University of Southern Queensland

Faculty of Health, Engineering and Sciences

Greenhouse gas reduction and biogas production potential through anaerobic digestion of biomass waste: an Australian perspective

A dissertation submitted by

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Abstract

Compared to other forms of renewables, bioenergy and biogas have seen very little growth over the past decade in Australia. This is not ideal, as the country will likely have to utilise every available renewable energy source to meet the requirements of the Paris agreement and achieve net-zero greenhouse gas emissions (GHGe) by 2050. Reasons for this lack of growth include low cultural motivation, minimal government support, and no clear knowledge of energy potentials. Therefore, better understanding of biogas potentials generated from anaerobic digestion (AD) of biomass in Australia is necessary.

This project will use open-source data and statistics to determine Australia-wide availability and characteristics of biomass from the selected sources (municipal solid waste (MSW), livestock animal manure and agricultural residues). This will include variables such as city population, crop residue proportion of harvest and animal manure production as well as availability and biogas potential from AD of each waste source. As there is no practical research element in this methodology, most of the allocated project time will be spent verifying and finding multiple credible sources for this data. The key outcomes of the research include Australia wide estimation of potential biogas, biomethane and biofertilizer production, net energy generation and net-GHGe reduction from anaerobic co-digestion (ACoD) of MSW, livestock manure and agricultural residue.

Key results and recommendations include:

- Overall, 5 700 Mm^3/year of biogas could be generated from ACoD of the biomass.
- Results found 58%, 37% and 5% of biogas production was attributed to agricultural residue, livestock manure and MSW, respectively.
- This biogas could supply 10% of Australia's electricity demand if combined heat and power generators are used, reducing CO_2e by 7 Mm^3/year.
- It is recommended that biogas is upgraded to biomethane to supply 46% of residential/commercial gas demand, as this is a 'hard-to-abate' sector and cannot be replaced by other renewables.
- An estimated 16 million tonnes of digestate byproduct is generated in ACoD, and with correct handling and management, could be used to completely replace imported synthetic fertiliser in the Australian agricultural sector.

Quantifying overall biogas potential is only half the problem however, and this project highlights several areas of further research required to achieve the potentials calculated. This includes investigation into logistics and cost-benefit analysis of transporting biomass, determining most efficient locations/sizes of reactors, and understanding conflicting uses of biomass and how government legislation will need to be updated to maximise biomass availability.

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Glossary of Terms

ABS – Australian Bureau of Statistics

ACoD – Anaerobic co-digestion

AD – Anaerobic digestion

BF - Biofuel

bioCNG – Compressed natural gas from biomethane

bioLNG – Liquefied natural gas from biomethane

CHP – Combined heat and power generator

CO2-e – Carbon dioxide emissions

FiT – Feed in tariff

FT – Fischer-Tropsch method

GHG – Greenhouse gas

GT – Gas turbine generator

ICE – Internal combustion engine

LCFA – Long chain fatty acid

LFG – Landfill Gas

MSW – Municipal solid waste

OFMSW – Organic fraction municipal solid waste

OLR – Organic loading rate

OM – Organic matter

POR – Partial Oxidative Reforming

Syngas – Synthesis Gas TS – Total Solid

TS – Total Solids

VFA – Volatile fatty acid

VS – Volatile solid

WWTP – Wastewater Treatment Plant

CHAPTER 1 - INTRODUCTION

1.1 Outline of Study

The need for further research into Australian biogas potential for energy generation and emissions reductions was made clear with an extensive literature search, revealing a lack of estimates combining biomass sources from municipal solid waste (MSW), livestock manure and agricultural residues in anaerobic co-digestion (ACoD). This topic is also highly relevant to achieving Australia's emission reduction goals for the Paris Agreement as well as future energy security. Project objectives and expected outcomes are covered in more detail in section 1.3-1.4, and methods are outlined in chapter 3. Results are presented in chapter 4 and in-depth discussion and conclusions in chapter 5 and 6 respectively.

1.2 Introduction

It is well known that rising global temperatures resulting from greenhouse gas (GHG) emissions are a serious societal threat, risking both natural environmental integrity and decreasing quality of life for future generations. This is a global problem that must be pro-actively solved by governments and cannot be ignored in favour of 'business as usual'. As a participant in the Paris Agreement, Australia is contributing by reducing GHG emissions to 43% below 2005 levels by 2030 and aiming for net zero carbon emissions by 2050 (*Australia's Nationally Determined Contribution Communication* 2022). The renewable energy sector has good potential to help achieve this goal, as it provides carbon neutral energy and is a path away from reliance on fossil fuels.

Electricity use was the largest emitter in 2021, contributing 32.9% of GHG emissions (*Quarterly Update of Australia's National Greenhouse Gas Inventory* 2021) and so developing the renewables sector is priority for emission reductions. Specifically, this research project focuses on potential for biogas generation from anaerobic digestion of combined biomass sources, and the potential this form of bioenergy has to reduce Australian greenhouse gas emissions.

In the financial year of 2020-21, 27% of Australia's total electricity generation was by renewable sources, however renewables only contributed to 8% of energy consumed across all Australian sectors (Australian Energy Statistics 2022). Oil is still the highest consumed energy (36.2%) followed by coal (28.7%) and gas (27.1%). There is need for improvement here, and bioenergy especially has high unutilised potential. This is due to its comparatively low average annual growth of only 2.5% over the last 10 years, in comparison to 33.6% from solar and 15.0% from wind energy (Australian Energy Statistics 2022). Figure 1 clearly shows the low contribution of bioenergy to overall consumed renewable energy and would suggest high potential for future growth. In saying this, the lack of growth may also mean there are factors limiting bioenergy uptake in industry, and these must be clearly outlined and understood to justify this study.

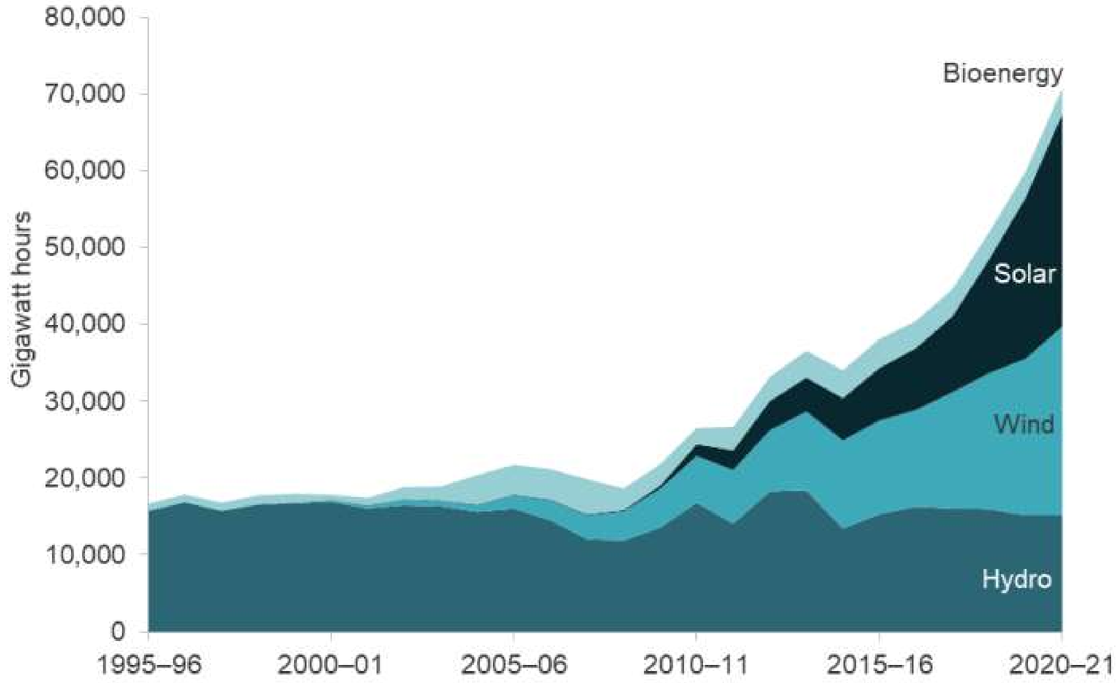

Figure 1 - Contribution proportion of renewable sources to Australian energy consumption, showing low growth in bioenergy source. Image source (Australian Energy Statistics 2022)

1.3 The Problem

Bioenergy and therefore biogas has seen very little growth over the past decade, as opposed to other forms of renewables. Reasons for this are investigated in the literature review in chapter 2 and can be summarised by lack of cultural motivation, government support, and clear knowledge of energy potentials. There is there for a need for better understanding of biogas potential in Australia, and so justifies this report specifically, where biogas energy potential of all MSW, livestock manure and agricultural residue is estimated. The problem remains of how accurate this estimate can realistically be, considering the many simplifications and real-world variables that cannot always be accounted for, and the methodology in chapter 3 covers how this is addressed in detail.

1.4 Project Objectives

This research aims to estimate the potential Australia-wide biogas supply and greenhouse gas emission reduction resulting from combined anaerobic digestion of livestock manure, agricultural residue, and municipal solid waste. The possible amount of biofertilizer generated will also be determined, along with GHG emission reduction potential, and total electricity or biofuel produced. To do this, the most suitable sources of biomass logistically and for the combined ACoD application must be identified and their availability/quantity determined. In doing so, it will be possible to make meaningful recommendations for potential future development of biogas infrastructure in Australia, and where government policy/financial support may be most efficient to help develop the industry.

