craggs, 2009). DAF sludge can undergo anaerobic digestion in a solids digestor, which is a different technology to a hydraulic digestor, which is designed to treat high COD wastewater and cannot be used for solids or sludge.

Fonterra produce approximately 61 million m³ of wastewater per year, which could yield an estimated **1.1 to 1.9 PJ** of biogas per year in a purpose build hydraulic digestor (Beca; GHD; Boffa Miskell;, 2020; Wabnitz et al., 2011). This would predominantly come from the South Auckland-Waikato region and the Taranaki region (NZ Institute of Chemistry, 2017). Meat processing plants produce approximately 20,000,000 m³ of wastewater per year. The COD of raw wastewater from a typical moderate sized beef processing plant is estimated to be 3600 g/m³. Anaerobic digestion of meat processing wastewater could thus yield **0.72 PJ** of biogas per year in a purpose built hydraulic digestor.

There are also opportunities (not considered in this section) to separate wastewater streams into high and low COD concentrations. This could further increase the success of industrial wastewater biogas production facilities by reducing the bulk volume going through the digestor and allowing for more specialised processing techniques for the various streams.

Pulp and paper

The pulp and paper industry are another significant user of water. The Kinleith mill in Tokoroa, New Zealand's largest mill, produce 32 million m³ of wastewater per year (Oji Fibre Solutions, 2019). The COD of pulp and paper wastewater is assumed to be 1759 g/m³ (Bantacut & Ardhiansyah, 2018). Based on these assumptions, pulp and paper wastewater from the Kinleith mill could yield approximately **0.58 PJ** per year of biogas in a high rate liquid digestor.

It is likely that the COD concentration and subsequent biogas yield is too low to make anaerobic digestion of pulp and paper wastewater a viable option. Furthermore, pre-treatment of pulp and paper wastewater may be required due to nutrient deficiency, lignocellulosic material and sulphur containing substances which can result in slower degradation (Al Seadi et al., 2008). A significant amount of fibrous waste is currently being landfilled, which incentivises the use of anaerobic digestion, but extensive pre-treatment is required and other disposal methods have also been investigated in recent years. Two of New Zealand's largest paper mills, Tasman and Kinleith, have implemented vermicomposting (a decomposition process using worms) for fertiliser application, which has proven successful (Quintern & Morley, 2014).

Other industrial plants

It should be noted that many industrial processing plants do not have on-site WWTPs. In these circumstances trade waste is sent to municipal WWTPs. Medium-sized WWTPs in Hawera and Morrinsville receive more than 50% of their discharge flow rate as trade waste. The Mangere WWTP (New Zealand's largest), receives approximately 10% of their discharge flow rate as trade waste.

Many additional by-products from industry exist, such as food waste from food manufacturers, trade waste, spent grain and yeast from distilleries and breweries, grease from grease traps and paunch grass from slaughterhouses. Spent grain from breweries yields 60 to 100 m³ of biogas per tonne of spent grain (with 20% TS content) (Jain, 2019). These streams, while not high enough in volume to constitute having their own AD plant, make good "booster" feedstocks to complement high volume, low-to-medium yield single feedstock digestion facilities. For example, animal manure has a low methane yield which benefits from co-digestion with oily food residue, fishing industry waste and brewery waste (Al Seadi et al., 2008).

Forestry Waste

According to (Hall & Gifford, 2007) an estimated 250,000 tonnes of forestry residue is harvested every year in New Zealand. This is only about 7% of total forestry residue available, leaving more than 2 million tonnes of unharvested residue. The present quantity available in the 2020's will be higher due to the large-scale planting that took place in the 1990s (Industrial Symbiosis Kawerau, 2012). However, woody biomass, which is a lignocellulosic biomass, yields only a small amount of biogas if untreated. Lignocellulose, found in cell plant walls, has a complex structure which is hard to decompose. In forestry residue, cellulose makes up 35 to 50% of its composition. Therefore, pre-treatment of the woody biomass is required before anaerobic digestion, adding to other costs of the process, such as transportation costs. For this reason, biogas from forestry residue has not been quantified, although it should be noted that there are well-established pre-treatment methods available, which makes use of New Zealand's forestry residue as a biogas feedstock certainly possible from a technology perspective. Pine, for example, if pre-treated hydrothermally (at 210°C to 215°C) with SO_2 as a catalyst, yields 180 m³ of biogas per tonne of volatile solids, which compares well with other feedstock yields. If untreated, pine only yields 54 m³ of biogas per tonne of volatile solids (Matsakas et al., 2016).

Purpose-grown energy crops

Purpose grown energy crops, which are not currently grown in New Zealand, have proven viable for biogas production overseas in countries such as Germany where they are supported with subsidies. While crops are harvested seasonally, a constant supply throughout the year can be maintained by preserving the crop via a process called ensiling for use as a feedstock when needed. Ensiling involves chopping then drying the crop, followed by compressing the crop and covering it to push out the air. Anaerobic fermentation then produces acidic conditions which preserves the crop for storage. Purpose grown energy crops are advantageous due to their high biogas yield, ranging from 180 m³/wet tonne to 650 m³/wet tonne, depending on the type of crop and processing conditions (Jain, 2019). Given that purpose grown energy crops are not an existing feedstock in New Zealand, and growing them at large scale would conflict with the use of arable land for food crops, their biomethane potential has not been quantified. However, it should be noted that there is potential for purpose grown energy crops to be incorporated into New Zealand's energy mix in the future. For example, small farms with quantities of manure on the verge of being financially viable may benefit from growing energy crops to boost their biomethane production.

A2.Digestate production

Digestate Properties

Digestate is nutrient rich and retains the phosphorous, nitrogen, potassium, sulphur and organic matter contained in the feedstock digested, enabling the recycling of nutrients back into the soil (Drosg et al., 2015). As an organic fertiliser, digestate improves the soil's physical properties, including bulk density, hydraulic conductivity, and moisture retention capacity (Aso, 2019). Digestion also neutralizes pathogens and seeds, so application of digestate as a soil conditioner inhibits the spread of pathogens and the growth of weeds.

The feedstock material to the AD process dictates the digestate properties, including total solids content, pH, nitrogen and phosphorus content (Drosg et al., 2015). Liquid slurry manure digestion is a wet-state process with a low total solids (TS) content of 6-12% TS, resulting in a liquid digestate in its unprocessed form. Digestate can be a stackable solid material when originating from dry state AD. For example AD of fresh manure (~25% TS) (Jain, 2019), crop residue, energy crops and source segregated organic municipal waste. The TS content is an important variable, as it dictates the volatile solids content, which can be up to 70% of total solids. Volatile solids have been shown to improve soil structure through input of inert organic matter and fibres, which contributes to the formation of humus.

The pH value of digestate is typically higher than the pH of the feedstock. For example, digested manure typically has a pH value ranging from 7.5 to 8.0, compared to undigested manure which has an average pH of 7.5. While an increase in pH positively reduces odour emissions, it also increases the degree of ammonia volatisation. To manage this, digestate should be immediately incorporated into the soil after application to prevent excess ammonia emissions. If properly managed, digestate has a lower risk of excess ammonia emissions compared to raw manure due to its superior infiltration speed into soil (Drosg et al., 2015).

Anaerobic digestion degrades the organic nitrogen compounds contained in the feedstock to produce ammonium, which is readily available for plants to absorb. The ammonium concentration of digestate, normally expressed as a percentage of total nitrogen, is determined by the nitrogen content of the feedstock. For example, pig slurry has a higher nitrogen content compared to cattle slurry and will thus produce digestate with a higher ammonium-N content.

Digestate potential in New Zealand

WWTPs produce around 300,000 wet tonnes of biosolids (stabilised sludge) annually, of which 68% is productively used either for quarry rehabilitation, landfill cover, agricultural land or forestry. Approximately 192,000 wet tonnes (64%) is produced via anaerobic digestion, which neutralises the pathogens contained in the unprocessed sludge, allowing for agricultural land application in some instances (Tinholt, 2019). Source-segregated organic waste can be used as a feedstock for digestate, however, as per the PAS 110 guidelines, the origin of the waste should be known, and sorting of incoming waste should use reasonable endeavours to remove non-biodegradable packaging (Waste & Resources Action Programme (WRAP), 2014). Source-segregated municipal waste is achievable under local food waste collections schemes. Care must be taken to ensure that this stream is not contaminated with non-biodegradable material and human waste such as nappies. Nonetheless, source segregated organic waste should not be overlooked as it makes a valuable plant fertiliser. New Zealand's first large-scale food waste biogas production facility, owned by EcoGas, is due to open in 2022 and is estimated to produce enough digestate for 2,000 acres of farmland (Sherrard, 2020). Agricultural waste is another potential source of digestate and presents fewer challenges under the PAS 110 guidelines as it is feasible and possible under current practices to control and know its origin, thus there is little to no non-biodegradable material present. Manure is already commonly being applied to land, for example, via irrigation. It is advantageous to anaerobically digest manure, as it increases the presence of readily available plant nutrients, such as ammonium-N, phosphorus and potassium.

The advantages of digestate are realised when its nutrient profile is compared to that of its raw (undigested) form. This is because digestate has higher proportions of plant-available nutrients compared to untreated manure and crop, thereby increasing its fertilizing value (Risberg et al., 2017; Sørensen et al., 2019). For example, ammonium-N as a percentage of total-N in cattle and pig slurry has been shown to increase 10-15% with anaerobic digestion (Risberg et al., 2017). It is therefore beneficial from a nutrient perspective for manure to undergo anaerobic digestion before it is applied to soil.

Nutrient leaching and runoff can occur with both synthetic and organic fertilisers, and both have adverse effects on the environment. Leaching occurs when dissolved nutrients move beyond the plant root zone, which can cause harmful contamination of ground water and waterways, and result in poor performance of the targeted soil (Fertiliser Association, 2013). An advantage of digestate, however, is it releases nutrient gradually at a slower rate compared to mineral fertilisers, reducing the risk of nitrogen leaching into water (European Biogas Association, 2015).

Application of digestate to soil

In Europe, the direct application of digestate to land is widely practiced. For example, Germany applies 100% of agricultural digestate to land. Sweden applies almost all except sewage sludge digestate to land. The vast majority of EU countries do not apply sewage sludge digestate to land (Wood Environment & Infrastructure Solutions UK Limited, 2019). Agricultural digestate is typically used overseas as a soil improver for use in agriculture, horticulture and in some cases hobby gardening. If the manure feedstock is in slurry form, it should be expected that the digestate will be liquid, unless it is further processed to separate the liquid from the solids. It is recommended by the European Biogas Association to apply liquid digestate with machinery that minimizes exposure to air to prevent ammonia volatilization. Trailing hoses, trailing shoes or direct injection to the topsoil are appropriate methods. The application limit of agricultural digestate varies in European countries between 10-40 m^3/hectare (4-16m^3/acre). Further limits are in place for areas vulnerable to nitrate (Wood Environment & Infrastructure Solutions UK Limited, 2019).

Direct application of digestate to land is the cheapest way of utilising it as fertiliser. Another option is to further process it to a value-added, marketable product, to be better suited to the specific needs of farmers. The digestate processing section below describes the various established digestate processing methods.

As a result of the distribution of agricultural practices across New Zealand, fertiliser demand differs by region in terms of nutrient type and quantity. For example, dairy pastures use more nitrogen, while sheep and beef rely more on phosphorous (Fertiliser Association, 2019). The nutrient quantity in digestate is defined by the feedstock properties and whether it has been processed. In most cases, it is reasonable to assume that digestate alone will not fulfil soil nutrient requirements. Furthermore, New Zealand's fertiliser demand is too high for digestate alone to meet. For these reasons, digestate should be considered as a solution to offsetting a portion New Zealand's synthetic fertiliser usage, not as a complete replacement. For example, digestate may be applied to soil and then dosed with synthetic fertiliser to meet the specific nutrient requirements for the soil and the application. In areas such as the Waikato, Canterbury, Southland and Taranaki regions, digestate application could be dosed with urea to meet higher nitrogen requirements.

Processing of digestate

Solid-liquid separation

The initial treatment of digestate comprises of dewatering, separating the solid and liquid phases of the whole digestate. This significantly reduces the cost of transportation and is the first step for the further processing of the solid and liquid phase. The most conventional methods for solid-liquid separation are the use of screw presses and centrifuges (Drosg et al., 2015).

Typically, wet state AD produces digestate with 3-15% TS and dry state AD produces up to 30% TS (Drosg et al., 2015). Upon solid-liquid separation, up to 90% of the digestate by volume comes out as the liquid fraction. The liquid fraction contains 2-6% dry matter and most of the soluble nitrogen and potassium content, which can then be applied directly to land or undergo further processing to enhance its concentration. The remaining solid fraction, which contains 20-30% TS, retains most of the phosphorous and can be easily stored or transported (Aso, 2019).

Complete nutrient recovery

Further processing of the solid and liquid fractions generates concentrated products. Drivers for complete processing include increased marketability, reduction in storage and transportation costs and compliance with environmental regulations (Aso, 2019).

Solid processing

The solid fraction from solid-liquid separation can be stored or directly applied as fertiliser. However, further microbial activity and odour emission can still occur. Further processing, via composting or drying, is therefore required to obtain a stable, concentrated and marketable fertiliser product from the solid fraction.

Liquid processing

Further treatment of the liquid fraction can be undertaken to enhance the concentration of the suspended and dissolved solids. Liquid processing technologies include membrane purification, evaporation, ammonia stripping, ion exchange and solar drying.

a. Membrane purification

Membrane purification is the only process that can allow direct discharge to receiving waters. Being the most of expensive and energy intensive of the processing options, it is more suited for the optimisation of large-scale processes (Drosg et al., 2015).

b. Evaporation

Evaporation of the liquid fraction requires excess heat from a biogas plant CHP unit. Fibrous material must be removed beforehand to avoid clogging the heat exchangers. The fertiliser concentrate obtained from evaporation can have a nitrogen concentration of 8,000 to 10,000 mg/kg, although this is very dependant the feedstock and liquid inflow concentration. There is the option to follow with reverse osmosis of the remaining liquid to allow direct discharge to receiving waters (Drosg et al., 2015).

c. Other liquid processing technology

Ammonia stripping, ion exchange and solar drying are other less common methods of concentrating digestate. Ammonia stripping has the advantage of producing a pure nitrogen product which can be used to enrich other digestate fractions to obtain a standardised nitrogen concentration (Drosg et al., 2015).

In summary, while whole digestate can be directly applied to land without the need for further processing, it is dilute with respect to nutrients which makes the relative costs of transportation high compared to synthetic fertiliser. Processing, therefore, is a necessary step for making digestate a marketable product. Large, centralised biogas plants could find processing to be economical. For smaller plants, it is likely more feasible to apply whole digestate directly to land because the costs associated with processing are too high.

A3.Feedstocks to Biogas Process

First, the hydrolysis stage is performed by acidogenic bacteria to break down long-chain proteins, carbohydrates, and lipids into their base constituents. Then, these same bacteria convert the small-chain compounds into volatile fatty acids or VFAs. Following this, acetogenic bacteria turn VFAs into acetic acid and hydrogen. Finally, the methanogenic bacteria take acetic acid, hydrogen and CO_2 and combine them to make what we call biogas (Gunnerson & Stuckey, 1986; United States Environmental Protection Agency, 2020).

Process Variables and Additives

d. Temperature

Firstly, temperature has a huge influence on the speed at which each step in the biogas process can progress. Generally, the methane producing bacteria can be labelled as either psychrophilic (10-20°C), mesophilic (20-40°C, or 30-38°C with the latter more common) or thermophilic (50-60°C). Higher temperatures lead to faster growth of bacteria and therefore mean faster and more effective conversion of organic waste to biogas per volume (Van et al., 2020). The biological reaction to produce biogas is exothermic in nature, so the reaction temperature is self-sustaining to some degree. Generally, external heat is still required to maintain heat lost to the external environment.

However, higher temperatures also create more sensitivity to temperature fluctuation. Methanogen bacteria are sensitive to deviations from their ideal operating temperatures, and swings can slow down or even entirely halt bacterial growth. Mesophilic bacterial growth can be disrupted by temperature swings as small as 2°C, and thermophilic bacteria are even more sensitive to thermal disruptions (Bekkering et al., 2010).

Additionally, the higher the operating temperature of the digester the higher the parasitic load resulting in increased gas production and the ability to maintain digester temperatures. Psychrophilic operations, while slow and inefficient, are the cheapest to design and run since little external heating and control is needed to keep the bacteria happy. This is why biogas installations on farms (where space for the effluent pond is not an issue) are generally not heated (Ministry of Agriculture & Forestry, 2008).

Choosing a design temperature for a reactor requires an assessment of capital impacts (both in terms of process complexity and reactor volumes) and operational impacts (chance of upsets and internal energy loads). Today, two thirds of large-scale anaerobic digestion plants operate under mesophilic conditions and one third operate under thermophilic conditions (Van et al., 2020).

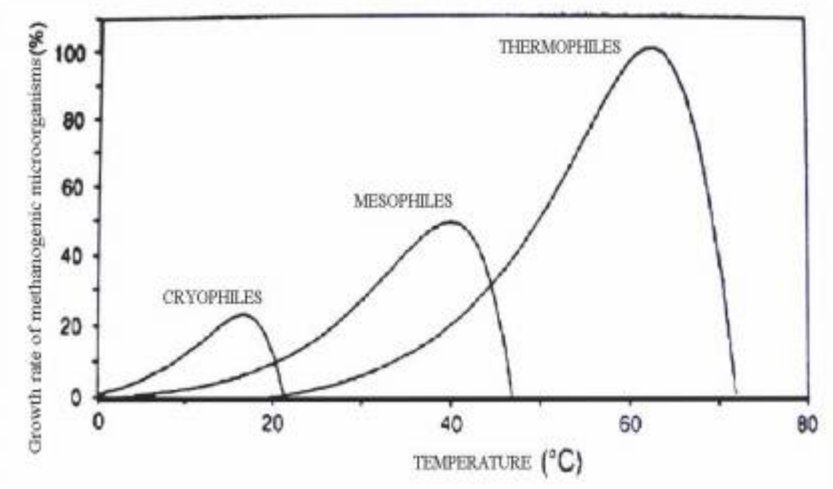


Figure 15: Effect of Temperature of Growth Rates of Methanogenic Organisms (Singh, Jain, and Singh 2017)

e. pH

Most microorganisms grow best in neutral pH conditions. Acidic or basic conditions can affect bacterial growth, either by altering chemical equilibria of reactions or by destroying enzymes (Ariunbaatar et al., 2014).

An intricacy of the anaerobic reactor system is that the pre-cursor reactions leading up to methane production themselves reduce the pH. As fatty acids and acetate are two of the key intermediary products on the route to biogas. The presence of carbon dioxide and bicarbonates can buffer pH changes, to an extent. If the buffering capacity is exceeded, the methanogens are the most affected performance-wise, which leads to even more acidic compound accumulation (Montgomery & Bochmann, 2014) and the biogas production can be severely affected. This means that the system may need external adjustment from time to time.

To control pH in a reactor, there are a few options pending digester design:

- If the feed material can experience pH swings, extra buffer capacity can allow acidic and basic inputs to cancel each other out and not upset the reactor pH balance
- In the case of acidic intermediate product build-up, adjusting or stopping the feed into the reactor can allow the methanogenic bacteria extra time to remove acidic compounds from the reactor and restore a neutral pH
- Finally, direct dosing of the reactor with chemicals to correct the pH can quickly restore the operating conditions in the digester

Controlling the pH of the reactor via buffering or chemical additives can have cost impacts (e.g. buffer tanks and the cost of ongoing chemical consumption), but at the same time having to pause reactor feeds frequently will impact reactor productivity and biogas yields.

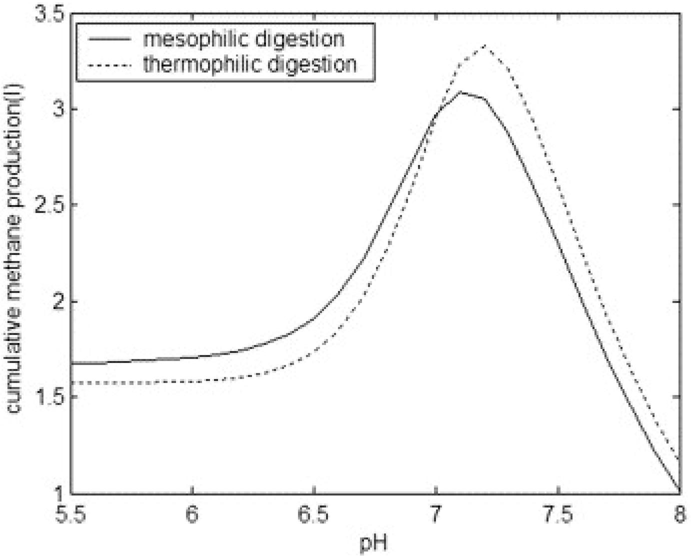


Figure 16: Effect of pH on Cumulative Methane Production (Liu et al. 2008)

f. Organic Loading Rate and Feedstock Control

With the Organic Loading Rate (OLR), it is important to understand what sort of organic materials are being referred to. Not all organic material can be decomposed in an anaerobic digester – materials with high amounts of lignin for example cannot be digested this way. The OLR for a digester system is a measure of the digestible material feed rate, or the feed rate of volatile solid materials. This is generally measured

indirectly by assessing the COD of the feed material. This quantifies the amount of readily oxidizable material in the material which can be used to predict biogas yields from the feedstock. Generally, systems are designed for a set OLR and it is not easy to implement process changes to boost this figure after an operating scheme has been selected.
A more thorough assessment of digestion suitability is a Biomethane Potential (BMP) test, conducted by digesting a small sample of the substrate in laboratory conditions (Biogas World, 2021a). These can be used in conjunction with COD values to assess the degradability of fresh feedstock materials and predict biogas yields.

Another important factor to note is the carbon to nitrogen (C/N) ratio of the incoming organic materials. High C/N ratios (e.g. manure and agricultural residues, around 25:1) mean good biogas yields from feeds, and lower C/N rations (human waste, around 6:1) mean reduced biogas yields. C/N ratios anywhere from 10:1 to 90:1 are acceptable (especially because not all of the organic material is digestible), but 30:1 is often considered optimal (Global Methane Initiative, 2016).

Phosphorous content is also important to monitor with Carbon and Nitrogen – Phosphorous supports cell health and growth (Ghafoori & Flynn, 2006).

Changes in the OLR can affect the balance of bacteria in the digester. A decrease in OLR can starve the bacteria of feed material and affect the balance of different cultures in the digester, where high OLRs can lead to the formation of toxic chemicals (as in the pH section, with an increased growth in acetogen bacteria) or cause by-product formation (Nsair et al., 2020).

The best way to minimize the potential impacts of changes in OLR is to use a consistent feedstock and level production of biogas as much as possible. However, this is not always possible when designing large-capacity systems requiring co-digestion or variable feedstocks e.g. food waste. Designing a reactor that is flexible and can cope with variances in OLR and COD over time means sacrificing potential efficiency and biogas yields but means there will be less operational upsets.

g. Nutrients

i. Sulfur

The concentration of sulfur, sulphates or H_2S in an anaerobic digester can greatly impact the production of biogas. There is a minimum level of sulfur compounds required for the reaction pathway from organic waste to biogas to proceed, but high concentrations of sulfur compounds in solution interfere with the methanogenesis stage of the reaction, preventing maximum conversion.
High levels of sulfur also lead to high levels of H_2S in the collected gas, which can be damaging to equipment designed to burn the gas and must be removed via processing (A. W. Khan & Trottier, 1978) and must be cleaned from the biogas. The conversion of a high sulfur feedstock to H_2S is the biologically-favoured reaction over the conversion to methane (A. W. Khan & Trottier, 1978). High levels of H_2S can pose a risk to the health and safety of operators and workers in the digester plant, as it is acutely toxic .

That being said, sulfur can also help the digester stay healthy by precipitating out harmful heavy metals, which can inhibit reactions and kill bacteria.
Understanding how much sulfur the feedstock needs based on optimum methanogenesis conditions and heavy metal presence is essential for optimal gas production, and then adjusting the level via pretreatment or sulphate dosing to a level that will promote maximum biogas yield.

ii. Ammonia

Ammonia is a naturally-occurring by-product of digestion of high-protein feedstocks. Optimum ammonia levels can keep the reaction chain stable and buffer the methanogenic stage of the reaction. The presence of too much ammonia however, especially at pH below 7, can be toxic to bacteria (Gunnerson & Stuckey, 1986). Ammonia can be the primary source of nitrogen for digester health.

As with sulfur, feedstocks that will create high ammonia concentrations can be assessed and steps can be taken to limit excess ammonia production e.g. mixing or buffering with other feedstocks, and ammonia concentrations can be assessed during reactor operation to enable intervention if necessary.

iii. Siloxanes

Siloxanes are formed via the breakdown of silicon compounds in landfills and WWTP sludges. Siloxanes can cause deposits on pipework and equipment which affect the operation of equipment and need to be removed (Nyamukamba et al., 2020).

Type of Feedstock Available

Different kinds of feedstocks for anaerobic digestion plants can have a wide range of physical and chemical properties (Bremont et al., 2020). The important properties to understand from the outset, and that ultimately determine the process configuration are:

- COD or volatile solids %; how much digestible matter is there present in this feedstock?
- Total solids content; is the digestible matter in solid form or in solution?

As an example, industrial effluent usually has a moderate COD or concentration of volatile organic material, but a very low TS. At the other end of the scale, energy crops have very high COD and are largely solid (Blanco-Canqui, 2016). These feedstocks will have to be processed very differently.

There is also the question of co-digestion and how you balance mixed feedstocks. Many biogas installations find success in combining a large, low biogas-yield stream (e.g. animal manure) with a small stream of high biogas-yielding feedstock (e.g. energy crops), leading to improved performance (J. H. Thiele, 2010). Sometimes it does not make sense to compromise the performance of a digester or to spend extra effort processing an additional feed material to combine streams, but it is very situational.

As well as the above, there are a wide range of other factors that affect how suitable the feedstock will be for digestion. In the next section we will review some of the most important properties to manage, and different methods of making feedstocks digestible.

Pre-Treatment Methods for Feedstocks

h. Mechanical Pre-Treatment

Generally, the first stage of feedstock pre-treatment will be physically screening the feedstock for non-organics or impurities and then physical re-sizing of solid feedstocks. This step serves multiple purposes; it is effective for removing inorganic materials from streams (within a certain size band) and it decreases the size of individual organic waste particulates which improves mixing and flow properties of the slurry and increases surface area of the feedstock (Pilli et al., 2020).

For a plant processing food waste or energy crops, physical screening is extremely important to remove any waste incorrectly disposed of e.g. plastics/other non-food waste from bin collections, or items mistakenly harvested with crops e.g. stones. This can be done with static screens or rotary drums, depending on the feedstock.

Physical re-sizing is generally done with either mills, screens or a mixture of both. Food waste slurries are normally screened using screens to remove inclusions larger than 2-5 mm in size. Energy crops, if not supplied pre-shredded, are then cut, shredded, or milled to break them down into a form that can be mixed into a slurry.

After the feedstocks are able to be pumped and/or mixed successfully, they can be further refined for better acceptance into the digester.

i. Optimising Feedstocks for Digestion – Thermal, Electrical or Chemical Pre-Treatment

The main objective of pre-treating the feedstock prior to digestion is to make it easier to process into methane by the bacterial cultures inside the reactors. To this end, there are many ways to alter the properties of the feedstock and prepare the organic material for digestion, including:

- Thermal
- Chemical/Biological, or
- Electrical.

Pretreatments discussed in this section are employed to increase methane yields, shorten retention times, and reduce post-treatment of digestate materials. As these processes can support the hydrolysis stage in the digestor, reducing longer chain polymers to simpler monomers ready for conversion.

In some cases, a combination of pretreatment operations may be employed to optimize biogas yields e.g. thermo-chemical pretreatment.

i. Thermal Pre-treatment

In feedstocks that contain organic waste 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 (Kamali et al., 2016).

This can be accomplished multiple ways:

- Feedstocks can be heated or mixed with hot water to increase enzyme activity and allow easier digestion. This is only effective for some feedstocks (Gunnerson & Stuckey, 1986).
- Feedstocks can also be heated to high temperature under pressure and then exposed to low pressure, which causes rapid boiling of the water in the organic material and cavitation/rupturing of cells. This technique is sometimes referred to as ‘steam explosion treatment’ and is sometimes used in conjunction with pasteurization (Esposito et al., 2011).
- Feedstocks can be extruded through orifices with screws, which shears the material at high pressure and high temperature. This method cannot be used for feedstocks where stones or hard materials may damage the mechanical components (Pilli et al., 2020).

ii. Chemical or Biological Pre-treatment

If there are reasons why heat and/or pressure cannot effectively alter the properties of the feedstocks, chemical or biological pre-treatment may be a suitable alternative. Similar to other kinds of pre-treatment processes, the goal is to use chemical reagents to break up cellular structures and reduce the downstream work for the anaerobic digester (Xu et al., 2014).

Chemical Pretreatments usually consist of addition of either an acid or an alkali to break down organic components in the feedstock. Operators must be careful of how pH is then adjusted before the feedstocks are added into the digester, as residual chemicals may upset the bacterial cultures in the anaerobic system. In addition, dosing chemicals is another operational cost to consider in the economics of the plant (Srisowmeya et al., 2020).

Biological pre-treatments can accomplish a similar function as chemical pre-treatment by employing bacterial cultures different to the bacteria used in the anaerobic digestion process, or enzymes, to perform the same work. Some plants compost or aerobically digest feedstocks to ease the initial stages of digestion before adding organic waste to the anaerobic system. Enzyme application is also effective but can be prohibitively expensive (Ariunbaatar et al., 2014).

iii. Electrical Pre-treatment

New-generation pretreatment technologies continue to be developed as operators look for more energy-efficient and non-invasive ways to prepare feedstocks for optimal digestion. Advanced treatments include microwave treatment (where feedstocks are exposed to microwave radiation) or ultrasound (where feedstocks are exposed to high-frequency vibrations) are not widespread but may feature more prominently in future biogas installations as the technology matures (Achinas et al., 2017).

j. Pasteurisation

Especially in feedstocks with high organic content, it is very likely that organic materials will pick up their own bacteria and other potentially harmful biological material on their way to a digestion facility. Because the conditions in the anaerobic digesters are designed to encourage bacterial growth and maximise proliferation of bacteria etc., it is vital to remove any possible biological contaminants from feedstocks before passing them into a digester (Swedish Gas Centre, 2012).