The following key objectives are required to achieve the project aim:

1. Understand how similar biogas estimates have been done before with existing studies and where the research gap exists specifically.
2. Determine best biomass sources within the specified category for best net energy production.
3. Conduct extensive literature review to collect data required to determine variables for calculating biogas of each source.
4. Collect data for methane-energy conversion, expected losses from efficiency and polluting factors which need to be considered (transportation of biomass, possible methane leaks etc.)
5. Process and summarise the collected data, excluding outliers, to determine most representative final values.
6. Perform calculations to estimate potential biogas and biofertilizer production, net energy generation and net-GHG emission reduction for whole of Australia.
7. Make recommendations for sourcing biomass, positioning reactors, required infrastructure development (e.g. waste storage, pipelines etc.), required supportive policy and funding to ensure potential biogas production is achieved in the future

1.5 Expected Outcomes

Due to the limitations in time and availability of data, the expected outcomes of this research are estimates only of the biogas potential for the specified reactor feedstock, which will provide a ballpark range for energy production and contribution to net zero emissions of the biogas sector. With this information, recommendations made are likely to include elevated government funding to facilitate new ACoD reactors, clearer policy aims and a value target for the future of biogas use in Australia. It is also expected that recommendations for future research into exact availability and factors limiting feedstock access will also be made, as well as studies outlining conflicting uses of agricultural residue, transport logistics and best locations/sizes of ACoD reactors.

CHAPTER 2 – LITERATURE REVIEW

2.1 Introduction

This literature review is an overview of the existing research relating to biogas production from anaerobic digestion (AD) in Australia, including its energy applications, reaction process, an overview of ACoD, current extent of its use, Australia specific challenges and overseas policy versus Australian policy. Literature relating to biomass sources is also reviewed, focussing on advantages, disadvantages, availability, biogas production potential and suitability for inclusion in ACoD of several available sources. Finally, similar studies aiming to determine country-wide potential for biogas production from combined biomass sources are reviewed, so that the research gap is clearly defined.

2.2 Anaerobic Digestion Background

2.2.1 Energy Applications

Anaerobic digestion of biomass is a complex biological process carried out by several naturally occurring bacteria in an absence of oxygen. The feedstock for the process can be any form of organic material, ranging from abattoir and dairy farm runoff/solid waste, animal manure/used bedding, organic fraction of municipal solid waste (OFMSW), wastewater/sewerage sludge and agricultural residues. With correct design, AD is a source of renewable energy and produces biogas or biomethane. With correct refinement, these gases can substitute fossil-fuel derived gas, and can be used for a variety of energy applications (Figure 2).

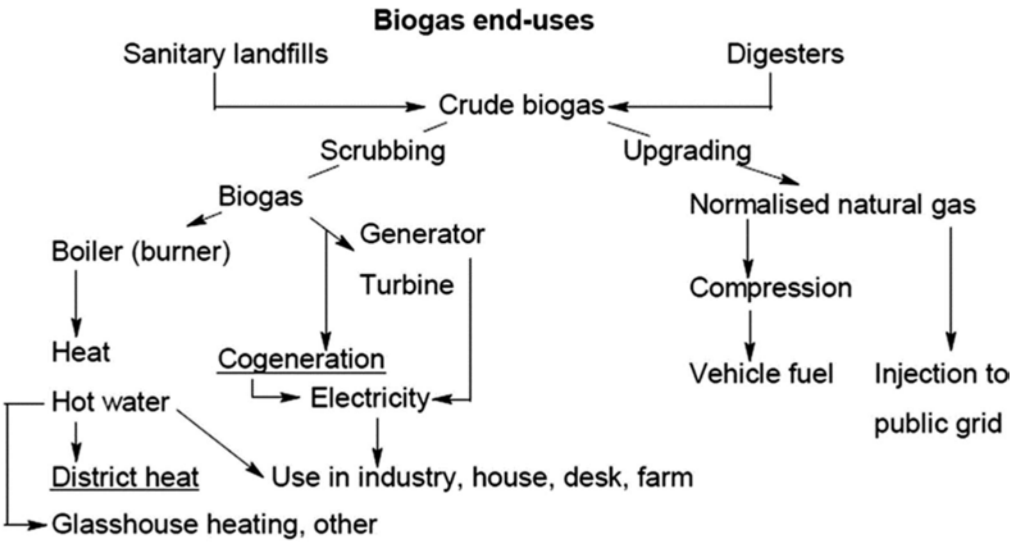

Figure 2 - Biogas end use pathways. Source:(Abanades et al. 2022)

The most common of these energy uses are outlined below:

Electricity generation – raw biogas can be converted to electricity on site with combustion engines/gas turbines etc. and either sold directly to the grid, used to charge batteries, or used on site for power required by the digester/upgrading process. If electricity generation is to happen off-site and the gas transported, it is beneficial to upgrade the biogas to biomethane (97-98% by volume CH_4), as it has higher heat content and is not corrosive as all hydrogen sulphide has been removed (Capodaglio et al. 2016).

Heating – biogas can be used for any heating requirements of the digester with specially modified boilers or can be used for industrial heating requirements. Australia's Bioenergy Roadmap (*Australia's Bioenergy Roadmap* 2021) specifically identifies 'hard to abate' sectors that are more difficult to convert to more traditional renewables like solar or wind. This report identifies renewable industrial heat generation as one of these sectors in Australia and therefore makes biomethane a very appealing future investment.

Gas grid injection and biofuel – After biogas is upgraded to biomethane and gas standards are met, it can be injected directly into existing gas grids or used instead of natural gas fuel for some cars/buses/trucks (*Australia's Bioenergy Roadmap* 2021). Established gas grid infrastructure being utilised with minimal change is a beneficial point in biomethane uptake in Australia. Gas grid injection is also considered another 'hard-to-abate' sector (*Australia's Bioenergy Roadmap* 2021).

Vehicle fuel – After further processing, biomethane can be used as compressed natural gas (bioCNG) or liquefied natural gas (bioLNG) for use in gas powered vehicles (Carlu et al. 2019) or can be further upgraded to synthesis gas (syngas) and used to produce hydrocarbon fuels for vehicles/aircraft (Lau et al. 2011).

Hydrogen fuel – Biogas can be upgraded syngas via dry or steam reforming, and used in emerging applications of hydrogen fuels e.g., fuel cells, hydrogen powered vehicles (Abanades et al. 2022).

Biomethane also has the benefit of being relatively easy to store and transport without relying on electricity grid infrastructure, and so offers alternatives to wired electricity and can supplement supplies when solar/wind are inadequate. AD also reduces potential pollution from organic waste products, capturing greenhouse gas that would otherwise be emitted as they break down naturally. The process also creates digestate by-product, which is useful as a natural agricultural fertiliser, and reduces the need for synthesised fertilisers in Australian agriculture.

2.2.2 Anaerobic Digestion Reaction Overview

There are four main steps to AD process, as follows (Figure 3) (Stamatelatou et al. 2011):

Hydrolysis – With the addition of water molecules, high molecular weight organic polymers (carbohydrates, proteins, fats) are hydrolysed by extracellular enzymes into monomers (simple sugars, amino acids, lipids, long chain fatty acids (LCFA)) which can be more readily accessed by bacteria.

Acidogenesis – Further breakdown of simple organic monomers into volatile fatty acids (VFA), alcohols and other simpler compounds by anaerobic heterotrophs.

Acetogenesis – Acetogenic bacteria convert organic molecules and VFAs (propionate, butyrate, valerate etc.) produced during previous acidogenesis into acetic acid, carbon dioxide, and hydrogen.

Methanogenesis – Two different types of methanogens convert products from the previous stages into methane (60-70% under ideal conditions), carbon dioxide, water, and trace amounts of toxic hydrogen sulphide. Acetoclastic methanogens use acetic acid and produce most of the methane (about 70%), while hydrogenotrophic methanogens produce the remainder.

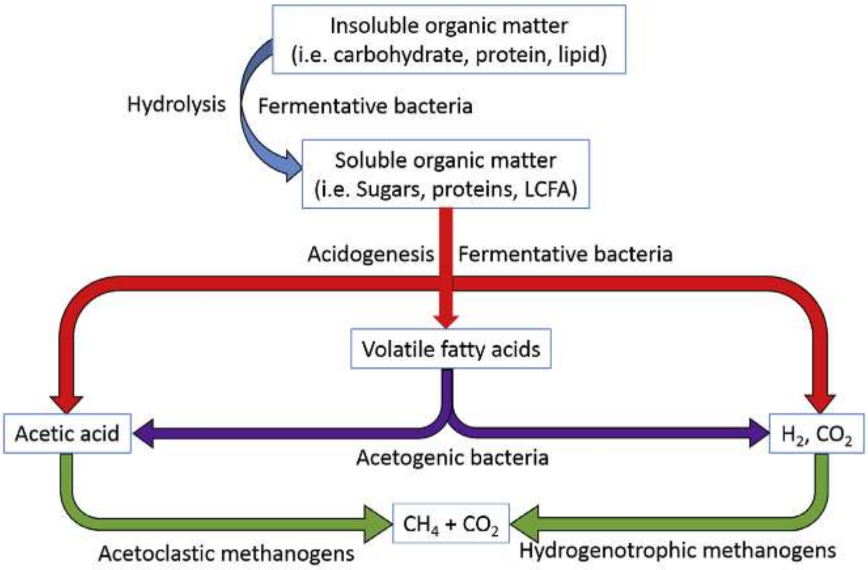

Figure 3 – Steps in the anaerobic digestion process. Source (Alexander et al. 2019)

These steps and the amount/quality of methane they produce is dependent on conditions in the reactor being correct chemically, and the presence of certain compounds must be within acceptable concentrations. Important factors that need to be considered when operating a digester are outlined as follows:

Feedstock nature – Final methane content is dependent on the oxidative state of carbon in compounds, and more reduced carbon means higher content of methane in biogas. In general, biogas can be composed of up to 60% methane, with the remaining being CO_2 and trace amounts of other gases. It is also important for the carbon and nitrogen in feedstock to be at a ratio of C:N of 20:30. This is the ratio they are used in by the microorganisms, and so results in the most efficient process with least waste product remaining. Anaerobic co-digestion (ACoD) can help maintain this ratio if managed properly. Pre-treatment may also be required if the waste feedstock is particularly 'complex' molecularly (e.g. of plant origin, agricultural residue), as it ensures hydrolysis process is fast enough and doesn't limit the rate of reaction (Stamatelatou et al. 2011).