Pasteurisation of a feedstock 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).
As digestion plants commonly process multiple tons of material in a day, this process consumes large amounts of energy per batch and is one of the largest heat loads on the digestion system along with maintaining digester temperature. However, the risk of not pasteurizing a batch properly leading to a digester failure is significant, so this process should not be skipped if the feedstock carries the risk of contaminants.

Some WWTPs in the UK combine pasteurization and thermal pre-treatment stages to both sterilize solids and also prepare the feedstocks for digestion (SAMCO, 2019).

Animal manure sources used for local, small-scale biogas production are generally not pasteurized or pre-treated, as an exception.

Digestion Processes

k. Dry and Wet AD Technologies

Feedstocks into a digestion process are usually a two-phase mixture of solid organic waste and a fluid containing dissolved COD. Depending on the proportion of solid to liquid material, the mixture can either be processed like a wet solid, a slurry or (more or less) as a liquid stream.

Dry digestion (where TS% >20) can either occur in plug flow systems where solids are continually pushed through a reactor body and digested, or in batch-type reactors where piles of organic material are deposited in a sealed bunker and left to decompose.

Generally, dry digestion is much more labour-intensive than wet digestion as the feedstocks cannot be pumped and must be moved/sorted manually for example by front end loader.

Wet digestion can be separated into two categories; suspended solid digestion (where 15% > TS >5%) or hydraulic digestion (<5%). Suspended solids digestion, where bacteria are mixed into the organic slurry, is common for wastewater treatment sludge and food waste where there is a lot of suspended organic matter. Hydraulic digestion, where bacteria are attached to a medium, is used for predominantly liquid organics streams like industrial wastewater.

Wet digestion involves a much higher amount of fluid entering and leaving the digester, which can be a constraint if the plant is not near a ready supply of fresh water or cannot properly filter and dry digested organic material, especially if the feedstock is dry to start with. However, the feedstock can be processed and treated like a liquid which allows for more autonomous control and processing.

Of the total installed capacity of biogas plants in Europe, 62% is from dry-type digesters (Van et al., 2020).

l. Batch vs Continuous

In all applications where the feedstock is low in solids content (TS <15%), the digestion process is usually continuous. Suspended organic matter is circulated and mixed with bacteria to achieve a more-or-less homogenous solution, and as biogas is generated additional feed is added.

In high solids feedstocks (TS >30%), a batch process can be used as a low-CAPEX alternative to a fully mixed reactor system or plug flow reactor. While a continuous reactor has a continual supply of organic material into a reactor and biogas/digestate is continually harvested from the reactor, a batch system fully processes a fixed amount of organic waste into biogas and digestate with no other additives or external inputs (except heating). Batch processes must be initialized with a sample of bacteria from a completed batch, while a continuous process always maintains a level of the required bacteria (Rocamora et al., 2020). Batch reactors are popular for energy crop or municipal source segregated food waste feedstocks, and they are easy to construct and operate. However, they do require more space so are most popular in rural areas.

In a batch process, the four stages of methane generation must occur in series in contrast to a continuous system where all four stages are proceeding in parallel. This means that the methane production is variable, and buffering/storage will have to be allowed for. A way around this is to design a plant where multiple batch processes are happening at once and the variable flows can be averaged out.

Of the total installed capacity of biogas plants in Europe, 76% is from continuous digesters (Van et al., 2020).

m. Thermophilic vs Mesophilic

Thermophilic digesters have become more popular in large-scale digestion installations in recent years, as researchers have observed large increases in achievable OLRs with increases in reactor operating temperatures. Thermophilic digesters can produce much larger yields of biogas and process more organic material than mesophilic digesters with similar volumes (Bekkering et al., 2010).

The downside of thermophilic digestion is that the process requires more energy to maintain the higher digester temperature, which creates a larger parasitic load on energy produced from biogas production. Thermophilic digesters are also more susceptible to temperature swing upsets than mesophilic digesters (Mckendry, 2018).

In short, thermophilic digestion is the most efficient digestion mechanism but it requires more energy and tighter control than mesophilic digestion, so is not suitable for smaller installations where the main function of the plant is dealing with organic wastes. The only way thermophilic digestion becomes economic is with scale of digestion, a guaranteed market/buyer for the biogas and when available land for the digestion plant is at a premium.

Of the total installed capacity of biogas plants in Europe, 33% is produced in thermophilic digesters.

n. Single Stage vs Multi-Stage

As discussed previously, there are four different biological stages in the conversion from organic material to biogas, undertaken by three different types of bacteria. Each of these bacteria are unique; they operate best under different conditions and respond to changes in their environment in different ways. The first and last stages in particular, hydrolysis and methanogenesis, have the smallest overlap in efficient environmental conditions (Van et al., 2020).

In large biogas processing installations, the digestion process can be broken down into multiple unit operations i.e. there are multiple digestion stages for the feedstock. Commonly, the hydrolysis and acidogenesis stages are separated from the acetogenesis and methanogenesis stages. This allows each 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.

Multiple stage digestion has not been popular for most of utility-scale anaerobic digestion's history as it does require more upfront costs and smarter plant control to operate efficiently. In recent years, a larger proportion of multiple stage systems are being constructed, but only 7% of European installed biogas capacity is multiple stage (Van et al., 2020).

A4.Choosing a Biogas Processing Operation for your Feedstock

Properties of Standard Feedstock Supplies

The five primary feedstocks we have analysed in this report have quite different properties and must be digested differently in order to achieve the best biogas yield for dollar spent on digester construction and operation.

Considering the variables discussed previously, here is a brief overview of each target feedstock with respect to digester selection.

a. Wastewater Treatment Sludge

Due to the degree of pre-processing wastewater treatment sludge receives before it is ready for an anaerobic digester, the properties of this feedstock are reasonably consistent for a given WWTP (Bachmann, 2015). Depending on the presence of large individual contributors to individual wastewater treatment systems e.g. a meatworks or dairy plant connected to the municipal wastewater system, there may be specific deviations from standard sludge properties for a given plant. However, it is likely the sludge from a single treatment plant will be consistent throughout the year.

- Variation in volume of feedstock available (or seasonality): Low variation
- Feedstock COD or volatile solids %: 70-80%
- Total Solids %: 15%
- Expected pH: Neutral
- Any required pre-treatment: Pasteurisation and possibly additional thermal pre-treatment
- Presence of sulphur, nitrogen, phosphorous, ammonia: Generally suitable
- Other contaminants: Siloxanes from wastewater (Li et al., 2019)

b. Animal Manure

The properties of animal manure are fairly consistent, depending on the diet of the animals in question. Cow manure is the least complicated manure source to digest, as manure from chickens and pigs can contain high levels of chemical contaminants that must be removed from the biogas, requiring additional processing (Sørensen et al., 2019).

- Variation in volume of feedstock available (or seasonality): Consistent throughout the year
- Feedstock COD or volatile solids %: 75-85%
- Total Solids %: 10-20%
- Expected pH: Neutral to mildly acidic
- Any required pre-treatment: N/A
- Presence of sulphur, nitrogen, phosphorous, ammonia: Higher presence of ammonia and sulphates in chicken/pig manure (Risberg et al., 2017)

c. Source-Segregated Food Waste

In a large enough collection, properties of the combined feedstock are fairly consistent from day to day. The biggest challenge in source-segregated food waste is changes in the composition of the feedstock with seasonal variations in available produce. If the plant accepts commercial and industrial food waste as well as municipal food waste, there may be the occasional large delivery of a single food source which could affect the consistency of material into the digester.

- Variation in volume of feedstock available (or seasonality): Constitution seasonal, volumes consistent
- Feedstock COD or volatile solids %: 85-90%
- Total Solids %: 15-20%
- Expected pH: Neutral to mildly acidic

- Any required pre-treatment: Screening and pasteurisation
- Presence of sulphur, nitrogen, phosphorous, ammonia: Generally suitable

d. Crop Silage

Different types of crops have different properties in terms of biogas yield and ease of digestion. Crop silage from a single crop source is relatively consistent in terms of feedstock properties, but the amounts of total feedstock available in a given month are highly variable. During harvest seasons, large quantities of feedstock are collected and ready for digestion. During non-harvest seasons, minimal material is available. To this end, it is best to either design a modular digester or to incorporate the crop material as a secondary feed material into digester primarily fed by another feedstock (Möller & Müller, 2012)(Blanco-Canqui, 2016).

- Variation in volume of feedstock available (or seasonality): Highly seasonal for singular crop sources.
- Feedstock COD or volatile solids %: 85-95%
- Total Solids %: 30-60%
- Expected pH: Neutral
- Any required pre-treatment: Screening and mechanical processing
- Presence of sulphur, nitrogen, phosphorous, ammonia: Generally suitable

e. Industrial Wastewater

There are two main challenges with processing industrial wastewater: the presence of highly acidic or highly basic wastewater streams e.g. caustic from CIP, and the variation/seasonality of wastewater based on variation/seasonality of the corresponding industrial process. Each industrial wastewater digestion plant will have to be reasonably bespoke depending on the quality and quantity of wastewater produced (Clarke, 2019).

- Variation in volume of feedstock available (or seasonality): Highly variable; depending on process highly seasonal also
- Feedstock COD or volatile solids %: Highly variable
- Total Solids %: <5%
- Expected pH: Highly variable
- Any required pre-treatment: Generally none
- Presence of sulphur, nitrogen, phosphorous, ammonia: Highly variable depending on process

Best Digester Configurations for Standard Feedstock Supplies

Based on our assessments of the feedstocks above, the best-fit standardised processing configuration for all sources above in different quantities is detailed in Table 34.

Table 34: Standard Digester Technology/Configuration by Feedstock Source Type and Volume

Feedstock	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

Feedstock	Small (<5,000 t/year)	Medium (<25,000 t/year)	Large (>30,000 t/year)
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
Industrial Wastewater[2]	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

a. Farm-scale Anaerobic Lagoon or PFR Digesters

For small-scale manure collections on farms, the best solution is usually a covered lagoon digester or a plug flow digester, depending on the water content of the feedstock source. Both of these systems are low capital i.e. require minimal capital investment and have little upkeep costs. The gas generated by these small systems can be scrubbed and compressed for use in heating or power generation or used as a vehicle fuel. This type of system is recommended for small-scale, isolated sources of manure only.

b. Small Dry Batch Digesters

In small-scale feedstocks with high TS percentages (>30%), dry batch digestion can be a cost-effective way to process organic waste materials without having to worry about tight process controls or screening/pre-processing feedstocks. After a batch of material is inoculated with bacteria, it is sealed in an airtight cell and left to decompose, releasing biogas.
This method of digestion is modular and requires little intervention but is more manual and biogas output is less stable than a continuous process. Because these systems can be designed to be small and modular, it is possible to install them in a variety of locations which can enable the biogas produced to be used in many applications.

c. Multiple Dry Batch Digesters

If given feedstocks are too dry for Fully-Mixed digesters and there is not a readily available source of water for dilution, then a modular dry batch digestion system may be a good alternative. By running multiple dry digestion cells in parallel, it is possible to treat more feedstock effectively than a single cell digester and the combined production of multiple cells evens out variable biogas production seen in single cell systems.
This requires a larger plant than a Fully-Mixed-type system as digestion times are generally longer, and more space is required for manual materials handling. There are many examples of successful dry multi-reactor systems overseas producing biogas and processing the gas into biomethane (Rocamora et al., 2020). At this scale, the dry batch reactor will often include a percolation loop which helps mix and recirculate liquid material in the feed and improve the rate of digestion.

d. Single-stage Fully Mixed Digesters

Single-stage fully-mixed digesters are by far the most popular processing arrangement for medium-sized sources of organic material with a TS percentage between 10 and 20%. It can also be used to process drier feedstocks like crop silage, but these require addition of water or waste oils first.
At the scale where this technology is employed overseas, mechanical pre-treatment and pasteurisation become economically feasible but the volumes do not support multi-stage digestion (Van et al., 2020). Continuous wet processes like single-stage Fully-Mixed digesters require active process control like heating, gas monitoring, mixing, feedstock screening and buffering as well as gas storage and scrubbing.

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[2] 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.

These systems generally require a centralised collection of feedstock, and at this scale extra investment in biogas upgrading or biomethane processing equipment becomes viable as observed overseas.

e. Multiple Stage Fully Mixed Digesters

At larger scales, the merits of multiple stage digestion plants start to stack up; faster digestion enabled by staged digestion units allow faster processing of equivalent feedstock volumes than single-stage processes which decreases vessel sizing and overall capital/operational costs.
Large multi-stage fully mixed reactors are still relatively new due to the required automation and tighter process controls required, but they are now the process arrangement of choice for large quantities of wet feedstocks.

f. Single Stage High-Rate Hydraulic Digesters

Small-scale low TS% digesters are becoming more and more advanced in recent years, with the smallest available digester units approaching 1 m^3 in size. The key operating principle of these kinds of reactors is separating and processing solid and liquid components at different rates to allow maximum biogas yields.
For low solids feedstocks, reactors that separately circulate liquid and solid feed components deliver the best overall COD reduction and produce the most biogas. There are many different kinds of liquid digester e.g. UASB (Upflow anaerobic sludge blanket) , EGSB,(expanded granular sludge blanket) or AF (Anaerobic filter)reactors, and the best choice is generally driven by the qualities of the feedstock as well as appetite for operational complexity (Clarke, 2019). Each design requires seeding by active granular activated sludges, a limitation to uptake in New Zealand is availability to sludge.
Depending on the site, a small to medium-sized wastewater digestion unit will usually be used to supplement heat energy used onsite, either dosed into boiler natural gas feeds etc. or to generate small amounts of heat or electricity for specific equipment.

Hydraulic reactors require seeding at commissioning to establish a working bacteria population.

g. Multiple Stage High-Rate Hydraulic Digesters

Similarly to single- vs multi-stage Fully-Mixed digesters, higher efficiencies of conversion and optimisation of individual conversion stages can become viable as required single reactor sizes increase.
Depending on the site in question and its own energy needs there may be a demand for the biogas produced onsite, or biomethane production may be a better use of the gas. A primary example of a high rate hydraulic system is seen in the IC (internal circulation) design which separates out the pre-acidification stage in increase methanogen performance and contact time.

h. Large-Scale Anaerobic Lagoons

In the case where a low solids waste stream like dairy runoff from a large farming complex or a large quantity of industrial effluent is produced in an area with lots of space, or if this waste is currently directed to a holding pool/lagoon-type treatment system, an alternative to high-rate hydraulic digesters could be an anaerobic lagoon system. These digestion systems require little-to-no interaction and are cheap to install (especially if the lagoon already exists). Retention times are much higher for this type of system, from 20 to up to 150 days (Moser et al., 2008). This is the current system utilised at the Fonterra Tirau plant discussed previously.

Capital Costs for Standard Digester Types

The main factors that affect the differences in capital costs for digester construction are:

- Size of the digester. This is determined by the type of digester and the specific operating conditions
- Required pre-treatment equipment. This is determined by the physical properties of the incoming feedstock
- Feedstock storage and handling. This is determined by the logistics and collection of feedstock supplies.