The pH – neutral pH is ideal as it is most efficient for production of undissociated acids/bases, and these allow for most efficient anaerobic digestion as they can most easily penetrate cell membranes. Low pH inhibits methanogen bacteria, and at pH 5-6 acidogens (during the acetogenesis stage) can make this effect worse by continuing to produce pH lowering acids. Due to high growth rate, acetogenesis must be carefully monitored and kept at a steady rate to avoid unbalancing pH.

Presence of toxic/inhibitory substances – The methanogens primarily responsible for methane production are anaerobes and any oxygen exposure is toxic. It is therefore important that sufficient facultative anaerobes are present in external layers of the digester to keep redox potential in acceptable levels (-400 mV) (Stamatelatou et al. 2011). Other substances that must be controlled lest they cause harm to bacteria populations include:

- Ammonia – Non-ionised ammonia is inhibitory to methanogens. Level of tolerance can vary, with conflicting research results, but there is potential for acclimatisation at the cost of reduced biogas production.
- Long chain fatty acids (LCFA) – LCFAs are absorbed on surfaces and interfere with molecule transfer mechanisms, causing reduced reaction rate and separation/flotation of biomass. They are possible to biodegrade in mesophilic and thermophilic conditions.
- Metals and heavy metals – Metals (sodium, potassium, calcium, and magnesium) are used for pH control and are required for microbial growth in small amounts but can cause inhibition/toxicity at high concentrations. Heavy metals (chromium, iron, cobalt, copper, zinc, cadmium, and nickel) in soluble free ionic form are toxic to bacteria and can be present in high quantities in wastewater especially. To avoid negative impacts, they should be removed with immobilisation via precipitation, sorption, or chelation.
- Sulphide and sulphate – Sulphate causes anoxic conditions in absence of oxygen as it accepts electrons. Sulphate reducing bacteria therefore compete with methanogens, and as they can utilise more substrates (acetate, hydrogen, propionate, butyrate), are likely to out compete them and limit biogas production. Sulphide is toxic to methanogens, however, can be acclimatised to up to a certain concentration.

2.2.3 Anaerobic Co-Digestion

Anaerobic Co-Digestion (ACoD) is a form of anaerobic digestion where more than one feed stock source is fed into the reactor. There are several reasons for this practice, including potential for increased biogas production, a more stable reactor that is adaptable to sudden condition changes (high buffering), and a more reliable supply of feedstock which is more consistently available year-round (Karki et al. 2021). ACoD also reduces the chance of build-up of contaminants/inhibiting compounds which can result from digestion of single source feedstock. There are very few drawbacks to the process, except a possible increase in complexity of management or logistical challenges of transporting and combining waste streams in correct amounts or correct time.

An imbalance of certain compounds in the reactor can inhibit bacteria activity and even cause enough loss of microbial diversity that total reactor failure occurs. For example, the concentration of heavy metals can build up to toxic levels if the same feedstock is used consistently and small amounts are added gradually overtime. Volatile fatty acids tend to accumulate and inhibit methanogens if feedstock is too easily biodegraded and acidogenesis occurs too rapidly. Also, if feedstock is overly high in protein (e.g., meat works waste) then there is more likely to be increased levels of ammonia (NH_3). If feedstock is high in sulphate, then increased hydrogen sulphide (H_2S) could result. It is therefore better to ensure feedstock includes a good mix of organics and inorganics, correct levels of trace elements and ideal C:N ratios which promote low retention time, high microbial biodiversity, increased biogas production and better quality digestate.

Optimal conditions like these can be achieved through better management of mono-digestion, for example by manually adjusting pH, adding microbial cultures, or feeding intermittently. These are however costly practices or increase operational complexity (Karki et al. 2021). Using ACoD instead and supplying feedstock from different waste streams can solve most issues arising from reactor imbalances, however, there still needs to be careful consideration of which feedstocks are mixed and in what ratios. Karki et al. (2021) states that highly biodegradable feedstocks like food waste/OFMSW should be mixed with lignocellulosic feedstock, which have much slower rates of hydrolysis. Sewage sludge on the other hand requires increased C:N ratio and additional alkalinity/trace elements, and so co-digestion with OFMSW or lipid rich wastes (fat, oil, and grease) increases biomethane potential. Animal manure biomass is similar, requiring increase in C:N ratio to avoid ammonia toxicity, and so should be combined with carbon rich biomass like food wastes or meat/dairy production wastes. Figure 4 shows a range of biomass sources and the effect combining them in ACoD has on methane yields.

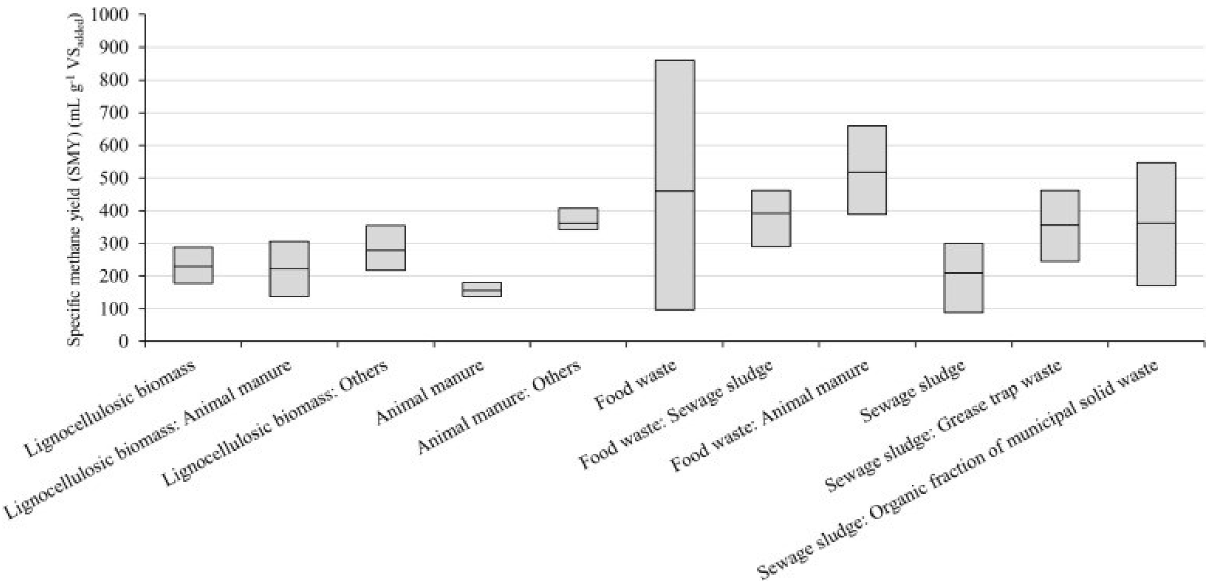

Figure 4 - Specific methane yield of various feedstocks, comparing results with mono-digestion and co-digestion. Source:(Karki et al. 2021)

Zahan et al. (2018) found that optimal biomethane production occurs with a 60:20:20 mix of chicken litter (manure): food waste: wheat straw (agricultural residue) at 2.0g total solids (TS)/litre/day organic loading rate (OLR) with feedstock with 4% TS. This paper highlights the importance of finding optimal C:N ratio for the chosen OLR, as it is not consistent. In summary, if feedstocks are properly managed and reactor conditions continually monitored, adoption of ACoD will be beneficial for Australia's future potential biogas production.

2.2.4 Biofertilizer from AD

Another major benefit of anaerobic digestion is that the solid leftover digestate is also extremely useful for fertilizer applications and has the potential to reduce Australian agricultural sector consumption of chemical fertilisers. In the 2016-17 financial year, 5 million tonnes of fertilisers were applied to 50 million hectares of land (Australian Bureau of Statistics 2017). Due to major world events the cost of imported fertiliser in Australia has almost tripled since 2020, with an import value of $4.9 billion in 2021-22 (Australian Government 2022). There are no signs of near-future price reductions, and reduced yields from decreased fertiliser use continue to force up costs of fresh produce for consumers. In this situation the benefits of developing Australia's circular economy and promoting self-sufficiency are obvious and increasing biofertilizer use/production is one way of contributing to this.

2.3 Biogas in an Australian Context

2.3.1 Current Biogas Production in Australia

With increased global attention on climate change and focus on developing renewables to replace fossil fuels, AD has seen a steady increase in use in many overseas economies (Figure 5). As stated previously, this is not the case in Australia however, with only 242 AD plants operating in 2017 (Alexander et al. 2019). Of these, only five were using food waste specifically, with the majority being associated with wastewater treatment plants (WWTP) and landfill gas (LFG). Over half of this gas was flared and not used for energy generation due to lack of purification infrastructure (Carlu et al. 2019). The remaining AD plants were associated with abattoirs, using pig manure and abattoir wastewater for AD. There were no examples of AD plants combining biomass from multiple waste sources. The Clean Energy Finance Corporation estimates that ‘bioenergy and waste energy’ creates 800MW of electricity as of 2017, however this estimate includes landfill gas and direct combustion as well as biogas generation (Deloitte 2017).