The most inexpensive plants in terms of capital investment per tonnage of waste processed are dry, single-stage mesophilic digesters. While waste handling and processing are a bit more manual than other options and production is a bit more variable than other installations, the simplicity and robustness of these plants make them attractive to small-scale generators.

Capital costs increase when moving to wet/continuous digestion as processing becomes more automated and feedstocks require dilution/mixing as well as more active control. These plants require more instrumentation as levels/temperatures and flowrates need to be monitored and managed. The payoff is in levelling out production, and reducing manual handling (Hengeveld et al., 2020).

Depending on the feedstock, pretreatments can become energy-intensive and require expensive equipment. Chemical additives or buffering tanks, heat exchangers and boilers for pasteurizing and de-naturing feedstocks etc. increase operational expenses and affect the proportion of biogas able to be sold rather than used. However, they can improve the processability of feedstocks and can increase yields to provide additional revenue in operation.

Moving to multi-stage or thermophilic systems increases capital costs again as the process becomes more automated and more energy-intensive. The biogas yields and organic loading rates of these plants are miles above what can be achieved in small-scale dry digestion systems, but only large-scale commercial generators with large sources of organic waste to process can finance these kinds of projects (Mckendry, 2018).

a. Single-stage Fully Mixed Digesters

Small-to-medium sized Fully-Mixed digesters for manure processing or food waste digestion are more expensive per unit of feed processed or gas produced than larger installations. At the lower ends of size for economic grid connection based on overseas case studies, digestion facilities can cost between $35,000 - $45,000 NZD per Nm^3/hr installed biogas generation capacity, or between $500 - $800 NZD per tonne of feed material processed per year (Moriarty, 2013; Truong et al., 2019). If plants are designed to receive material with higher upfront pre-treatment requirements e.g. energy crops, then investment costs can increase by 20% (Cleanleap, 2013).

At the lower end of the size scale for biogas plants, costs for digestion plant installation can vary significantly. Depending on the specificities of the feedstock and possible variations in incoming feed material, biogas plants may need to be designed to be more flexible and therefore more complex than some larger installations (Truong et al., 2019).

b. Multiple Dry Batch Digesters

As an alternative to Fully Mixed digesters for feedstocks with high solids content, multiple cell dry digester units can be used but these are generally more expensive to build than fully mixed liquid reactors, with the majority of capital expenditure going towards concrete structures for the sealed cells (Biogas World, 2021b). Case studies for medium-sized food waste or manure digestion plants show costs of between $35,000 - $65,000 NZD per Nm^3/hr installed biogas generation capacity (Spencer, 2010). The largest dry digestion facility in the world in San Jose processes 90,000 t of feed material and produces electricity and compost as valuable products.

c. Multiple Stage Fully Mixed Digesters

Overseas case studies of this technology suggest that as biogas plants increase in size their cost per capacity begins to decrease. Digesters producing between 500 and 1000Nm^3/hr of biogas can cost between $25,000 - $30,000 NZD per Nm^3/hr capacity. At higher capacities, this cost can decrease to below $20,000 NZD per Nm^3/hr biogas generation capacity (Truong et al., 2019). At larger sizes, economies of scale can drive down the costs per unit capacity and having a larger feedstock supply with buffering capacity means that the plant can afford to be less specialised (Mckendry, 2018).

Based on the capacity of the upcoming Reporoa biogas plant (75,000 t/year of source-segregated food waste) this plant would expect to produce close to 2,000 Nm^3/hour. With an expected price tag of $30 million NZD, this plant is being constructed for around $15,000 NZD per Nm^3/hr biogas generation capacity, or $400 NZD/tonne of feed material processed per year (Sherrard, 2020). This lines up with observations from overseas installations, and provides confidence that these projects can still be completed in New Zealand for equivalent costs.

d. High-Rate Hydraulic Digesters

Based on estimates from vendors, at grid-scale these types of reactors can be installed for around $27,000 per Nm^3/hr capacity (SAMCO, 2019). These digesters are less expensive that other types of digesters discussed in this section on a biogas production capacity basis – this is primarily due to the shorter required retention times and therefore smaller reactors. However, the initial cost to seed the digester could be significant.

A5.Biogas to Biomethane Processing

Biogas produced from the breakdown of organic materials will contain a variety of components that can be beneficial or detrimental to further uses. Raw biogas will typically contain methane (CH_4) concentrations greater than 50 mol%, with the remainder being comprised mostly of carbon dioxide (CO_2). The CH_4 and CO_2 content of raw biogas can be considered as potential value streams for biogas upgrading schemes.

Table 35: Methane and carbon dioxide content (% by volume) of landfill gas and biogas from anaerobic digestion

Component	**Landfill Gas** (Nyamukamba et al., 2020; Sun et al., 2015)	**Biogas from AD** **% by volume at standard conditions** (Al Seadi et al., 2008; Nyamukamba et al., 2020; Sun et al., 2015)
Methane	30-60 mol%	50-75 mol%
Carbon dioxide	15-40 mol%	25-45 mol%

For biogas to be utilised as fuel in reticulated natural gas networks, the CV requires upgrading to meet the appropriate gas specification. In New Zealand, all reticulated natural gas is required to meet constituent and Wobbe specifications according to NZS 5442-2008. Further details of the requirements of NZS 5442 and their influence connecting a biomethane production plant to a reticulated network are outlined in Section 5.4 of this report.

There are three steps when upgrading biogas to biomethane and exporting:

- Pre-treatment (cleaning)
- Biogas to biomethane processing (upgrading)
- Network injection

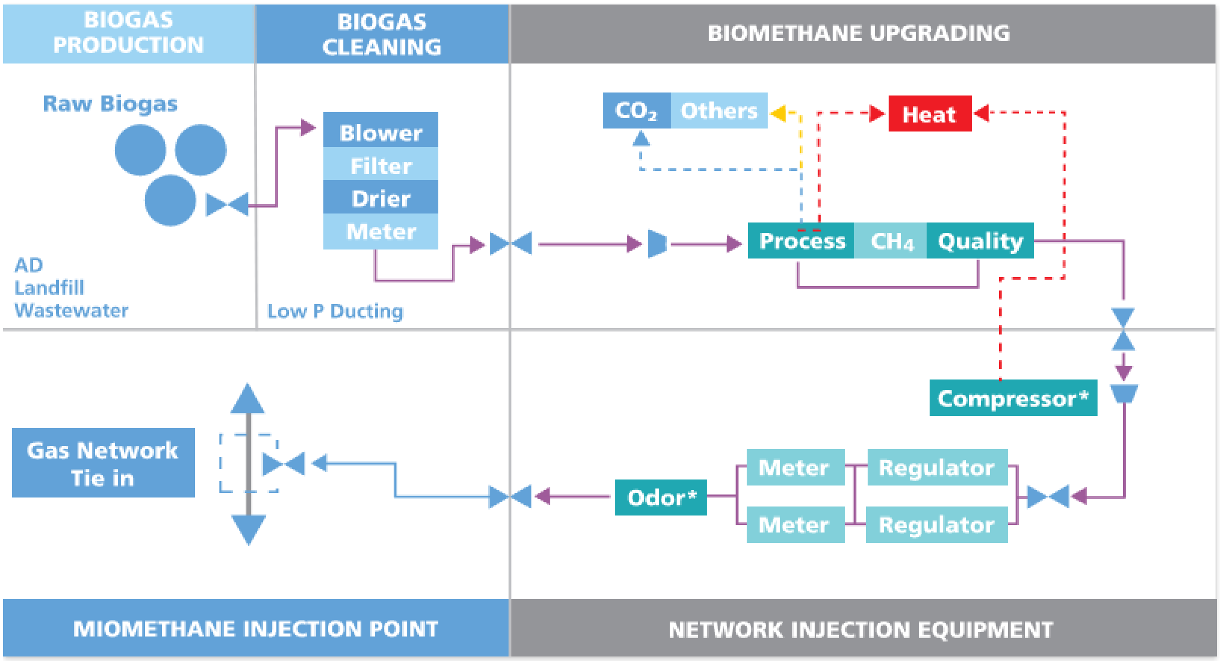

Figure 17: Typical biomethane upgrading process

Depending on the type of feedstock the biogas is produced from, there can be smaller concentrations of components such as sulphur (S), hydrogen sulphide (H_2S), silicon organic compounds (siloxanes), oxygen (O_2), water (H_2O), ammonia (NH_3), Nitrogen (N_2) and particulates that are viewed as contaminants to the raw biogas (Sun et al., 2015b), outlined in Table 36. The actual concentration of these contaminants varies depending on the feedstock quality but are typically viewed as detrimental to downstream equipment.

Table 36: Contaminants in raw landfill gas, biogas from AD, and limits for reticulated gas in NZ

Contaminant	Landfill Gas % by volume at standard conditions	Biogas from AD % by volume at standard conditions	Reticulated NG % by volume at standard conditions
Nitrogen – atmospheric N_2 is introduced during AD feeding or landfill gas extraction	0-15 mol%	0-1 mol%	Not specified
Water vapour – AD process is saturated & reactor temps are typically higher than ambient	1-5 mol%[1]	1-5 mol%[1]	<0.00001 mol%[2]
Oxygen – atmospheric O2 is introduced during AD feeding, H_2S control or landfill gas extraction	<2 mol%	<2 mol%	<1% (low and medium pressure grids) <0.1% (all other cases)
Ammonia – AD treatment of feedstocks with high levels of nitrogen	0-5 mg/m^3	0-100 mg/m^3	Not specified
Siloxanes – caused by the digestion of silicone compounds in landfills or WWTP sludge	0-50 mg/m^3	0-20 mg/m^3 (WWTP sludge can produce high levels of Siloxanes)	Not specified
Hydrogen sulphide – caused by the digestion of sulfide/protein containing feedstocks	100-10,000 mg/m^3	0-1000 mg/m^3	<5 mg/m^3
Hydrogen – from the digestion of sugars & VFA's	0-3 mol%	<1 mol%	<0.1 mol%
Total Cl	0-100 mg/m^3	0-100 mg/m^3	<25 mg/m^3
Volatile Organic Compounds – typically found in landfill gases	<2000 mg/m3	-	Not Specified
Source	(ATSDR, 2001; Nyamukamba et al., 2020; Sun et al., 2015(Soleilhavoup & DESOTEC, 2020))	(Al Seadi et al., 2008; Nyamukamba et al., 2020; Sun et al., 2015)	(Standards New Zealand, 2008)

[1]Temperature dependent

[2]At standard conditions

Sulphur, H_2S and NH_3 pose a risk to human health and a risk of corrosion to downstream equipment. Siloxanes also pose a human health risk and can foul combustion equipment (Nyamukamba et al., 2020a). The water content of raw biogas is dependent on bulk properties i.e. temperature and pressure, but will typically be saturated at the outlet of any anaerobic process. The moisture content will condense in pipework and equipment and cause corrosion and related issues if the condensate is not managed and/or the gas dehumidified. Due to the inert nature of nitrogen gas any concentration will negatively affect the calorific value of the biogas (Angelidaki et al., 2018).

The acceptable levels of the components within the gas stream are determined by the end use of the biogas. Combined heat and power equipment can accept biogas with higher levels of contaminants than reticulated gas end uses (Sun et al., 2015b). Both end uses will require some degree of pre-treatment to remove quantities of moisture, dust, oil and aerosols in the raw biogas prior to or as part of biomethane upgrading. Acceptable levels of H_2S for different end uses is outlined in Table 37.

Table 37: Acceptable levels of H_2S by end-use

End Use	H_2S limit (ppm)
Gas heating boilers	<1000
Combined heat and power (CHP)	<1000
Fuel Cells	<1
NZ Reticulated Natural Gas	<4

References

1. (Choudhury et al., 2019)

2. (NZS 5442-2008)

Pre-Treatment

The pressure of raw biogas from an anaerobic digester is typically less than 10 mbarg and requires a blower close to the source to allow transport to the pre-treatment drier and filter (Lemmer et al., 2017). Raw biogas leaving the source can be metered & sampled to help determine performance of the biogas production facility. Blower operation on AD production must be controlled to ensure a vacuum is not created within the production process. There have been digestion systems designed to operate as much higher pressure, but this is uncommon at scale (Zhao et al., 2020).
In contrast, blowers used for extraction of landfill gas create a small vacuum to pull gases out of the gathering system (US EPA, 2000).

Once the raw biogas has left the blower the water content is removed by either condensation drying using cooling, adsorption / desiccant drying, or the relative humidity is reduced by a further increase in pressure. Levels of ammonia are also removed during drying. Solid particulates and dusts are filtered using mechanical filters.

Oxygen and nitrogen are typically not present in high concentrations in biogas produced from AD, however, landfill gas can have elevated levels due to air entrainment. O_2 and N_2 are not detrimental to combustion, however, removal for reticulated gas is typically handled during the upgrading process.

H_2S can be precipitated to sulphur within the digester using iron ions and processed with the spent digestate. Depending on concentration at the digester outlet, H_2S can be removed by adsorption on activated carbon filters, scrubbed using water/amines or chemical absorption media such as iron oxides or sodium hydroxides. (Petersson & Wellinger, 2009). If residual H_2S concentrations remain in the separated gas stream post-upgrading; thermal oxidation, activated carbon adsorption or bio-trickling filters can be used to neutralise the H_2S, and thus make it safe, prior to collection/utilisation or discharge to atmosphere of the separated gas stream. Activated carbon filters also serve to remove siloxanes that are common in gas produced from landfill and WWTP (Nyamukamba et al., 2020b).

The level of pre-treatment will depend on the upgrading equipment requirements as some contaminants can damage processing elements. Most types of upgrading equipment can be used for biogas from all types of feedstocks, providing adequate pre-treatment and cleaning equipment is included as part of the design (Al Seadi et al., 2008). A summary of different pre-treatment options for contaminants is included in Table 38.

Table 38: Pre-treatment Summary . (Sun et al., 2015a)

Impurity	Technology	Outlet levels	Comment
H_2S	Biological desulphurisation	< 50 ppm	Most common
	Iron Chloride	100 - 150 ppm	Used for high quantities
	Impregnated Activated Carbon	< 0.1 ppm	Common prior to PSA
	Iron Hydroxide or oxide	< 1 ppm	Finite regeneration cycles
	Sodium hydroxide Scrubbing	< 1 ppm	Regeneration of reagent not possible
Siloxanes	Activated carbon	< 0.87 ppm	Carbon unable to regenerate. Sensitive to humidity
	Cooling	26% - 99% removal	-27°C to -70°C
O_2/N_2	Activated carbon		
	Molecular sieves		
	Membranes		
H_2O	Adsorption with Silica Gel or Aluminium Oxide	Dew Point -10°C to -20°C	at atmospheric pressure
	Absorption with Triethylene glycol or glycol	Dew Point -5°C to -15°C	at atmospheric pressure, Regeneration required to 200°C

Biogas to Biomethane Processing / Upgrading

This report focuses on the commercial processing technologies used to upgrade raw biogas to biomethane:

- Pressure Swing Adsorption (PSA)
- Water Scrubbing
- Physical Scrubbing – Organic Solvents such as ‘Selexol’
- Chemical Scrubbing
- Membrane Separation

There are other methods to process impurities from biogas such as cryogenic separation, in-situ removal, biological methods and hydrate separation that have yet to be made readily available to the commercial market (Angelidaki et al., 2018). 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 available.