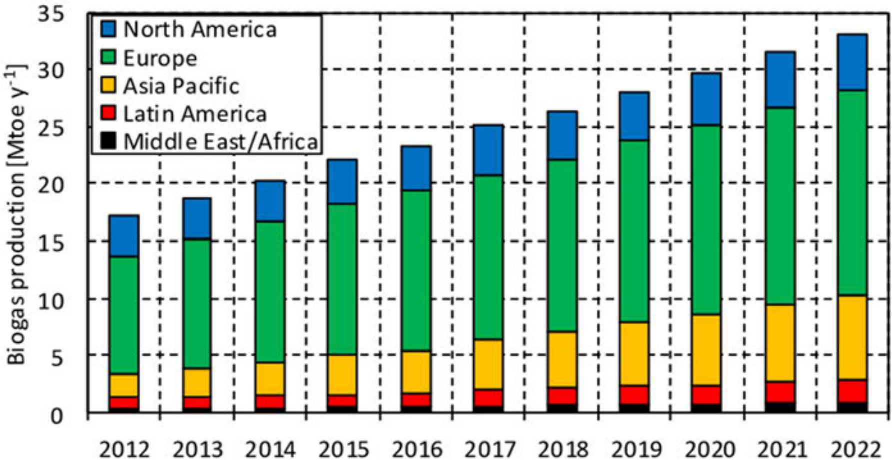

Figure 5 - Biogas production trends across the globe (Raboni et al. 2015)

The fact that there are no ACoD reactors or biomethane upgrading facilities in Australia (*Australia’s Bioenergy Roadmap* 2021) represents a lack of large-scale planning surrounding biogas utilisation and energy generation in the past. Biogas reactors were historically installed on small scales by individual farms, processing plants and wastewater treatment facilities, were there was not necessarily motivation or need to combine waste streams. It may also hint at difficulties surrounding practical implementation of ACoD, such as high transport costs, low density agriculture and lack of policy support, all Australia specific challenges which cannot be overlooked.

2.3.2 Biogas Production Challenges in Australia

Logistical Challenges and Available vs Accessible Feedstock

The biggest challenge in maintaining productive large centralised ACoD reactors is logistical, as there is a large gap between biomass that is theoretically available because it exists, and biomass that can be accessed in a timely and cost-effective manner for use in ACoD. Efficient biogas production is highly dependent on OLR and correct waste source mixing ratio, so any shortages or delays in delivery to centralised digesters from poor logistical planning could be costly.

Australia's Bioenergy Roadmap states that growth of bioenergy use in Australia is limited by 'accessibility considerations', and with business-as-usual waste management practice, approximately only 45% of potential biomass is accessible for biogas generation (*Australia's Bioenergy Roadmap* 2021). There are ways to increase availability however, and looking to overseas examples, correct policy implementation makes this possible. For example, countries with high biogas production like Germany or Sweden have specific targets to reduce the amount of waste in landfill, achieved through uniform levies between states and banning organic matter in landfills. If Australia can achieve this too, success and uptake of bioenergy from biogas will be more likely and more sustainable in the future.

Another factor inhibiting biogas uptake in the Australian economy is simply high land area. As Australian agriculture is more spread out and less intensive than in places like Europe, transportation costs for things like manure or agricultural residue will always be higher and take longer in general. Also, it is more common for Australian cattle/dairy farms to use rotational grazing instead of feed lots. This is the opposite of most farms in Europe, making it less practical and more expensive to collect manure.

Also, the majority of Australian farmland is very dry or has infertile soils, so relatively small amounts of land are suitable for cropping. This leads to significant conflict of interest between growing energy crops as opposed to food crops. This problem could be solved by intercropping energy crops with food crops, using marginal land for energy crops or increasing crop yields through better farming practice. There is also the issue of agricultural residue being required for carbon sequestration on soils, and so is unavailable for use in ACoD (*Australia's Bioenergy Roadmap* 2021).

Climate

As stated previously, the microbes and bacteria responsible for the generation of biogas from biowaste are dependent on several environmental factors, both within the reactor itself and externally. Australia's climate offers several unique challenges to this balance, which must be understood and properly managed for efficient biogas generation.

Australian temperatures are generally very different to other nations which have already progressed into high biogas production, and they offer both benefits and drawbacks. Higher average temperatures are beneficial to the AD process and thermophilic (>50°C) or mesophilic (30-40°C) ranges are preferable. Some of the benefits of these reaction types include higher metabolic rate of bacteria, meaning higher methane production rate and increased allowable OLR (Stamatelatou et al. 2011). There are also benefits including highly stabilised waste sludge, with more thorough destruction of viral and bacterial pathogens and increased ease of post treatment dewatering of sludge. However, thermophilic reaction especially can be more sensitive to ammonia inhibition, and a build-up of fatty acids is more likely.

So overall, higher temperature is preferred, and Australia's climate generally allows for this to be achieved with minimised energy loss for heating. However, Australian temperatures are also highly variable, with common ranges from -10 to 45 °C in some areas and almost all possible climatic conditions experienced around the country (Geoscience Australia 2023). This variability is a very important factor to consider in the management of AD reactors. There is a maximum temperature beyond which bacteria cells start to become inactive, while temperatures below 20°C will result in psychrophilic conditions, which involve entirely different bacteria to continue efficient biogas production (Stamatelatou et al. 2011). Also, acetolactic methanogens, which are responsible for up to 70% of methane generation, are highly sensitive to changes in temperature. So, for best practice, reactor temperature must be kept stable and at a temperature which suits the specified OLR and bacterial population in use.

Another climatic factor to consider is the availability of fresh water for use in the reactor. The requirements for water will depend on the type of reactor and feedstock being used, however there will always be some demand. Australia is well known for drought and extremely low average annual rainfall, and freshwater allocation is a highly contentious social and political issue. The introduction of anaerobic digesters on a large scale could provide enough of a demand for water that societal pushback may result, and this possibility must be carefully managed in the future.

Public Opinion and Economic Motivation

Wilkinson (2011) aimed to 'contextualise' the socio-economic, biophysical, political, and institutional situation of Australia and how this affects uptake of AD technology, specifically on individual farms. They found that on farm AD is underutilised mostly due to lack of government financial support. As an example, waste management mandates on their own have not been sufficient to encourage wide scale AD uptake in places such as Germany, and Australia will likely be in a similar situation. Besides securing feedstock streams, scarcity of trained operators of AD plants makes initial costs very high, and return won't be seen for years to come. Also significant is the fact that Australia is a net energy exporter, with two-thirds of all domestic energy being exported (QLD Government 2021). So, in general political motivation for energy generation from de-centralised sources has been historically low.

Public opinion and interest are often key driving forces behind new technologies, and so must be understood and embraced for the future of biogas in Australia. There is already misconception that there will be competition between agricultural land use for food vs fuel, or negative effects on farming processes if agricultural residue is removed, reducing soil carbon sequestration. This doesn't have to be the case, and it is preferred that the growth of energy crops is not necessary for sustainable biogas generation. Also, not all crop residues are left on soils, and this estimation will incorporate only those which would otherwise be burnt off or wasted in some other way. Also, digestate can be returned to soil as a more efficient fertiliser source in many cases, and the public should be made aware of this point.

Besides awareness of the benefits of anaerobic digestion, there also needs to be education and training on its implementation. Not only will the availability of skilled workers make operating plants cheaper and more successful, but public awareness is likely to encourage better personal management of municipal solid waste and so increase availability of OFMSW. One possibility of increased awareness could be government incentives for small scale backyard digestors in homes or schools, as well as widespread advertising of how Australia will meet energy demands in the future as coal power is gradually phased out. One third of all coal power plants have been closed since 2012 in Australia (Goh et al. 2018), and so change is progressing rapidly and the public needs to be aware of what the future energy market will look like. Most important is communication of where new job opportunities are being created with growing biofuel industry, especially to demographics that are likely to be losing jobs due to shutdown of coal mining operations.

The challenges surrounding feasibility of ACoD and energy from biogas in Australia can only be solved with continued research and practical application of the research recommendations through policy and industry practice. Hence, the research being undertaken in this report is justified and necessary.

2.3.3 Biomass Sources in Australia

Livestock Manure Source

The most important factors to consider when selecting manure sources is overall quantity (number of animals) and availability. There will be high variability in availability depending on the type of animal and the type of farming practice in use. For example, as animals are in a contained area for a period every day, dairy farm manure will have higher availability then grass fed beef. This is a variable that must be considered even though the manure is from the same animal, and estimates would be inaccurate if it were overlooked. Also, the specific chemical properties of each manure type must be found so that total and volatile solids content per kilogram are known. This value will be universal as it is only dependant on the animals' biology, and so overseas values will be relevant. There may also be conflicts of interest with other uses for certain manure types/sources, and this will need to be factored in with availability.

Agricultural Residue

Like manure, deciding on agricultural residues to include in energy estimates depends on quantity and availability, however, should also consider the suitability of each residue type for inclusion in ACoD. This is because there is higher variability in agricultural residue chemical properties, and their effects when added to ACoD are not universal and may sometimes be detrimental if not managed properly. There is also higher variability in demand for residues outside of biogas production, as some such as bagasse, are already used for energy production or other purpose such has carbon sequestration, livestock feed or bedding.

Municipal Solid Waste

Municipal solid waste is different to the previous waste examples as it is already being deliberately transported, and availability factor is therefore dependant on government waste management policy and not necessarily restricted by geographical issues surrounding collection. The quantity estimate will need to be found for each Australian city and will be an estimate of waste quantity per person. Volatile and total solids content is also highly variable depending on the location and time of collection, and the final value used for each location needs to be carefully researched.