Biological hydrogen methanation (BHM) holds the most potential out of the pre-commercial methods and allows for easy integration with any future green hydrogen economy. The method is to inject hydrogen into the anaerobic digestion process to provide the conditions for the ‘Sabatier’ reaction to be biologically catalysed by the specific archaea of Methanothermobacter at elevated reactor temperatures (~60˚C). The

Sabatier reaction yields methane from hydrogen and carbon dioxide and is endothermic. Deployed at scale this process can increase methane output from typical anaerobic digestion processes by 70% thereby reducing, and in some cases eliminating, the requirement for physiochemical biogas upgrading prior to biomethane injection into reticulated gas networks (Rusmanis et al., 2019).

The synergies possible between BHM and green hydrogen stem from the increased energy density possible (x3) when injected & transported as biomethane instead of hydrogen gas, therefore employing biomethane as a hydrogen carrier with the added benefit of not having to change gas appliances to be compatible with hydrogen at point of use.

These emerging technologies are not further described in this study but should be considered as part of future biogas production schemes as the technologies evolve and become more commercially available.

The design of pre-treatment and upgrading equipment are complimentary of each other and depend on the constituents of the raw biogas. Generally upgrading equipment is chosen during detailed design of the biogas upgrading scheme. Indicative gas sampling from the biogas production process with the expected feedstocks is necessary to ensure the cleaning and upgrading equipment are fit for purpose.

All types of commercially available upgrading have been used successfully for different feedstocks.

a. 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).

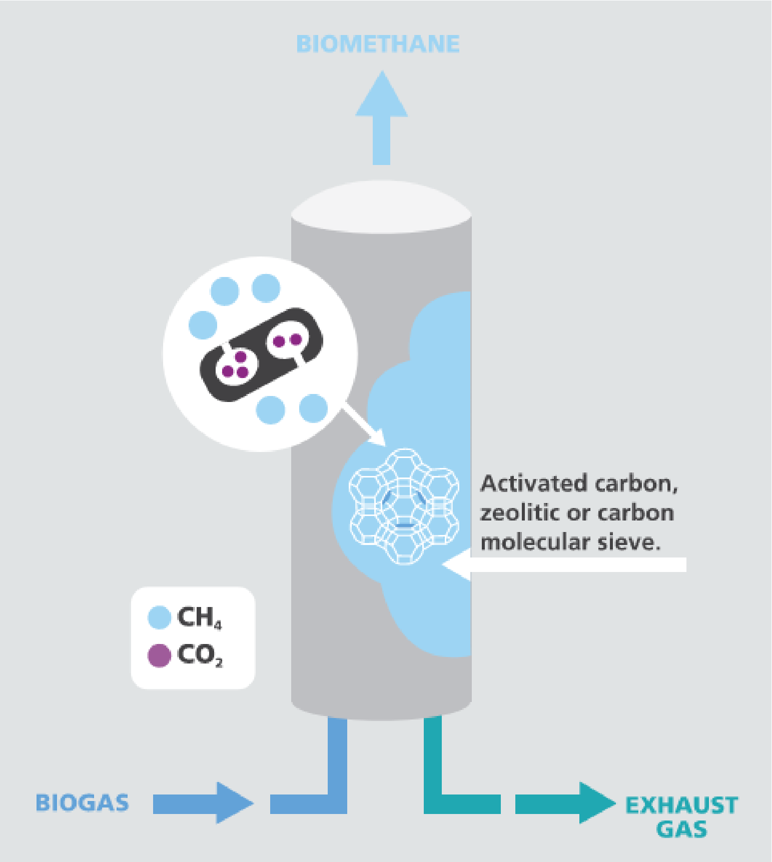

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Figure 18: PSA sieve pressurization (UNIDO & German Biogas Association, 2017)

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.

b. 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.

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.

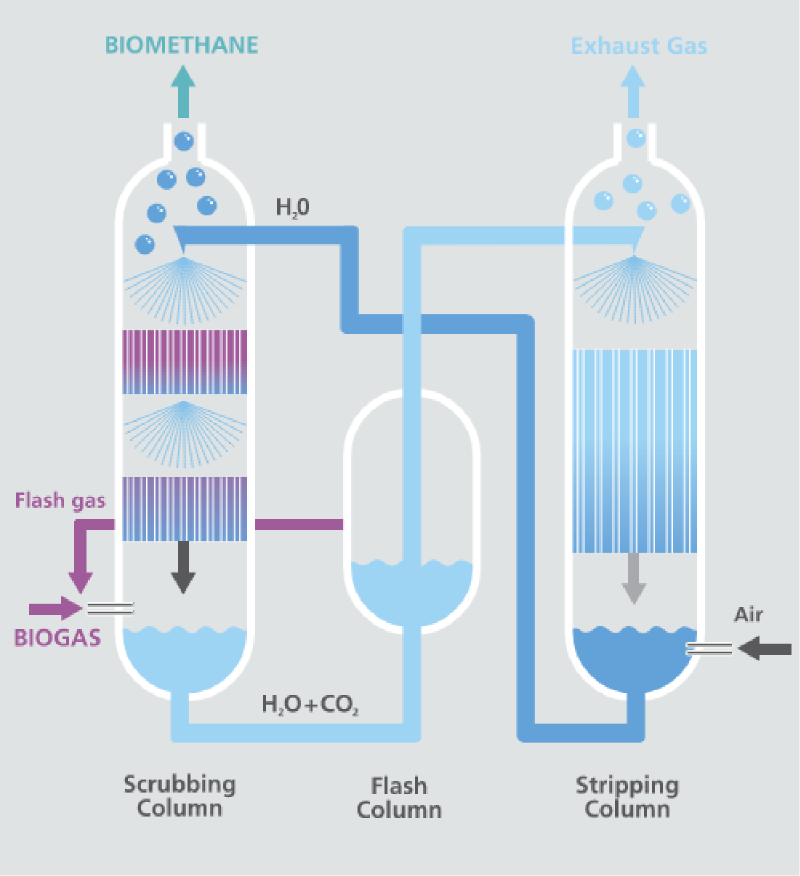

Figure 19: Scrubbing technologies schematic (UNIDO & German Biogas Association, 2017)

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).

c. 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.

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

e. 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.

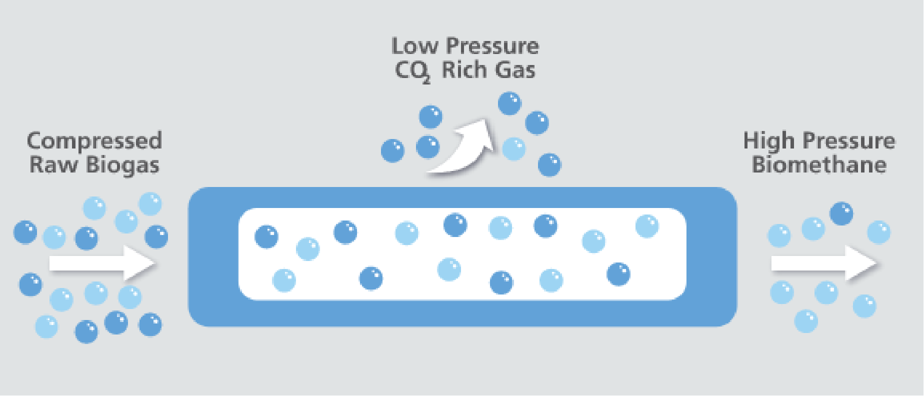

Figure 20: Membrane Separation Fundamental (Pentair Haffmans)

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

f. 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 membrane and PSA equipment to remove these along with CO_2 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 39.

Table 39: 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
PSA	3 - 10	4 - 5	0.15 – 0.35	96 - 98	<4	Yes	Medium
Water Scrubbing	4 - 10	7 - 10	0.2 – 0.4	96 - 99	<2	Recommended	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	High

References

1.(UNIDO & German Biogas Association, 2017)

2.(Adnan et al., 2019)

3.(Angelidaki et al., 2018)

4.(Sun et al., 2015b)

Network injection equipment

Once the biogas has had the majority of CO_2 and other contaminants removed to upgrade the CV, the biomethane can be injected into the natural gas network. Like other natural gas producers, the biomethane producer is required to ensure the biomethane adheres to NZS 5442 prior to network injection. Certain equipment is required by the network operator to enable biomethane injection into the network. This injection equipment can be located at the biomethane production facility or at the BIP to the network. Packaged equipment options of Grid Entry Units (GEUs)are available from vendors that perform the following functions. The potential ownership models for this equipment is outlined in Section 3.C.iii.

a. Gas Chromatograph

Processing equipment may incorporate some fast-acting instrumentation / performance measurement devices to aid in operation and control of the processing equipment. However, a gas chromatograph (GC) is required by the network operator to measure the components of the biomethane and ensure the gas meets the specification essential for reticulated customer use. A GC will typically be incorporated to provide an online measurement of gas quality to the network operator gas control for safety and billing purposes. Should the biomethane go out of specification limits, the network operator will require the BIP to be isolated from injecting into the network. During the out of specification event the biogas can be reprocessed or diverted to a flare capable of handling the entire flow of raw & upgraded biogas. This rejection requirement will be included in the overall equipment design.

b. Pressure Compression or Regulation

Depending on the outlet pressure of the processing equipment, a second stage of compression may be required to ensure the biomethane pressure can overcome the network pressure to be injected. Compressors can be controlled to ensure that the maximum allowable operating pressure (MAOP) of the network is not exceeded, and a second stage of pressure regulation such as a pressure relief valve will be required according to either AS/NZS 2885 or AS/NZS 4645.

In instances where the outlet pressure of the processing equipment exceeds the MAOP of the network (such as injection into some distribution networks), then pressure regulators are required. Each network operator will have their own regulator equipment specifications that they will provide for the biomethane producer.

c. Wobbe Index Adjustment

To ensure biomethane being supplied into the natural gas network is consistent with energy content requirements, in-line monitoring of the Wobbe index of the resultant biomethane is required. To ensure an acceptable gas quality is reached prior to injection, the gas can be dosed with propane to elevate its energy content (Angelidaki et al., 2018; Energiforsk, 2016)

d. Gas Metering

Each network operator requires accurate gas metering as part of their network injection equipment. Accurate metering allows network operators to measure the quantity of gas entering the network and allocate gas sales to specific producers. Each network operator will have their own metering equipment specifications that they will provide for the biomethane producer.

e. Gas Odorisation

As natural gas does not have any odour, part of the requirements of NZS 5442 for reticulated gas networks requires natural gas in reticulated networks to be odorised as a safety measure for being able to identify gas leakage. The recognisable smell is the odorant added to natural gas, which is a mix of 80% tertiary butyl mercaptan and 20% iso propyl mercaptan (Firstgas Ltd, 2020b). Most transmission pipeline networks in New Zealand transport odorised gas, but a select few transport unodorised gas.

Most BIPs will likely require odorisation equipment to provide a consistent small percentage of odorant (minimum 3 mg/Nm^3) to the gas stream. Odorisation equipment is mostly owned and operated by the transmission network operator, but some producers own and operate their own odorisation equipment.

f. Network Isolation Valve & Interconnection

To connect a biomethane production facility to an existing network, a BIP will require interconnection equipment. Depending on the chosen location of the BIP, the equipment required to connect to the existing network could include modifications to an existing delivery point. Connecting through an existing DP will involve pipework connections, isolation valves and monitoring equipment to be retrofitted. The network operator will be able to supply the biomethane producer information on existing assets and advise whether a tie -in can be made using an existing DP, or whether a new dedicated tie-in point is required.

A biomethane production facility located away from any existing delivery points will require a dedicated delivery point or network tie in point. A dedicated tie-in point will require the use of some hot-tap or saddle tee equipment depending on the network pressure and material. All BIPs require an isolation valve to be safely isolated from the existing network and network operators may require this isolation valve to be automated for remote operation.

There may be instances where a BIP cannot be located close to a gas network with capacity available, and a dedicated pipeline may be required to interconnect into the nearest suitable network. The lateral pipeline construction will depend on the network operating pressure.

Additional factors to consider

a. Reject CO_2 use/quality

Raw biogas typically includes 30-40 mol% CO_2 which must be substantially removed during the biomethane processing stage. This means that a substantial quantity of CO_2 will be constantly removed from the gas stream and there may be opportunities to utilise this gas. The biogenic CO_2 gas could be vented to the air, but this is the least preferable solution. The CO_2 can be processed to a certain level and either bottled or transported for commercial use, such as a commercial greenhouse/plant growing business to enhance the crop yields.

The waste CO_2 could also be further processed and sold as “food grade” CO_2 for many commercial business opportunities. This is particularly useful in New Zealand currently where there are limited sources of “food grade” CO_2 from renewable sources. These opportunities should be evaluated to consider the potential value stream that could be created in the overall biogas processing scheme.

Filtration systems are available to achieve a quality of CO_2 which can be sold to improve the overall viability of any potential biogas scheme being considered.

b. Reject Heat use

Gas compression used to increase the biogas pressure for biomethane processing may also be used to increase the biomethane pressure for injection into the gas reticulation system. If injection is required into the high-pressure transmission network, the required compression will generate waste heat in the biomethane gas which must be cooled to meet network temperature limits. This waste heat can be repurposed within the biogas plant design to be used efficiently to reduce overall plant running costs (i.e. to help provide heat to anaerobic digestion or digestate treatment). The practicality of using the waste heat will depend on each plant’s specific design and should be considered as part of the initial system design to improve overall plant efficiency.

c. Redundancy of equipment vs shutdown and recycle

The standard design approach for gas distribution and transmission pressure regulation stations includes equipment redundancy to operate with a primary regulator stream running and a second stream in standby, which will automatically take over if needed. This arrangement ensures that gas flows from the station are uninterrupted, whether due to equipment fault/ failure or during times when maintenance is undertaken.

Duplicate pressure regulation at biomethane injection points may not be required if the overall biogas plant is designed to recycle or store significant gas volumes. Gas recycling or rejection would generally be required for biomethane gas that does not meet specification. It will need to be established whether the best economic decision is to shutdown the gas installation during planned maintenance or equipment fault/failure and recycle the biomethane, or to provide injection equipment redundancy to allow the biomethane to continue to be injected into the gas network during these times.

The gas processing plant and filtration systems will also require periodic maintenance i.e. to change filtration elements, service rotating equipment, and this system is rarely duplicated. Hence shutdown of this system for maintenance will require recycling, storage or flaring of biogas.

At large biogas production sites (4,000-16,000 Nm^3/hour) multiple biogas upgrading ‘trains’ are typically deployed in conjunction with raw biogas buffer storage (either integrated into digester volumes or as standalone storage). This allows for maintenance activities to be conducted on one upgrading train whilst ramping down organic loading/feeding rates and storing the balance of the biogas not upgraded in the other trains. This typically allows for a 12-18 hour outage window with minimal flaring of biogas required

d. Fugitive Methane Emissions - also known as 'Methane Slip'

All the biogas upgrading technologies described above are affected by the phenomena of methane slip. When permeating, absorbing or adsorbing contaminants by physical or chemical means, a small but measurable amount of CH_4 is also captured alongside the targeted contaminants. The separated components continue to the next step of the process which can include venting to atmosphere, adsorption to media, biological treatment or thermal oxidation. With the exception of thermal oxidation this small amount of methane will be eventually vented to atmosphere and become fugitive emissions. There is a great responsibility placed on designers and operators of biogas upgrading equipment to ensure that methane slip is measured and minimised so as to not undo the emissions mitigation that anaerobic digestion and biomethane utilisation provide.