2.3.4 Australian Policy Affecting Biogas Production

All research suggests that anaerobic digestion has only been adopted on a small, isolated scale in Australia, with opportunistic businesses like abattoirs and WWTP using the technology where they can save on operational costs. However, this is not ideal for increased biogas production, as efficiency increases with larger combined digesters (Energy Networks Australia 2022). Future Fuels CRC found that digesters combining multiple streams of feedstock significantly increases cost savings, and when incorporating bio-fertiliser profit, OM waste gate-fee avoidance and possible renewable heat incentives/carbon credits, can reduce production costs below Sydney natural gas prices and turn profit for the facility (Figure 6).

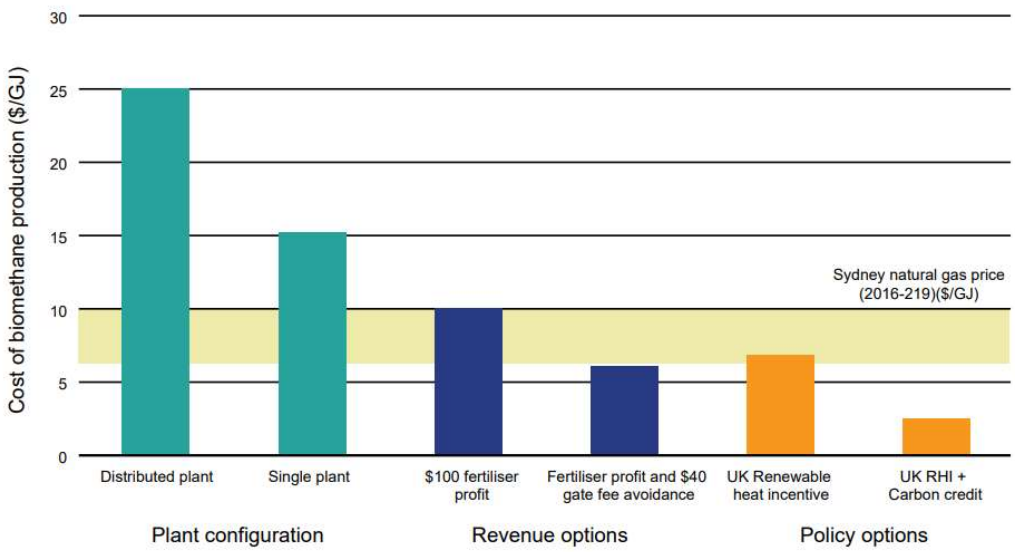

Figure 6 - Revenue options for biomethane production facilities to help biomethane approach natural gas prices (Energy Networks Australia 2022)

Historically, there has been very little government support to develop the bioenergy sector in Australia to a level of self-sufficiency. This has meant very slow uptake of the technology, and low overall biogas production country wide. Along with increased overall production amounts, it is crucial that biomethane develops as an energy source that can be integrated into existing infrastructure. This will mean it can be used alongside other renewables in a carbon-neutral future. This goal will only be achieved with proper policy development in Australia.

Overseas Policy Examples

Australian policy promoting bioenergy sector development can learn from overseas countries and how they have facilitated strong growth in AD digester installation and incorporation into the energy sector. Germany produces 50.3% (100 TWh) of all European biogas, and has achieved such high production via 20 year fixed price feed in tariffs (FiTs), investment support for biomethane plants and banning of landfilling waste with greater than 5% OM since 2002 (Carlu et al. 2019). However, since the FiTs have been replaced with direct sale to the energy market, and restrictions placed on energy crop use, new biogas plant development in Germany has stalled since 2012 (Torrijos 2016).

Being the second largest producer in Europe (23 TWh), the UK implemented similar policies to Germany, including a FiT policy in 2010. The UK also introduced laws to ensure landfill gas is collected as well as incentives for heating generated by biomethane and biomethane injection into the grid (Carlu et al. 2019). There are obvious trends here and would suggest the best policies to ensure biogas sector development are introduction of long-term FiTs, restrictions/taxes on landfilling OM and investment support for new digester development.

Current Policy in Australia

Current policy affecting biogas development in Australia:

Emission reduction fund (ERF) (*Australia's Bioenergy Roadmap* 2021) - for biomethane announced by the government in December 2020, led by the Clean Energy Regulator, and will ultimately allow biomethane producers using waste/agriculture to receive Australian carbon credit units.

National gas decarbonisation plan (Energy Networks Australia 2022) – By 2030 carbon neutral gas is to compose at least 10% of natural gas pipelines and 100% of supply to new residential developments, also to ensure 100% supply is possible by 2050. This report states that as of 2022 these targets have had some progress made towards achieving them, but still require further development. It specifies the importance of joint planning across networks as availability of biomethane or renewable hydrogen will be highly variable depending on the region. The report also highlights the importance of establishing a 'renewable gas target', like the renewable energy target, as a unified target does not yet exist for Australia. This would be beneficial in supporting investment confidence.

Law reforms (*Australia's Bioenergy Roadmap* 2021) – in 2021 energy ministers agreed to reform National Gas Law and National Energy Retail Law to include biomethane and renewable hydrogen, meaning that legal standing for biomethane producers is clear and guaranteed.

Landfill policy/bans/levies – As per the National Waste Policy Action Plan 2019, by 2030 the Australian government aims to have achieved 80% recovery rate from waste streams, as well as successfully halving the amount of organic matter sent to landfill (Australian Government 2019). Having national unification of waste levies in very important in encouraging AD uptake, and avoids waste being preferentially sent to states with lower levies (Carlu et al. 2019). This is not seen in Australia (Figure 7) and there is high variability between states.

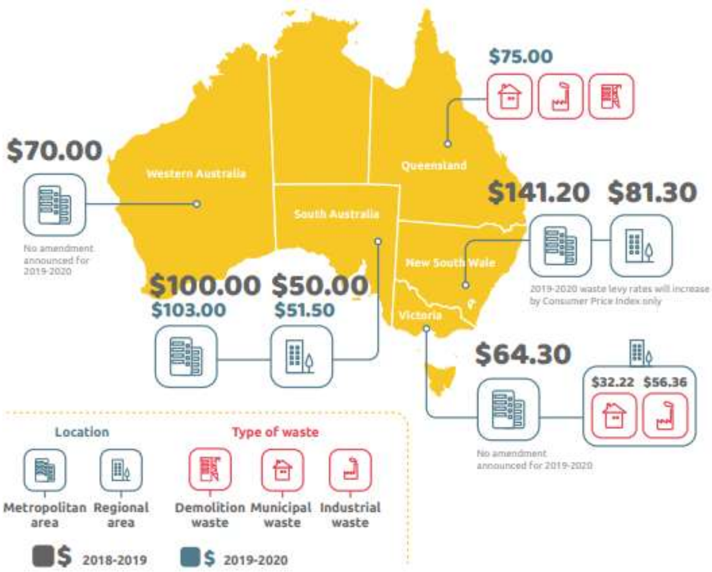

Figure 7 - Waste levies per Australian state (A$/tonne). Source: (Carlu et al. 2019)

Ideal Policy Development in Australia

Ideal policy development in Australia will ensure 'support mechanisms' for the biogas sector, including feed in tariffs, investment support and tax rebates. Correct support will facilitate rapid development in a way which is also sustainable so that the sector can be self-sufficient when support is removed. It is also important to encourage use of feedstocks which do not promote competition with other sectors e.g. specially grown energy crops taking up farm land, water resources etc. Good constraints around landfill are ideal, with strict limitations to OM quantities thrown away by individuals/industries, or levies charged on landfilling this material. Finally, so that there is sufficient demand, there also needs to be support in biogas uptake and use, not just its production. For example, targets to decarbonise the transport sector with biofuels or new legislation for injecting biomethane into natural gas distribution networks (Carlu et al. 2019).

2.4 Studies

2.4.1 Government Reports

There have been multiple Australia-wide reports on bioenergy and biogas future targets commissioned by the government, including 'Australia's Bioenergy Roadmap' and the 'Gas Vision 2050' report. These documents make estimates of potential biogas production, however, do not provide details on how final values were reached. According to A*ustralia's Bioenergy Roadmap* (2021), Australia can potentially generate 2600 PJ/year from bioenergy. This value is not necessarily just biogas/biomethane from waste (also includes combustion, other bioenergy sources etc) and the source acknowledges further research is required to increase 'clarity and detail' of bioenergy feedstock resources. Figure 8 shows a per state breakdown of this estimate.

Energy Networks Australia (2022) found that 371 PJ/year could be generated Australia wide from biogas produced from all municipal solid waste, food processing waste and agricultural cropping waste. This report also states the advantages of upgrading biogas, as existing gas pipelines, networks and appliances won't require alterations to use biomethane instead of traditional natural gas.