Capital Cost of Biogas Upgrading and Key Cost Drivers

Every biogas production scheme will be slightly different; however, most will fit into three categories according to their feedstock types:

- WWTP
- Landfill
- Anaerobic Digestion

The expected size of biogas production plants in New Zealand could be further classified into three production scales outlined in Table 40.

Table 40: Biogas to Biomethane Scales

Scale	Raw Biogas Production (Nm^3/hr)	Biomethane Production (Nm^3/hr)	Energy Produced (MW)
Small	40 - 400	20 - 240	0.2 - 2.4
Medium	400 - 1000	200 - 600	2 - 6
Large	1000 - 1500	500 - 900	5 - 9
Large +	1500+	900+	9+

As part of this research project, manufacturers of packaged biogas to biomethane processing equipment have been consulted to provide indicative costing for offerings that fit each of these categories. Additional information has been provided by research team member's involvement in similar projects. Scales in the Large+ category may have packaged equipment solutions but may start to approach custom plant design scales, so have been left out of this study.

Every biogas production and injection ownership scheme may be slightly different, however, for the purpose of this study, there have been ownership demarcations according to 5 schemes, outlined in Figure 21. These ownership models range from the biogas producer being responsible only to produce raw biogas and the network operator owning the balance of equipment. Conversely, the biogas producer could choose to own and operate all equipment up to the interconnection to the gas network. Each ownership scheme will have benefits and drawbacks dependent on the specific goals of the production and injection scheme.

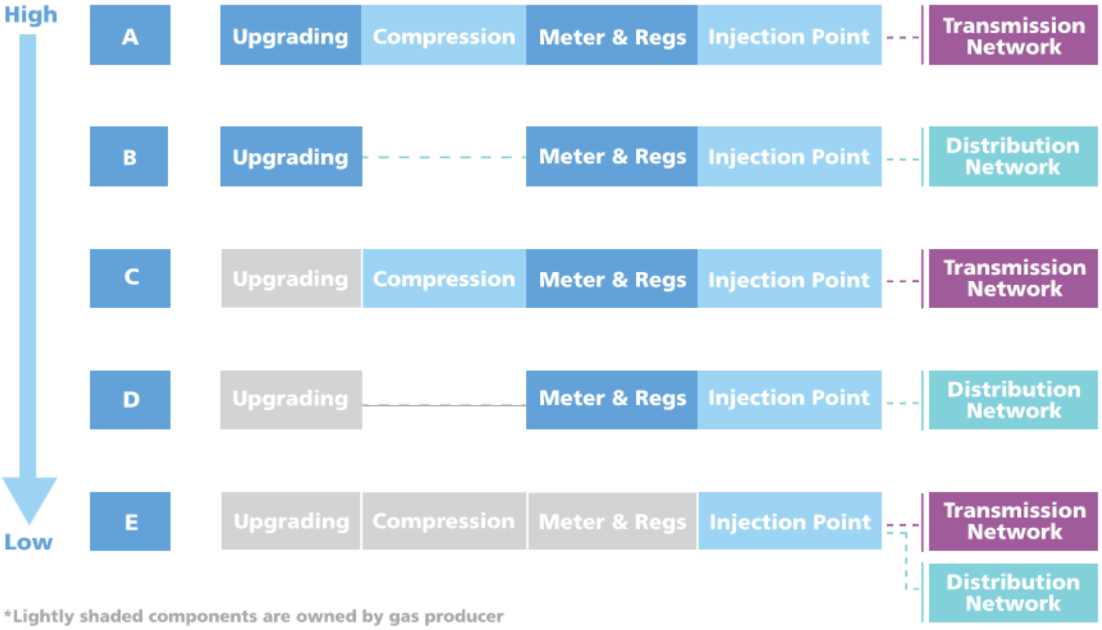

Figure 21: Network operator equipment ownership models

As part of this study, best efforts have been made to provide ownership demarcations which coincide with each stage of the upgrading and injection process. Although this study has suggested ownership models, each biogas project could have an individual ownership and cost model that differs from this study.

To inform this study, costs associated with production equipment are given as ranges of rough orders of magnitude costing. Actual equipment and running costs will be heavily dependent on the detailed design of each project, and this study does not attempt to quantify these details.

Table 41: Biogas Upgrading Cost Matrix ($NZD)

Biogas Processing Plant Costs							Biomethane Injection Costs		
		Raw Biogas source					Components		
Option	Biogas (Nm^3/hr)	AD	Landfill	WWTP	Food Grade CO_2	Biomethane (Nm^3/hr)	Compression	Metering & Regulation	Injection Point
A transmission	40-400	1.9 M	~2M	~2M	0.7M – 1.4M	20-240	0.5M - 2M	0.3-0.5M	0.5M - 1M
	400-1000	2.4M - 2.9M	2.49M-3.13M	2.47M-3.07M		200-600			
	1000-1500	3M-4.2M	3.22M-4.54M	3.17M-4.46M		500-900			
B distribution	40-400	1.9M	~2M	~2M	0.7M – 1.4M	20-240	N/A	0.3-0.5M	0.3M - 0.5M
	400-1000	2.4M - 2.9M	2.49M-3.13M	2.47M-3.07M		200-600			
	1000-1500	3M-4.2M	3.22M-4.54M	3.17M-4.46M		500-900			
C transmission	40-400	N/A				20-240	0.5M - 2M	0.3-0.5M	0.5M - 1M
	400-1000					200-600			
	1000-1500					500-900			
D distribution	40-400	N/A				20-240	N/A	0.3-0.5M	0.3M - 0.5M
	400-1000					200-600			
	1000-1500					500-900			
E transmission distribution	40-400	N/A				20-240	N/A	N/A	0.5M - 1M 0.3M - 0.5M
	400-1000					200-600			
	1000-1500					500-900			

Add Ons	$/unit	Unit	Range
Odorisation	$ 100k	ea.	± 10%
Distribution Pipeline	$ 300k	km	± 20%

Add Ons	$/unit	Unit	Range
Transmission Pipeline	$ 750k	km	± 30%
Gas Chromatograph	$ 80k	ea.	± 10%
Land use	$ 300	m2	± 30%
Telemetry Connection	$ 45k	ea.	± 10%
Compression to IP pressure (19.6barg)	$ 0.5M – 2M	ea.	± 50%

References: (Sun et al., 2015a) , (Pentair Haffmans, 2021), (Galileo Technologies, 2020), (Sauer Haug Compressors, 2021), (Xebec, 2020), (Firstgas Ltd, 2020a)

A6. Biomethane in Areas without a Reticulated Gas Network

In areas without natural gas reticulation systems, the case for production of biomethane may not be the best use of generated biogas. Other opportunities for the use of biogas include direct use of the biogas for direct heating or electrical generation. Both of these options are less capital-intensive than biomethane refining, but the products generated are lower quality and cannot generate the same revenues. A key challenge is the lack of potential for CO_2 generation, which can become a valuable revenue stream for the biomethane operation.

In the case where a direct user of the energy generated is located nearby and is able to accept untreated biogas as a fuel, it may make sense to not pursue biomethane generation. However, the flexibility provided by converting the biogas into biomethane is still worth considering. Below are some descriptions of ways to utilise biomethane without a distribution network nearby.

Dedicated biomethane pipelines

There are no natural gas reticulation networks on the South Island, so this opportunity does not exist for biogas producers on the South Island. However, for biogas producers on the North Island, there may be the opportunity to construct a dedicated pipeline to connect to existing pipeline infrastructure. Depending on the proximity to the closest gas network able to accommodate the biomethane flow, there may be the opportunity to construct a small diameter pipeline to interconnect to the networks. The cost of the interconnection pipeline is likely to prove inhibitive for small producers having to transport long distances to the existing network. The indicative costs associated with constructing dedicated pipelines are included in Section 5.3.4. It is likely that a small diameter pipeline would be enough for the flowrates indicated in this report for typical biogas production schemes, however, the pipeline construction material and technique will depend on project specific injection pressures.

Biomethane to Compressed Natural Gas (CNG)

Biogas producers away from pipeline infrastructure can compress the biomethane to allow export using tube trailers. For CNG, the upgraded biomethane is compressed to pressures greater than 200barg and injected into transportable tube trailers The CNG market in New Zealand is limited but finds uses in CNG vehicles and could be transported for reinjection into the natural gas system on the North Island. A major benefit of biomethane trucks is that existing diesel trucks can be retrofitted with dual-fuel engines to allow them to run on biomethane and diesel, which decreases the required capital to decarbonise truck fleets when compared with purchasing brand new electric or hydrogen-powered trucks. While CNG trucks may be cheaper to run and produce less particulates, CNG trucks generally have less range than their diesel equivalents and there is less infrastructure available to refuel CNG vehicles on long trips (Quartier, 2020). Biomethane vehicles could be utilised in New Zealand to decarbonise transport in combination with EVs, fuel cell vehicles and biodiesel, but would need support to work out its strategic place in transport and to what degree we see it being utilised for the different kinds of vehicles in New Zealand.

Bioenergy hub connecting multiple biogas producers to central upgrading plant

In areas where multiple sources of raw feedstock are available (such as prominent farming areas) there is the opportunity to produce biogas local to each feedstock and transport clean and dry biogas to a central hub. The cleaned biogas from multiple sources could be upgraded to biomethane at the central hub using a single upgrading and compression facility. The bioenergy hub could be used in areas close to infrastructure or areas without pipeline infrastructure to rely on a single CNG plant and tube trailer filling facility. Combining multiple biogas streams to utilise a single biomethane upgrading and injection or compression plant would help reduce the overall unit cost of biomethane.

Local combined heat and power (CHP) electricity generation

There will be instances were raw feedstock and biogas production is unable to be practically upgraded to biomethane for export by pipeline or tube trailer. However, these valuable renewable biogas resources can be cleaned and combusted in a gas engine generator to produce electricity. Running a gas generator results in waste heat that can be collected for use to improve the efficiency of the conversion process from raw feedstock to energy. Waste heat can be used to aid raw biogas production, or to provide heat to other facility uses.

Biomethane conversion to hydrogen

There remains the opportunity to convert biomethane into green hydrogen using steam methane reforming (SMR). Traditional SMR plants have been large capacities to convert fossil based natural gas to hydrogen, however, recent advances have developed SMR plants to produce hydrogen at scales to match biomethane production schemes (HyGear, 2020). For effective utilization, the hydrogen would likely require compression to pressures of either 350 barg or 700 barg for transportation and vehicle fuel cell use. As the biomethane fed into the SMR process is a low carbon or carbon neutral gas, the hydrogen would be considered the same.

Bibliography

Achinas, S., Achinas, V., & Euverink, G. J. W. (2017). A Technological Overview of Biogas Production from Biowaste. *Engineering*, *3*(3), 299–307. https://doi.org/10.1016/J.ENG.2017.03.002

Al Seadi, T., Rutz, D., Prassl, H., Köttner, M., Finsterwalder, T., Volk, S., Reviewers, R. J., Sioulas, K., Kulisic, B., Teodorita, E., Seadi, A., Catrineda, S. M., & Cybulska, I. (2008). *Biogas Handbook*. http://lemvigbiogas.com/http://www.sdu.

Ammenberg, J., & Gustafsson, M. (2020). *The Swedish biogas roadmap*. http://www.biogasresearchcenter.se/

Anaergia. (2021, January 28). *Anaergia and Universal Waste Systems to Construct Organics Waste Processing Plant in City of Los Angeles, Supporting Landfill Diversion Goals*. https://www.anaergia.com/anaergia-and-universal-waste-systems-to-construct-organics-waste-processing-plant-in-city-of-los-angeles

Angelidaki, I., Treu, L., Tsapekos, P., Luo, G., Campanaro, S., Wenzel, H., & Kougias, P. G. (2018). Biogas upgrading and utilization : Current status and perspectives. *Biotechnology Advances*, *36*(2), 452–466. https://doi.org/10.1016/j.biotechadv.2018.01.011

Appunn, K., Haas, Y., & Wettengel, J. (2020, December 21). *Germany's energy consumption and power mix in charts*. Clean Energy Wire. https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts

Ariunbaatar, J., Panico, A., Esposito, G., Pirozzi, F., & Lens, P. N. L. (2014). Pretreatment methods to enhance anaerobic digestion of organic solid waste. In *Applied Energy* (Vol. 123, pp. 143–156). Elsevier Ltd. https://doi.org/10.1016/j.apenergy.2014.02.035

Aso, S. (2019). Digestate: The Coproduct of Biofuel Production in a Circular Economy, and New Results for Cassava Peeling Residue Digestate. In *Renewable Energy - Technologies and Applications*. IntechOpen. https://doi.org/10.5772/intechopen.91340

ATSDR. (2001). *Landfill Gas Primer - An Overview for Environmental Health Professionals. Chapter 2: Landfill Gas Basics*. https://www.atsdr.cdc.gov/hac/landfill/html/intro.html

Australian Energy Statistics. (2020). *Australian Energy Update 2020*. https://www.energy.gov.au/sites/default/files/Australian Energy Statistics 2020 Energy Update Report_0.pdf

Australian Renewable Energy Agency (ARENA). (2020a, July). *Bioenergy Roadmap - Australian Renewable Energy Agency (ARENA)*. https://arena.gov.au/knowledge-innovation/bioenergy-roadmap/#read-the-overview

Australian Renewable Energy Agency (ARENA). (2020b, November 23). *Australian first biomethane trial for NSW gas network*. https://arena.gov.au/news/australian-first-biomethane-trial-for-nsw-gas-network/

Bachmann, N. (2015). Sustainable biogas production in municipal wastewater treatment plants. *IEA Bioenergy*, 20.

Banja, M., Jégard, M., Motola, V., & Sikkema, R. (2019). Support for biogas in the EU electricity sector – A comparative analysis. *Biomass and Bioenergy*, *128*, 105313. https://doi.org/10.1016/j.biombioe.2019.105313

Banks, C. J., Heaven, S., Zhang, Y., & Baier, U. (2018). Food waste digestion: Anaerobic Digestion of Food Waste for a Circular Economy. In *IEA Bioenergy Task* (Vol. 37).

Bantacut, T., & Ardhiansyah, E. L. (2018). *Chemical Oxygen Demand Balance and Energy Recovery in Wastewater Treatment Plant of Pulp and Paper Industry (Corrugated Board)*. https://www.researchgate.net/publication/328039598_Chemical_Oxygen_Demand_Balance_and_Energy_Recovery_in_Wastewater_Treatment_Plant_of_Pulp_and_Paper_Industry_Corrugated_Board

Barłóg, P., Hlisnikovský, L., & Kunzová, E. (2020). Effect of Digestate on Soil Organic Carbon and Plant-Available Nutrient Content Compared to Cattle Slurry and Mineral Fertilization. *Agronomy*, *10*(3), 379. https://doi.org/10.3390/agronomy10030379

Beca; GHD; Boffa Miskell; (2020). *The New Zealand Wastewater Sector*.