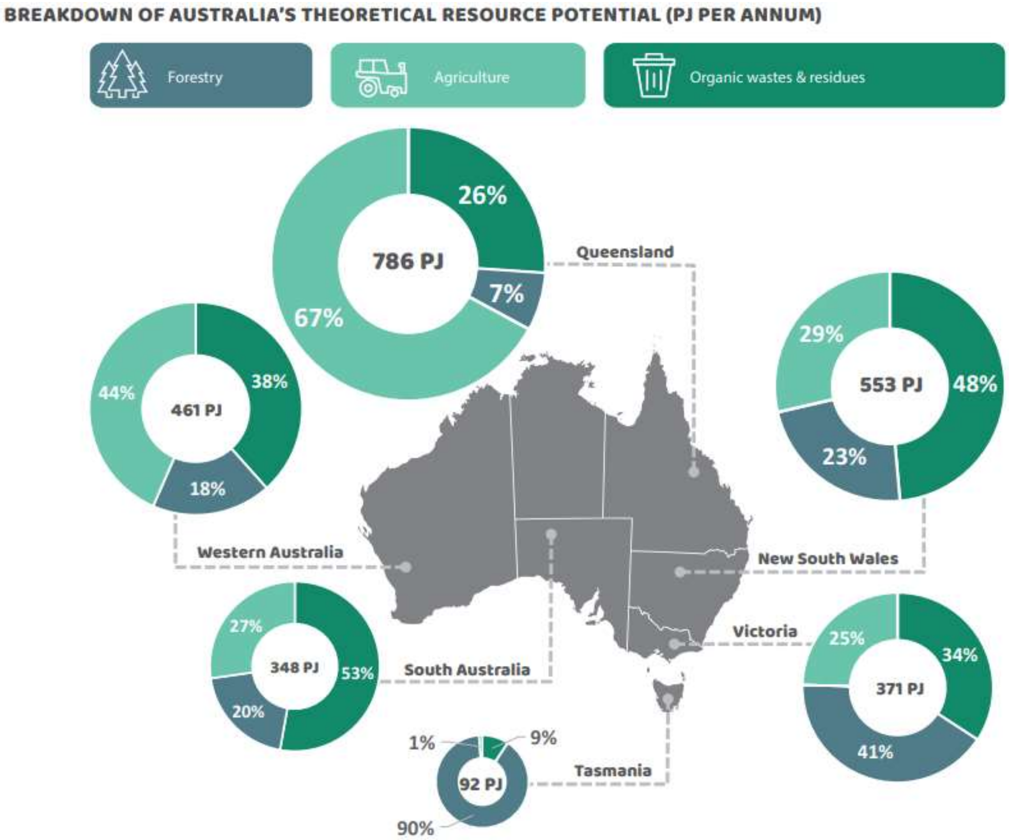

Figure 8 - Theoretical energy potential of forestry, agricultural and OFMSW for each Australian state. Source:(Australia's Bioenergy Roadmap 2021)

2.4.2 Slaughterhouse Waste

A study by Tait et al. (2021) found the potential energy generation from red meat and dairy processing by-product to be approximately 13.8 PJ/year. The liquid biomass sources (~79 GL/year) used for calculating this estimate included dairy farm/processing effluent, whey, and piggery/red meat processing effluent, while solid biomass sources (~2 megatons/year) included spent piggery litter, beef feedlot manure, and red meat processing by-product. Tait et al. (2021) states that there needs to be a 'consolidated review of key information gaps' regarding aggregated ACoD opportunity in Australia and encourages further research of combined biomass source potential.

Mofijur et al. (2021) estimates an Australia wide energy potential of 4.44E+13 kWh/year (158 400 PJ/year) from biogas generated from cattle, sheep, lamb, pig and poultry manure and abattoir waste (blood and rumen). This value is much higher than the previous studies of similar biomass sources, indicating literature discrepancy around energy estimates. Mofijur et al. (2021) uses the Australian Bureau of Statistics (ABS) to find primary data for livestock numbers. Biofertilizer potential is also calculated as 4.52E+10 tonnes/year, and GHG emission reductions of 1.33E+13 kg CO_2 from using AD facility, 4.12E+13 kg CO_2 from using biomethane in place of diesel vehicle fuel were found. However, Mofijur et al. (2021) found leaked methane could be up to 5.30E+11 kg CH_4, although this is very easily offset by CO_2 emission reductions resulting from using AD.

Jensen et al. (2014) found a biogas energy potential from individual slaughterhouses around Australia of up to 400 GJ/day. Waste streams considered in this estimate are wastewater runoff from slaughterhouse processing, including cattle yard, paunch, slaughter floor and rendering. Jensen et al. (2014) also reports variable methane potential of waste streams from 250-1000 L/kg VS, suggesting more efficient biogas/digestate generation if traditional anaerobic lagoons were replaced with bioreactors that can cater to each waste stream specifically.

Harris & McCabe (2020) also looks at the challenges of optimising biogas production from red meat production waste and concludes it is not sufficient on its own to completely cover site energy demand. The article does mention linking with 'co-located' industries to increase energy produced and benefit waste disposal for surrounding producers but doesn't go into any detail. It is this point of papers looking at AD feasibility with biosolids sourced from multiple waste supplies that seems to be lacking in research so far.

2.4.3 Wastewater Treatment Plants

Nguyen et al. (2021) found a potential 1.37 PJ/year of energy potential from biogas production at all fifty-four Australian WWTP that have reactors installed. These reactors successfully supply the WWTP energy demand in full, or in some cases, generate surplus electricity which is sold back to the grid. This paper found that ACoD digestion of sewerage sludge (high in nutrients) and OFMSW (high in carbon) increases efficiency of biogas production by increasing organic loading rate and keeping hydraulic loading about the same.

2.4.4 Municipal Solid Watse (MSW)

As well as capturing and utilising methane that would otherwise be released into the atmosphere, AD also has the potential to decrease Australia's CO_2 emissions (CO_2-e). Ngo et al. (2021) found that the Jankadot bioenergy AD facility was able to annually reduce CO_2 emissions by 7139 tonnes from 50 000 tonnes of commercial/industrial biowaste. According to this source, all other MSW treatments (landfill, incineration, composting) generate additional CO_2 emissions, but AD saves 0.143 tonne per 1 tonne waste. Ngo et al. (2021) also states that 222 kWh of electricity can be generated per tonne of MSW via AD, which is very efficient compared to potential generation from landfill gases or incineration methods.

Lou et al. (2013) found that all of Australia's food waste, compiled at multiple sites across the country, could only generate 1 915 GW electricity annually. This value contributes only 3.5% of energy supply from renewables (as of 2013), so shows how a single feedstock source is not ideal for biogas generation. Lou et al. (2013) also suggest that AD is more beneficial for use in low population density rural areas, as it is a very flexible, decentralised source of power.

Dastjerdi et al. (2019) found that the energy potential of NSW MSW and commercial/industrial food waste to be 1.01 PJ/year when diverted to AD. This study also found potential CO_2 emission reduction from these waste streams being diverted from landfill to be 2.24 E+5 tonne CO_2 equivalent/year.

Zaman & Reynolds (2015) found that biogas yield from AD of South Australian food waste to be up to 265 m^3/tonne, and assuming 15% of projected 2021 food waste estimates, has the potential to generate 0.0074 PJ/year. This is a relatively low value compared to previous estimates by Dastjerdi et al. (2019) of NSW OFMSW, and to rectify this Zaman & Reynolds (2015) suggests including chicken meat processing waste and manure in ACoD to increase energy output. In this scenario biogas production increased to 727 m^3/tonne, and total energy potential to 0.103 PJ/year.

Mahmudul, Rasul, et al. (2022) found 10% of food waste being processed can lead to production of 1.22 - 35.4 GWh/year of electricity. In another study, Mahmudul, Akbar, et al. (2022) found a value of 152.32 GWh/year using all processed food waste. In comparison, a study by Lou et al. (2013) found total Australian food waste could potentially generate 1915 GWe (0.219 GWh/year). This is a much smaller value than found by the previous studies, so there is discrepancy in the literature values.

Papers investigating AD potential from the meat production sector are the most common, followed by dairy industry and WWTP. Agricultural residue, manure and MSW are less common and so mirror the underutilised potential of these waste sources. No examples of overall viability for AD Australia wide, combining multiple bio-waste sources (especially those specified in this study) were found, or those that did had conflicting values or also combined combustion or other forms of bioenergy.

2.4.5 Livestock Manure

Deloitte (2017) found a biogas production estimate of 29.3 PJ from ‘livestock residues’, with most of this energy being sourced from livestock in NSW, Victoria, and QLD (Figure 9). It is unclear from the source if these ‘livestock residues’ include any wastes other than manure. This study also states that livestock residue bioenergy comes with low or even negative costs, depending on proximity of residue source to reactor and reactor to gas distribution network, and estimates $11-18/GJ. Nationwide estimates of biogas from livestock manure were difficult to find, and studies instead focussed on analysing benefit of on farm-digestion for piggeries especially. One such study by Tait & McCabe (2020) found that biogas from manure was feasible for medium and larger size piggeries, and if more than 250 m^3/hr of biogas was generated, then energy in excess of the piggery operations would be generated. In this case the piggery could on sell electricity to the grid for a small profit or involve a third-party gas manufacturer-supplier under careful contract stipulations.

2.4.6 Agricultural Crop Residue

Deloitte (2017) found that straw and chaff left over from agricultural crop harvest (including bagasse in QLD) can potentially produce 319.4 PJ of energy from biogas Australia wide. This study found agricultural residue to have the largest potential energy of all waste residues tested, however also states that it is less suited to anaerobic digestion due to its dry consistency. This report does not explain how these values are calculated, however does state that the Australian Biomass for Bioenergy Assessment (ABBA) is used as the information source for available feedstocks. This assessment was carried out from 2015 – 2020 and was funded by the Australian Renewable Energy Agency (ARENA) (NSW Government 2020). The data was collated on the 'National Map' which will be a useful resource for spatial distribution of potential biomass sources for this study.

State	Urban waste	Agricultural crop residue	Livestock residue	Food processing residue	Total biogas (PJ)	Biogas potential (excluding agricultural crop residues)	Total biogas potential
NSW	3.5	75	8.8	0.6	88	15%	103%
VIC	2.4	38	6.8	0.4	48	5%	27%
QLD	8.6	66	8.8	0.6	84	70%	327%
SA	3.3	40	1.9	0.2	46	17%	142%
WA	1.7	100	1.4	0.4	103	13%	384%
TAS	0.2	0.4	0.4	0.0	1	23%	36%
ACT	0.2	0.0	0.0	0.0	0.3	2%	3%
Total	**19.9**	**319.4**	**29.3**	**2.2**	**371**	**14%**	**102%**

Figure 9 - Potential biogas energy equivalent from waste sources Australia wide, including percentage of regional gas demand via distribution networks. Source: (Deloitte 2017)

2.5 Research Gap

Throughout the literature review process, it was clear that very little research has been done considering AD from combined sources of biomass, with the aim of total estimates of biogas generation potential alone for the entirety of Australia. It seems more common for research to focus on improving the AD process, methods used in AD to speed up the process, best methods for refining biogas, what the costs are and what is preventing the uptake of AD in Australia. Very few papers were found that analyse the potential and logistics of AD from combined sources, including animal manure, agriculture residue and MSW. The papers that did make estimates of AD from combined sources also did not clearly explain how the results were calculated. The methodology of this project is therefore unique, where a simple equation is provided for the biogas estimate and a systematic literature review carried out to determine the unknown variables.