Beca, Daly, J., Fonterra, & Beuger, B. (2016). *CHALLENGES AND INNOVATIONS IN DAIRY FACTORY WASTEWATER TREATMENT*. *August*.

Bekkering, J., Broekhuis, A. A., & van Gemert, W. J. T. (2010). Optimisation of a green gas supply chain - A review. In *Bioresource Technology* (Vol. 101, Issue 2, pp. 450–456). https://doi.org/10.1016/j.biortech.2009.08.106

Benato, A., & Macor, A. (2019). *Italian Biogas Plants: Trend, Subsidies, Cost, Biogas Composition and Engine Emissions*. https://ideas.repec.org/a/gam/jeners/v12y2019i6p979-d213579.html

Bia, J. (2020, February 14). *2020 - an unprecedented year of opportunity for biogas in the UK*. Anaerobic Digestion & Bioresources Association. https://adbioresources.org/2020-an-unprecedented-year-of-opportunity-for-biogas-in-the-uk/

Bioboost. (2017). *Bioboost: Natural Organic Fertiliser*. New Plymouth District Council. http://www.bioboost.co.nz/

Bioenergy Association New Zealand. (2019). *Role of organic waste and biogas in the transition to low carbon economy in New Zealand*. *June 2016*.

Bioenergy Association New Zealand. (2021). *The Production and Use as Biofertiliser of Digestate Derived from Source Segregated Organic Waste*. www.bioenergy.org.nz

Bioenergy Insight. (2018). *UK's Feed In Tariff fade out confirmed | Bioenergy Insight Magazine*. Bioenergy Insight. https://www.bioenergy-news.com/news/uks-feed-in-tariff-fade-out-confirmed/

Bioenergy Insight Magazine. (2020, October 7). *Chevron USA, Brightmark form dairy biomethane joint venture*. Bioenergy Insight. https://www.bioenergy-news.com/news/chevron-usa-brightmark-form-dairy-biomethane-joint-venture/

Biogas Association of New Zealand. (2019). *Role of organic waste and biogas in the transition to low carbon economy in New Zealand*. *January*.

Biogas Go Global. (2020). *Biogas Production*.

Biogas World. (2018). *Biogas and Biomethane Market in Italy: Current State and Perspectives*. https://www.biogasworld.com/news/development-biomethane-italy-present-situation-prospects/

Biogas World. (2020). *What is the state of biogas and biomethane in France?* https://www.biogasworld.com/news/biogas-biomethane-market-france/#:~:text=At the end of 2019,production capacity of 24TWh %2F year

Biogas World. (2021a). *Biomethane potential test sets*. https://www.biogasworld.com/product/anaerobic-digestion/process-pilot/anaero-biomethane-potential-test-sets/

Biogas World. (2021b, April). *Wet and Dry Anaerobic Digestion Systems - BiogasWorld*. Biogas World. https://www.biogasworld.com/news/dry-wet-anaerobic-digestion-systems/

Blaisonneau, L., El Fadili, S., Faure, M., Gondel, A., Julien, E., & Rakotojaona, L. (2017). *Overview of the biomethane sector in France*. *October*, 1–55. https://www.enea-consulting.com/en/overview-of-the-biomethane-sector-in-france-and-ideas-for-its-development/%0Ahttp://www.enea-consulting.com/wp-content/uploads/2018/04/ENEA-2017-10-biomethane-france-2017-en.pdf

Blanco-Canqui, H. (2016). Growing Dedicated Energy Crops on Marginal Lands and Ecosystem Services. *Soil Science Society of America Journal*, *80*(4), 845–858. https://doi.org/10.2136/sssaj2016.03.0080

Bouskova, A. (2021). *Personal Communication from Bioenergy Association*.

Boykew, F. (2020). *Why the Government's Proposed Green Gas Support Scheme Underestimates Biomethae's Potential*. https://www.futurebiogas.com/why-the-governments-proposed-green-gas-support-scheme-underestimates-biomethanes-potential/

Bremont, U., Bertrandias, A., Steyer, J.-P., Bernet, N., & El Ene Carrere, H. (2020). *A vision of European biogas sector development towards 2030: Trends and challenges*. https://doi.org/10.1016/j.jclepro.2020.125065

Budde, B., & Newman, D. (2019, January 8). *Biogas in Germany: Maintaining momentum*. Euractiv. https://www.euractiv.com/section/energy-environment/opinion/biogas-in-germany-maintaining-momentum/

Buli, N., & Adomaitis, N. (2021, January 9). *Norway's plans to raise carbon tax draw oil industry ire*. Reuters. https://www.reuters.com/article/us-climate-change-norway/norway-aims-to-more-than-triple-national-co2-price-by-2030-idUSKBN29D1BD

Business Energy. (2017). *Biogas Renewable Electricity Explained*. https://www.businessenergy.com/blog/biogas/

CarbonNews. (2021). *MARKET LATEST: NZUs*. http://www.carbonnews.co.nz/story.asp?storyID=19740

Chen, Q., & Liu, T. (2017). *Biogas system in rural China: Upgrading from decentralized to centralized?* https://doi.org/10.1016/j.rser.2017.04.113

Clarke Energy. (2021). *CHP efficiency for biogas*. https://www.clarke-energy.com/2013/chp-cogen-efficiency-biogas/

Clarke, N. (2019). *AD101: Anaerobic Digestion Selection Considerations*.

Cleanleap. (2013). *6.1 Capital costs for biogas | Cleanleap*. https://cleanleap.com/6-biogas/61-capital-costs-biogas

Consorzio Italiano Biogas. (2016). *Deliverable D2.1: State of the art and best practices collection*.

Dairy NZ. (2018). *QuickStats about dairying - Waikato Region*. https://www.dairynz.co.nz/media/5791537/quickstats-about-dairying-waikato-2018.pdf

Danish Energy Agency. (2020). *Facts about bioenergy in Denmark*. Danish Ministry of Climate Energy and Utilities. https://ens.dk/en/our-responsibilities/bioenergy/facts-about-bioenergy-denmark

Danish Energy Agency. (2021). *Biogas in Denmark* . Danish Ministry of Climate, Energy and Utilities. https://ens.dk/en/our-responsibilities/bioenergy/biogas-denmark

Decorte, M., Tessens, S., Fernández, D., Repullo, F., McCarthy, P., Oriordan, B., Maggioni, L., Pieroni, C., Protas, M., Rogulska, M., Pukšec, T., Stanbasky, J., Alexandridis, K., Mozgovoy, A., Reinholz, T., Matosic, M., Vegere, K., Geletukha, G., Matveev, Y., … Papageorgiadis, G. (2020). *Mapping the state of play of renewable gases in Europe*.

Department for Business Energy & Industrial Strategy. (2020, July 17). *Greenhouse gas reporting: conversion factors 2020*. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020

Department for Business Energy and Industrial Strategy. (2020a). *Consultation on a Green Gas Levy*.

Department for Business Energy and Industrial Strategy. (2020b). *Future support for low carbon heat: consultation*.

Drosg, B., Fuchs, W., Al, T., Madsen, S. M., & Linke, B. (2015). *Nutrient Recovery by Biogas Digestate Processing*.

Ecoprog. (2014). *Biogas plants in France - Market and new site potentials*. www.ecoprog.com

Electricity Authority (Te Mana Hiko). (2021). *Wholesale Electricity Price Trends*. https://www.emi.ea.govt.nz/Wholesale/Reports/W_P_C?DateFrom=20200429&DateTo=20210428&_rsdr=L364D&WeightedBy=DEMAND&TimeScale=MONTH&_si=v%7C3

Ember Climate. (2021). *Carbon Price Viewer - Ember*. https://ember-climate.org/data/carbon-price-viewer/

ENDS Waste and Bioenergy. (2021). *Denmark: Countries largest biogas plant under construction | European Biogas Association*. European Biogas Association. https://www.europeanbiogas.eu/denmark-countries-largest-biogas-plant-under-construction/

Energiforsk. (2016). *Biogas Upgrading – Technical Review*. http://vav.griffel.net/filer/C_Energiforsk2016-275.pdf

Energy Saving Trust. (2021). *Feed-in tariff scheme information*. Energy Saving Trust. https://energysavingtrust.org.uk/grants-and-loans/feed-in-tariff/

Environmental and Energy Study Institute. (2017). *Fact Sheet* | *Biogas: Converting Waste to Energy*. https://www.eesi.org/papers/view/fact-sheet-biogasconverting-waste-to-energy

EPA USA, & Change Division, C. (2020). *AN OVERVIEW OF RENEWABLE NATURAL GAS FROM BIOGAS*.

Esposito, G., Frunzo, L., Panico, A., & Pirozzi, F. (2011). Modelling the effect of the OLR and OFMSW particle size on the performances of an anaerobic co-digestion reactor. *Process Biochemistry*, *46*(2), 557–565. https://doi.org/10.1016/j.procbio.2010.10.010

European Biogas Association. (2015). *Digestate Factsheet: the value of organic fertilisers for Europe's economy, society and environment*.

European Biogas Association. (2018). *EBA Statistical Report 2018*. 18. https://www.europeanbiogas.eu/eba-statistical-report-2018/

European Biogas Association. (2021). *The 'European Biomethane Map 2020' shows a 51% increase of biomethane plants in Europe in two years*. https://www.europeanbiogas.eu/the-european-biomethane-map-2020-shows-a-51-increase-of-biomethane-plants-in-europe-in-two-years/

European Commission. (2021). *EU funding possibilities in the energy sector*. European Commission. https://ec.europa.eu/energy/funding-and-contracts/eu-funding-possibilities-in-the-energy-sector_en

Eyl-Mazzega, M.-A., & Mathieu, C. (2019). *Biogas and Biomethane in Europe: Denmark, Germany, Italy lead*. Energy Post. https://energypost.eu/biogas-and-biomethane-in-europe-denmark-germany-italy-lead/

Federal Agency for Nature Conservation. (2016). *BfN: Areas Under Cultivation for Renewable resources*. https://www.bfn.de/en/service/facts-and-figures/the-utilisation-of-nature/renewable-energy/renewable-resources.html

Fertiliser Association. (2013). *Code of Practice for Nutrient Management*. https://www.fertiliser.org.nz/site/code-of-practice/

Fertiliser Association. (2019). *Fertiliser use in NZ*. https://www.fertiliser.org.nz/site/about/fertiliser_use_in_nz.aspx

Foundation for Arable Research. (2013). *Review of the role and practices of stubble burning in New Zealand, including alternative options and possible improvements A report prepared for the Canterbury Regional Council 2013 Written by*.

Frédéric Simon. (2019). *The future of biogas in Europe: it's a local affair*. Euractiv. https://www.euractiv.com/section/energy/news/the-future-of-biogas-in-europe-its-a-local-affair/

Fulton, M., Capalino, R., & Auer, J. (2012). *The German Feed-in Tariff: Recent Changes*. https://www.db.com/cr/en/docs/German_FIT_Update_2012.pdf

Geerolf, L. (2018). *The biogas sector development: Current and future trends in Western and Northern Europe The Biogas Sector Development: Current and future trends in Western and Northern Europe Miroslav Petrov-KTH/ITM/EGI*.

German Biogas Assocation. (2021). *Feedstocks for Biogas*. https://www.biogas.org/edcom/webfvb.nsf/id/en-feedstocks-for-biogas

Ghafoori, E., & Flynn, P. (2006). *Optimum Sizing for Anaerobic Digestion*.

Global Methane Initiative. (2016). *Global Methane Initiative Overview of Anaerobic Digestion for Municipal Solid Waste*. *October*.

Greenlane Renewables. (2021). *Greenlane Biogas*. https://www.greenlanerenewables.com/biogas/technology/

Gunnerson, C. G., & Stuckey, D. C. (1986). *Anaerobic Digestion Principles and Practices for Biogas Systems*.

Hall, P., & Gifford, J. (2007). *Bioenergy Options for New Zealand: A situation analysis of biomass resources and conversion technologies*.

Hamilton, D. (2017). *Anaerobic Digestion of Animal Manures: Understanding the Basic Processes*. https://extension.okstate.edu/fact-sheets/anaerobic-digestion-of-animal-manures-understanding-the-basic-processes.html

Hamilton, R., Fonterra, Rule, G., & AWT Water. (2011). *Understanding the Population Dynamics from an Industrial Wastewater Treatment Plant and How to Use it as an Operational Tool*. https://www.waternz.org.nz/Attachment?Action=Download&Attachment_id=994

Heiberger, R. M., & Holland, B. (2019). *Data and Statistics* (pp. 13–27). https://doi.org/10.1007/978-1-4939-2122-5_2

Helmen, G., & Lidén, M. (2021). *LBG as a maritime fuel*. Gasum. https://www.gasum.com/en/sustainable-transport/maritime-transport/liquefied-biogas/

Hengeveld, E. J., Bekkering, J., Van Dael, M., van Gemert, W. J. T., & Broekhuis, A. A. (2020). Potential advantages in heat and power production when biogas is collected from several digesters using dedicated pipelines - A case study in the “Province of West-Flanders” (Belgium). *Renewable Energy*, *149*, 549–564. https://doi.org/10.1016/j.renene.2019.12.009

Hermann, K., Ranek, L., Hougaard, N., Larsen, P. P., Meincke, S., & Andersen, T. (2019). *Denmark, a Food and Farming Country - Facts and Figures*. www.agricultureandfood.dk

Heubeck, S., & Craggs, R. (2009). *POTENTIAL CONTRIBUTIONS OF THE WASTEWATER SECTOR TO NEW ZEALAND’S ENERGY SUPPLY*.

Hivos. (2016a). *Africa Biogas Partnership Program* . https://hivos.org/program/abpp/

Hivos. (2016b). *Africa Biogas Partnership Programme wins prestigious award*. https://hivos.org/news/africa-biogas-partnership-programme-wins-prestigious-award/

IEA. (2020a). *Outlook for biogas and biomethane - Prospects for organic growth*. https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf

IEA. (2020b). *World Energy Outlook 2020*. https://www.iea.org/reports/world-energy-outlook-2020

IEA. (2021). *United Kingdom - Countries & Regions - IEA*. https://www.iea.org/countries/united-kingdom

Industrial Symbiosis Kawerau. (2012). *IS Kawerau-Biomass Residues Background Study*. www.embracechange.co.nz

Jackson, S., & Brodal, E. (2019). Optimization of the energy consumption of a carbon capture and sequestration related carbon dioxide compression processes. *Energies*, *12*(9), 1603. https://doi.org/10.3390/en12091603

Jain, S. (2019). *Global Potential of Biogas*. https://www.worldbiogasassociation.org/wp-content/uploads/2019/09/WBA-globalreport-56ppa4_digital-Sept-2019.pdf

Kamali, M., Gameiro, T., Costa, M. E. V., & Capela, I. (2016). Anaerobic digestion of pulp and paper mill wastes - An overview of the developments and improvement opportunities. In *Chemical Engineering Journal* (Vol. 298, pp. 162–182). https://doi.org/10.1016/j.cej.2016.03.119

Khan, A., Irvine, D., & Oliver, C. (2014). *TRADE WASTE CHARGES-A SPECTATORS VIEW*.