There was also a lack of overall analysis of numeric potential for energy generation and CO_2 pollution reduction for the entirety of Australia, with many papers instead focusing on individual farm/abattoir plants or regions in Australia. There were no papers found that investigate potential of centralised digestors in major cities or population hubs. There is therefore a clear research gap regarding biogas production from combined sources of biomass Australia wide, which can possibly be filled by this project. The 'Biogas opportunities for Australia' report states that future work in the biogas industry should move towards 'refining the biogas resource potential, assessing feedstock availability and its productive utilisation.' (Carlu et al. 2019). These are all goals of this project and so there is good justification and need for the research.

2.6 Expected Findings

Based on the literature review and similar studies, it is expected that the estimate for potential biogas production found by this project will be significant, possibly around the range of 371 PJ Australia wide (Deloitte 2017).

Due to many real-world complications and conflicts of interest, sourcing biomass will probably be the biggest challenge for ACoD reactors. It is also likely that energy demands of the biogas plant itself, including biomass transportation, reactor heating and biomethane upgrading/fuel production will be significant. This means a significant proportion of the produced biogas is lost to cover energy demand, so net production of biogas is expected to be significantly smaller than gross.

The findings of this research, especially energy estimates, are likely to contribute to biogas sector development by providing more certainty of industry potential and possible future development goals. Is also likely to highlight where more research is required, and this will most likely relate to biomass source availability, planning of biogas production networks that maximise net energy production/emission reduction, and possible Australian waste management policy changes that maximise biogas production and help ensure self-sufficiency for ACoD reactors.

2.7 Consequential Effects

The consequential effects of this project ultimately work towards continued development of the bioenergy sector and further advancement towards net zero in Australia. The biogas sector provides a twofold reduction in greenhouse gas emissions, both from less reliance on fossil fuels as well as CH_4 capture that would otherwise be freely released into the atmosphere as wastes degrade. Bioenergy is an alternative source of renewable energy that doesn't depend on weather, time of day or battery storage, and so is a good backup to solar/wind.

Anaerobic digestion can also contribute to increasing efficiency of Australian agricultural industry through generation of biofertilizers, and encourages better waste management, both key aspects of developing a circular economy. Reactor construction and management can also provide new infrastructure projects and jobs for rural regions that are being phased out with the move away from fossil fuels. There are a few possible negative effects of biogas expansion, such as conflicts over biomass/water/land resource allocations and pollution from leaked methane, however these problems can be avoided or minimised with planning and continued research.

2.8 Ethics

The ethical considerations are very light as the research activity itself does not have any potential to negatively impact individuals in any way. Considering the possible tangential outcomes of the research findings also has little associated risk. In fact, if the project contributes at all to encouraging biogas expansion in Australia, then the research outcomes are highly morally upstanding. This is especially true considering the quality of life of future generations, as potential net reduction of CO_2 emissions made in the near future will have significant positive long-term consequences.

CHAPTER 3 – METHODOLOGY

3.1 Introduction

This project will use open-source data and statistics to determine available quantity and characteristics of biomass from the selected sources (MSW, animal manure and agricultural residues) around Australia. With this data, potential for biogas generation will be calculated, along with net greenhouse gas reduction, potential energy generation and digestate biofertilizer potential.

3.2 Project Steps

1: Literature Review – Previous studies of Australian biogas potential from various sources were analysed to get an understanding of approximate expected ranges of energy potential.

2: Data Collection: Open-source data is collected to determine the variables required for biogas estimation, including production rate, dry matter content, volatile solids, and availability factors of each selected biomass source, so that all variables in table 2 can be determined.

3: Calculations of biogas potential, energy generation, possible pollution sources and biofertilizer production

4: Evaluation of results, checks to ensure accuracy with other literature estimates

3.3 Resource Requirements

As there is no practical research being carried out, the physical resources required for the project are very easily obtained, and simply include a computer with internet access and Microsoft Word/Excel, access to login information for paid subscription to online journals and time. The university supports free student access to most of the main scientific publishing platforms, however access to specific journals/articles not supported may need to be paid for individually. Library access may also be valuable, however due to large distance from USQ, books may only be accessed by post or from local libraries.

Resource datasets that need to be accessed for methodology calculations can be found with the Australian Bureau of Statistics, Australian government departments such as the Department of Agriculture, Fisheries and Forestry, government sponsored reports and published journal articles.

3.4 Safety Issues

The safety issues associated with the research/methodology of the project are almost insignificant and basically involve the usual risks associated with long periods of sitting and extended screen time. These are covered in detail in the 'Risk Management Plan (RMP)', attached in Appendix B.

3.5 Project Timeline

The project is limited by time constraints, and the Gantt chart in appendix C shows the planned schedule and important milestones required to be met for successful completion.

3.6 Phases of Project

The project can be broken down into phases as outlined in table 1.

Table 1- Table of project phase descriptions

Phase 1 – Literature Review	
1A	Broad term review, understand overall use/potential of biogas in Australia
1B	Understand specifics of the anaerobic digestion process and required infrastructure
1C	Understand biomass sources and investigate the research gap
Phase 2 – Collection of Secondary Data (from Table 2)	
2A	Collect data for methane generated from livestock manure source.
2B	Collect data for methane generated from agricultural residue source.
2C	Collect data for methane generated from MSW source.
2D	Collect data for converting methane to electricity, expected losses from efficiency/leaks, calculating polluting factors of biogas generation, equivalent net CO_2 reduction, bio-fertiliser production etc.
Phase 3 – Systematic analysis of collected data	
3A	Convert units, rule out outliers, and account for differing methodologies with scaling factors
3B	Combine all processed collected data and perform statistical analysis to determine mean, most representative value for each parameter.
3C	Finalise the parameters and confirm they are as accurate as possible.
Phase 4 – Calculations and findings	
4A	Using finalised parameters, perform calculations of electricity, vehicle fuel and CO_2 reduction potential from three combined sources of biogas.
4B	Calculate CO_2 generation from transportation of biomass, biogas production, possible leaks, compare with CO_2 saved for net reduction.
4C	Analysis of CO_2/cost saving benefits of bio-fertiliser compared to imported synthetic fertiliser in Australia.

3.7 Project Scope and Limitations

The scope of the project is very specific, including an estimate only of biogas production from the three specified biomass sources (manure, MSW and agricultural residue) and doesn't include any other sources. The research is also not looking to optimise the ACoD process or suggest best digester types for maximum biogas potential. It is also not looking to make new Australian biogas policy but will be able to contribute information of estimates for policy makers, and possibly make general recommendations for reactor locations and most suitable biomass sources.

Besides time constraints, the project is most limited by the availability of open-source datasets required for determining Australian biomass availability and amounts, as access to private industry values is not possible. The methodology also makes several simplifying assumptions surrounding reactor function/biogas treatment and can never incorporate all real-world variables. There is also no way to accurately predict for certain the real-world availability of each biomass source, as there will always be unexpected factors which affect supply. Also, data will always be slightly outdated, as the economic/social/agricultural climate of Australia is changing constantly, and any predictions made must take these trends into account. Confidence in the results can be increased with comparisons to similar studies, especially those completed in Australia for the same biomass sources, or overseas in similar economies.

3.8 Variables

The following table of variables will be determined through a literature search and used to calculate biogas production potential of each biomass source:

Table 2- Variables determined from open-source data required for biogas estimation.

Calculating Theoretical Methane Potential	
Variables for livestock manure source	
Population (where 'i' corresponds to cattle, sheep, pigs or poultry)	N_i
Manure production rate of livestock type i (kg/head/day)	MPR_i
Availability factor of manure type i (%)	AF_i
Dry matter content of manure type i (%)	TS_i
Volatile solids content of manure type i (%)	VS_i
Biogas potential of manure type i per kg volatile solid $(m^3/kgVS)$	BP_i
Variables for agricultural residue source	
Residue generation rate of crop j (kg/kg yield)	RGR_j
Yield of crop type j (million tonnes/year)	Y_i
Availability factor of crop type j (%)	AF_j

Dry matter content of crop type j (%)	TS_j
Volatile solids content of crop type j (%)	VS_j
Biogas potential of crop residue type j per kg volatile solid ($m^3/kgVS$)	BP_j
Variables for municipal solid waste source	
Waste generation rate per capita per year for city 'k' (kg/capita/year)	WGR_k
Population of city 'k'	P_k
Organic fraction of the MSW (%)	OF_k
Availability factor of MSW (%)	AF_k
Dry matter fraction of MSW (%)	TS_k
Volatile solid content of MSW (%)	VS_k
Biogas potential of organic fraction of area k MSW ($m^3/kgVS$)	BP_k

3.9 Theoretical Biogas Production

3.9.1 Biogas from Livestock Manure (LM)

The most common livestock in Australia are cattle (meat and dairy), sheep, lamb, pigs, and chickens (meat and eggs). The Australian Bureau of Statistics is used to determine populations sizes as of 2022, as shown in Table 3. As discussed previously, the potential for biogas from each livestock source depends on livestock population (N_i), the amount of manure each animal produces (MPR_i), its availability (AF_i) and the properties of the manure including percent of total solids (TS_i) and proportion of these that are volatile solids (VS_i). Total biogas potential volume (BPV_i) can be found by multiplying the total available volatile solids for each manure type with the biogas potential (BP_i) they produce in anaerobic digestion (Equation 1).

$$BPV_i = N_i \times MPR_i \times AF_i \times TS_i \times VS_i \times BP_i \qquad (1)$$

Of the biogas produced by each manure type, the proportion of pure methane will vary depending on the source manure material, and a 'methane content' (MC_i) factor is applied to each before final calculation of methane potential (Noorollahi et al. 2015).