Khan, A. W., & Trottier, T. M. (1978). Effect of Sulfur-Containing Compounds on Anaerobic Degradation of Cellulose to Methane by Mixed Cultures Obtained from Sewage Sludget. In *APPLIED AND ENVIRONMENTAL MICROBIOLOGY*. http://aem.asm.org/

Klackenberg, L. (2019). *Biomethane in Sweden-market overview & policies*.

Li, Y., Alaimo, C. P., Kim, M., Kado, N. Y., Peppers, J., Xue, J., Wan, C., Green, P. G., Zhang, R., Jenkins, B. M., Vogel, C. F. A., Wuertz, S., Young, T. M., & Kleeman, M. J. (2019). Composition and Toxicity of

Biogas Produced from Different Feedstocks in California. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.9b03003

Liu, C., Yuan, X., Zeng, G., Li, W., & Li, J. (2008). Prediction of methane yield at optimum pH for anaerobic digestion of organic fraction of municipal solid waste - ScienceDirect. *Biresource Technology*, *99*(4), 882–888. https://www.sciencedirect.com/science/article/abs/pii/S0960852407000910

Matsakas, L., Rova, U., & Christakopoulos, P. (2016). Strategies for Enhanced Biogas Generation through Anaerobic Digestion of Forest Material - An Overview. In *BioResources* (Vol. 11, Issue 2). www.eubia.org

Mavrokefalidis. Dimitris. (2020, November 24). *“Australia’s first” biomethane-to-gas project launched - Energy Live News*. Energy Live News. https://www.energylivenews.com/2020/11/24/australias-first-biomethane-to-gas-project-launched/

McConville, A., Jamieson, R., Davies, S., Griffiths, J., Dillon, A., & Bethune, G. (2020). *Gas Vision 2050*.

Mckendry, P. (2018). Overview of Anaerobic Digestion and Power and Gas to Grid Plant CAPEX and OPEX Costs. *International Journal of Bioprocessing and Biotechniques*, *02*, 109. https://doi.org/10.20911/IJBBT-109.100009

Mingyu, Q. (2016). *Opportunity and challenge of Biogas market in China*.

Ministry for the Environment. (2003). *Guidelines for the Safe Application of Biosolids to Land in New Zealand*.

Ministry for the Environment. (2011). *National Summary of Landfills and Organic Waste Processing Sites*. https://www.mfe.govt.nz/publications/waste/waste-facilities-survey-methodology-and-summary-results/3-national-summary

Ministry for the Environment. (2019). *New Zealand’s Greenhouse Gas Inventory*. *1*(April).

Ministry for the Environment. (2020). *New Zealands Greenhouse Gas Inventory 1990-2018* .

Ministry for the Environment. (2021). *Waste and Government*. https://www.mfe.govt.nz/waste/waste-and-government

Ministry of Agriculture & Forestry. (2008). *Methane from Animal Waste Management Systems Final Report.*

Ministry of Business Innovation & Employment. (2021). *Energy Prices*. https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/energy-prices/

Ministry of Business Innovation and Employment. (2020). *Energy in New Zealand Report 2020*. http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/publications/

Ministry of Foreign Affairs of Denmark. (2021a). *Bioenergy Opportunities in Denmark*.

Ministry of Foreign Affairs of Denmark. (2021b). *Clean and renewable energy | Denmark leads the way*. Ministry of Foreign Affairs of Denmark. https://denmark.dk/innovation-and-design/clean-energy

Möller, K., & Müller, T. (2012). Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. *Engineering in Life Sciences*, *12*(3), 242–257. https://doi.org/10.1002/elsc.201100085

Montgomery, L. F. R., & Bochmann, G. (2014). *Pretreatment of feedstock for enhanced biogas production Pretreatment of feedstock for enhanced biogas production (electronic version)*.

Moriarty, K. (2013). *Feasibility Study of Anaerobic Digestion of Food Waste in St. Bernard, Louisiana* . www.nrel.gov

Moser, M. A., Mattocks, R. P., Gettier, S., & Roos, K. (2008). The AgSTAR Program Documents , Tools and Resources Benefits , Costs and Operating Experience at Seven New Agricutural Anaerobic Digesters. *Current*, 1–9.

Murray, S. (2017). *Hamilton City Council: Waste Assessment*.

New Zealand Dairy Statistics. (2020). www.lic.co.nz/about/dairy-statistics,

Nsair, A., Cinar, S. O., Alassali, A., Qdais, H. A., & Kuchta, K. (2020). Operational Parameters of Biogas

Plants: A Review and Evaluation Study. In *Energies* (Vol. 13, Issue 15, p. 3761). MDPI AG. https://doi.org/10.3390/en13153761

Nyamukamba, P., Mukumba, P., Chikukwa, E. S., & Makaka, G. (2020). Biogas Upgrading Approaches with Special Focus on Siloxane Removal—A Review. *Energies*, *13*(22), 6088. https://doi.org/10.3390/en13226088

NZ Institute of Chemistry. (2017). *ENVIRONMENTAL ISSUES IN DAIRY PROCESSING*.

Oji Fibre Solutions. (2019). *Sustainability Report*.

Pilli, S., Kumar Pandey, A., Katiyar, A., Pandey, K., & Dayal Tyagi, R. (2020). Pre-treatment Technologies to Enhance Anaerobic Digestion. In *Sustainable Sewage Sludge Management and Resource Efficiency*. IntechOpen. https://doi.org/10.5772/intechopen.93236

Pratt, C., Walcroft, A., Shilton, A., Guieysse, B., Chung, M., Craggs, R., & Heubeck, S. (2012). Revised Methane Emissions factors and Parameters for Dairy Effluent Ponds. In *Bag* (Vol. 11052). www.landcareresearch.co.nz

Quartier, D. (2020). *Natural Gas Trucks vs Diesel Trucks*. New Energies - Europe. https://freightliner.com/blog-and-newsletters/natural-gas-trucks-vs-diesel-trucks/

Quintern, M., & Morley, M. (2014). *VERMICOMPOSTING AND LAND UTILISATION OF BIOSOLIDS BLENDED WITH PULPMILL SOLIDS*.

Regatrace. (2020). *Mapping the state of play of renewable gases in Europe*.

Renewable Energy Agency, I. (2017). *Biogas for domestic cooking: Technology brief*. www.irena.org

Reynolds, C. J., Mirosa, M., & Clothier, B. (2016). *New Zealand's Food Waste: Estimating the Tonnes, Value, Calories and Resources Wasted*. https://doi.org/10.3390/agriculture6010009

Risberg, K., Cederlund, H., Pell, M., Arthurson, V., & Schnürer, A. (2017). Comparative characterization of digestate versus pig slurry and cow manure – Chemical composition and effects on soil microbial activity. *Waste Management*, *61*, 529–538. https://doi.org/10.1016/j.wasman.2016.12.016

Rocamora, I., Wagland, S. T., Villa, R., Simpson, E. W., Fernández, O., & Bajón-Fernández, Y. (2020). Dry anaerobic digestion of organic waste: A review of operational parameters and their impact on process performance. *Bioresource Technology*, *299*, 122681. https://doi.org/10.1016/j.biortech.2019.122681

Rollo, M., Ledgard, S., & Longhurst, B. (2017). *Trends in dairy effluent management Final Report Prepared for the Ministry for Primary Industries by*. http://www.mpi.govt.nz/news-and-resources/publications/

Rowarth, J. S., Milet, A., & Scrimgeour, F. G. (2015). Potential for anaerobic digestion of dairy farm effluent in New Zealand. *Journal of New Zealand Grasslands*, *77*, 71–76. https://doi.org/10.33584/jnzg.2015.77.486

Rusmanis, D., O'Shea, R., Wall, D. M., & Murphy, J. D. (2019). Biological hydrogen methanation systems–an overview of design and efficiency. *Bioengineered*, *10*(1), 604–634.

SAMCO. (2019). *How Much Do Biological Wastewater Treatment Systems Cost?* https://www.samcotech.com/anaerobic-wastewater-treatment-systems-cost-factors/

Scion. (2013). *Technical Sheet: Anaerobic Digestion*. www.scionresearch.com

Sherrard, A. (2020). *Construction start for New Zealand's first large-scale food waste-to-bioenergy plant*. Bio Energy International. https://bioenergyinternational.com/biogas/construction-start-for-new-zealands-first-large-scale-food-waste-to-bioenergy-plant

Silk, K., Burrell, M., & Bennetts, M. (2021). *Submission to the Climate Change Commission on 2021 Draft Advice for Consultation*.

Singh, G., Jain, V. K., & Singh, A. (2017). Effect of Temperature and other factors on Anaerobic Digestion Process, responsible for Bio Gas Production. In *International Journal of Theoretical and Applied Mechanics* (Vol. 12, Issue 3). http://www.ripublication.com

Smart City Sweden. (2020). *Biogas Summary - Sweden*. https://smartcitysweden.com/focus-areas/climate-energy-environment/biogas/

SNV World. (2021). *Africa Biogas Partnership Programme (ABPP)*. https://snv.org/project/africa-biogas-partnership-programme-abpp

Soleilhavoup, A., & DESOTEC. (2020). *Removing pollutants from landfill biogas*. https://www.desotec.com/en/carbonology/carbonology-cases/removing-pollutants-landfill-biogas

Sørensen, P., Mejnertsen, P., & Møller, H. B. (2019). *Nitrogen fertilizer value of digestates from anaerobic digestion of animal manures and crops*. http://orgprints.org/20269a

Spencer, R. (2010). High Solids Anaerobic Digestion Of Source Separated Organics | BioCycle. *BioCycle*, *51*(8), 46. https://www.biocycle.net/high-solids-anaerobic-digestion-of-source-separated-organics/

Srisowmeya, G., Chakravarthy, M., & Nandhini Devi, G. (2020). Critical considerations in two-stage anaerobic digestion of food waste – A review. In *Renewable and Sustainable Energy Reviews* (Vol. 119, p. 109587). Elsevier Ltd. https://doi.org/10.1016/j.rser.2019.109587

Standards New Zealand. (2008). *NZS 5442:2008. Specification for reticulated natural gas*.

Statista. (2018). *Energy mix in Italy in 2018*. https://www.statista.com/statistics/873552/energy-mix-in-italy/

Stats NZ. (2015). *Nitrogen and phosphorus in fertilisers*. 2015. https://www.stats.govt.nz/indicators/nitrogen-and-phosphorus-in-fertilisers

Stockler, M., Harder, B., Berman, D., & Young, T. (2020). *Biogas production: Insights and experiences from the Danish Biogas Sector*. www.danskdesignrum.dk

Sun, Q., Li, H., Yan, J., Liu, L., Yu, Z., & Yu, X. (2015). Selection of appropriate biogas upgrading technology-a review of biogas cleaning, upgrading and utilisation. In *Renewable and Sustainable Energy Reviews* (Vol. 51, pp. 521–532). Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.06.029

Swedish Gas Centre. (2012). *Basic Data on Biogas*. 29. www.sgc.se.

Taranaki Regional Council. (2016). *DH Lepper Trust Piggery Monitoring Programme Annual Report Technical Report 2015-64*. *1467*(February).

Tenz, C. (2021, May 3). *Working together for a carbon neutral future – the Stora Enso and Gasum collaboration at Nymölla biogas plant has been inaugurated*. Stora Enso. https://www.storaenso.com/en/newsroom/news/2021/5/working-together-for-a-carbon-neutral-future

Thiele, J. (2018). *BIOGAS PRODUCTION POTENTIAL FROM MUNICPAL WASTEWATER TREATMENT FACILITIES*.

Thiele, J. H. (2010). *Regional Co-digestion Facilities for Piggery Manure and Selected Industrial Waste Motivation of the participants*.

Tinholt, R. (2019). *the Value of Biosolids in New Zealand-an Industry Assessment*. 1–17.

Total. (2021, January 11). *Total Acquires Fonroche Biogaz*. Total Energies. https://www.totalenergies.com/media/news/press-releases/total-acquires-fonroche-biogaz

Trading Economics. (2019). *New Zealand - Urban Population (% Of Total)*. https://tradingeconomics.com/new-zealand/urban-population-percent-of-total-wb-data.html

Truong, T., Carlu, E., & Kundevski, M. (2019). *Biogas Opportunities for Australia*. https://www.enea-consulting.com/wp-content/uploads/2019/06/ENEA_Biogas-Opp-for-Australia_Web050519.pdf

UK Government. (2020, March 11). *Changes to Landfill Tax rates from 1 April 2020*. https://www.gov.uk/government/publications/changes-to-landfill-tax-rates-from-1-april-2020/changes-to-landfill-tax-rates-from-1-april-2020

Underhill, J. (2018, July 11). *BOC says second CO2 source to meet growing demand from dairy, food processing*. National Business Review. https://www.nbr.co.nz/article/boc-says-second-co2-source-meet-growing-demand-dairy-food-processing-bd-158415

United States Environmental Protection Agency. (2020). *AN OVERVIEW OF RENEWABLE NATURAL GAS FROM BIOGAS*.

Van, D. P., Fujiwara, T., Tho, B. L., Toan, P. P. S., & Minh, G. H. (2020). A review of anaerobic digestion systems for biodegradable waste: Configurations, operating parameters, and current trends. In *Environmental Engineering Research* (Vol. 25, Issue 1, pp. 1–17). Korean Society of Environmental Engineers. https://doi.org/10.4491/eer.2018.334

Wabnitz, G., Archer, H., Thiele, J., Jones, K., Renquist, R., & Heubeck, S. (2011). *NZ Biogas Strategy 2010 to 2040*. https://www.biogas.org.nz/documents/biogas/BANZ-Biogas-Strategy-110224.pdf

Waste & Resources Action Programme (WRAP). (2014). *PAS110: Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials*.

Water New Zealand. (2021). https://www.waternz.org.nz/WWTPInventory

Watercare Services Ltd. (2019). *BIOENERGY GENERATION AT WATERCARE*.

Wilcock, B. (2006). *Assessing the Relative Importance of Faecal Pollution Sources in Rural Catchments*.

Williams, R., Poole, N., Fraser, T., Grant, D., & Hanson, N. (2013). *Review of the role and practices of stubble burning in New Zealand , including alternative options and possible improvements*. 68. https://www.far.org.nz/assets/files/blog/files/f71f0977-b1e4-4ddd-9b05-85017b37d535.pdf

Wood Environment & Infrastructure Solutions UK Limited. (2019). *Digestate and compost as fertilisers: Risk assessment and risk management options*. *February*. https://ec.europa.eu/environment/chemicals/reach/pdf/40039 Digestate and Compost RMOA - Final report i2_20190208.pdf

Xu, J., Yuan, H., Lin, J., & Yuan, wenxiang. (2014). Evaluation of thermal, thermal-alkaline, alkaline and electrochemical pretreatments on sludge to enhance anaerobic biogas production. *Journal of the Taiwan Institute of Chemical Engineers*, *45*(5), 2531–2536. https://doi.org/10.1016/j.jtice.2014.05.029

Zhao, J., Li, Y., Marandola, C., Krooneman, J., & Euverink, G. J. W. (2020). Comparison of the microbial communities in anaerobic digesters treating high alkalinity synthetic wastewater at atmospheric and high-pressure (11 bar). *Bioresource Technology*, *318*, 124101. https://doi.org/10.1016/j.biortech.2020.124101

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