Table 3 is a summary of these variables determined in the literature search and used to estimate biogas potential from Australian livestock manure in June 2021 – June 2022.

Table 3 – Australian livestock manure variables for June 2021- June 2022

Manure Source	Population [a] (2021-22)	Production Rate [b]	Availability Factor [c]	Total Solids [d]	Volatile Solids [e]	Biogas potential [f]
	N_i	MPR_i	AF_i	TS_i	VS_i	BP_i
Units	(million)	(kg/head/day)	(%)	(% of total)	(% of TS)	(m^3/kg VS)
Cattle (dairy)	2.15	20.0	12.5	27.5	80.0	0.205
Cattle (meat)	22.25	20.0	20.4	27.5	80.0	0.205
Sheep/lamb	70.23	2.0	13.0	21.5	80.0	0.310
Pig	2.40	3.1	50.0	6.5	77.0	0.275
Poultry (meat)	104.76	0.1	99.0	19.5	70.0	0.240
Poultry (layers)	15.79	0.1	99.0	19.5	70.0	0.240

Sources: [a](Agriculture Victoria 2021; Australian Bureau of Statistics 2022; Australian Pork 2022)

[b](Nguyen Van & Vu Dinh 2010; Avcioğlu & Türker 2012; Ngwabie et al. 2018)

[c](Birchall et al. 2008; Tucker et al. 2015; Mofijur et al. 2021)

[d](Chastain et al. 1999; Mofijur et al. 2021)

[e](Chastain et al. 1999; Halder et al. 2016)

[f](Angelidaki & Ellegaard 2003; Rahman et al. 2018)

3.9.2 Biogas from Agricultural Residue (AR)

The crops and their corresponding residues used in ACoD were chosen based on statistics of major Australian crops yields from the Department of Agriculture, Fisheries and Forestry (Table 4). The potential for biogas production from each crop source is dependant both on yield (Y_j) and the residue generation rate (RGR_j) based on this yield, which will be highly variable between crop types as well as between different types of residues if more than one exists for a specific crop. Also important is the availability factors of these residues (AF_j), as they must account for other uses the residues may have (carbon sequestration, mulching, animal feed) before they can be considered for ACoD. Biogas potential (BP_j) generated from each residue type is also highly variable and needs to be determined in an Australian context for Australian cropping varieties. These variables are all multiplied to determine total biogas volume potential (BPV_j) of each agricultural residue (equation 2).

$$BPV_j = Y_j \times RGR_j \times AF_i \times TS_i \times VS_i \times BP_i \qquad (2)$$

Table 4 – Australian aggricultural residue variables for June 2021- June 2022

Crop and residue type [a]	**Yield** [b]	**Yield to residue ratio** [c]	**Availability Factor** [d]	**Total Solids** [e]	**Volatile solids** [f]	**Biogas potential** [g]
	Y_j	RGR_j	AF_j	TS_j	VS_j	BP_j
Units	*(tonne/year)*	*(kg/kg yield)*	*(%)*	*(%)*	*(%)*	*(m^3/kg VS)*
Wheat (Straws)	36,237	1.75	7	92	94	0.300
Canola (Stalks)	6,820	1.50	12	91	91	0.290
Barley (Straws)	14,377	1.20	12	81	98	0.230
Oats (Straws)	1,735	1.30	12	90	81	0.320
Sorghum (Straws)	2,648	1.30	12	88	86	0.334
Cottonseed (Stalks)	1,274	2.75	24	88	50	0.326
Rice (Straws)	691	1.76	48	87	54	0.340
Rice (Bran)	As above	0.08	68	91	50	0.130
Chickpeas (Straws)	1,062	1.90	7	80	50	0.350
Faba beans	646	1.90	7	80	50	0.350
Field Peas	261	1.90	7	80	50	0.350
Lentils (Straws)	999	1.90	7	80	50	0.350
Lupins	958	1.90	7	80	50	0.350
Maize (Stalks)	1,735	2.00	60	88	50	0.340
Maize (Cobs)	As above	1.03	80	85	50	0.175
Maize (Husks)	As above	0.20	50	88	50	0.355
Soybean (Straws)	57	1.90	7	80	50	0.350
Sunflower (Stalks)	30	1.50	12	87	90	0.264
Vegetables (Wastage)	3,400	0.40	18	80	50	0.355
Sugarcane (Bagasse)	28,669	0.25	21	51	74	0.278
Sugarcane (Tops)	As above	0.30	70	50	50	0.291

Source: [a] (Australian Bureau of Statistics 2022)

[b] (Rahman et al. 2018; Australian Bureau of Statistics 2022)

[c] (Kim & Dale 2004; Rahman et al. 2018; Momayez et al. 2019)

[d] (Garcia-Peña et al. 2011; Rahman et al. 2018; Agriculture Victoria 2023)

[e] (Kim & Dale 2004; Antonopoulou et al. 2010; Rahman et al. 2018)

[f] (Rahman et al. 2018)

[g] (Kim & Dale 2004; Murphy et al. 2011; Deepanraj et al. 2014; Vasco-Correa et al. 2018; Thamizhakaran Stanley et al. 2022; Agriculture Victoria 2023)

3.9.3 Biogas from Organic Fraction of Municipal Solid Waste (OFMSW)

Characteristics of municipal solid waste will vary depending on where it is being collected, and so major population centres of Brisbane, Darwin, Perth, Sydney, Melbourne, Canberra, Adelaide, and Hobart will be used as best representations for wider state areas (Table 5). The population of these capital cities is approximately 17.5 million people which is about 68% of Australia's total population as of 2022. This is a majority however will still result in slightly lower estimates of potential biogas production, especially if regional digesters are implemented.

The literature search must determine waste generation per capita per year (WGR_k) of each city, along with most recent population figures (P_k). As only major population centres are being used in the estimate, availability factor (AF_k) should be uniform for each city, as each city council will have uniform waste disposal policy for the population region. The same principle should apply to variability of organic fraction(OF_k) of each region, as only the organic fraction of MSW is available for use in anaerobic digestion. Finally, total solids (TS_k) and the volatile solids fraction of them (VS_k) will need to be found in literature, so that a biogas volume (BPV_k) estimate can be made (equation 3).

$$BPV_k = P_k \times WGR_k \times OF_k \times AF_k \times TS_k \times VS_k \times BP_k \quad (3)$$

Table 5 – Australian MSW residue variables for June 2021-June 2022

City	**Population [a]**	**Waste generation rate [b]**	**Organic Fraction [c]**	**Availability Factor [d]**	**Total Solids [e]**	**Volatile solids [e]**	**Biogas potential [g]**
	P_k	WGR_k	OF_k	AF_k	TS_k	VS_k	BP_k
		(kg/person/day)	(%)	(%)	(%)	(%)	(m^3/kg VS)
Brisbane	1,242,825	1.38	62	52	29.4	77.2	0.45
Sydney	4,820,047	1.64	52	65	29.4	77.2	0.45
Melbourne	4,817,834	1.49	57	62	29.4	77.2	0.45
Adelaide	1,368,209	1.13	59	77	29.4	77.2	0.45
Hobart	226,653	1.55	55	33	29.4	77.2	0.45
Perth	2,098,239	1.66	52	39	29.4	77.2	0.45
Canberra	490,517	1.49	57	79	29.4	77.2	0.45
Darwin	127,215	1.49	57	9	29.4	77.2	0.45

Sources: [a] (Australian Bureau of Statistics 2021)

[b] (SA Government 2017; WA Waste Authority 2017; UTas Infrastructure Services and Development 2019; QLD Government 2020; NSW EPA 2021; Pickin et al. 2022)[c](Australian Government 2023)

[d] (Australian Government 2021)

[e] (Campuzano & González-Martínez 2016)

[f] (Kigozi et al. 2013; Vasco-Correa et al. 2018)

3.10 Electricity Generation from Biogas

There are several types of generators to convert biogas to either heat or electrical energy, including combined heat and power plant (CHP), internal combustion engine (ICE) or gas turbine (GT). For use in all these options, it is best to upgrade biogas to biomethane to avoid damage to machinery by H_2S impurities. The most common generator used with AD reactors are ICEs, and these engines have an operable capacity of between 100 kW – 3 MW of electricity equivalent biomethane. Multiple are therefore required if this range is exceeded at the plant (Ayodele et al. 2018). To calculate potential energy generation (E_p) from available biomethane, the following equation is used:

$$E_P = MPV \times E_{ff} \times LHV_{CH4} \times CF \qquad (4)$$

Where MPV is the potential volume of methane generated at the plant, E_{ff} is the efficiency of the engine, LHV_{CH4} is the lower heating value of biomethane and CF is the capacity factor of the ACoD plant.

Internal combustion has a 31-39% efficiency, so a middle ground value of 35% is assumed for E_{ff}. Note, internal combustion engines are a less efficient use of biomethane, as the thermal conversion efficiency of gas turbines is 50% (Patterson et al. 2013) and combined heat and power plants (CHP) can be anywhere from 55-80% (US EPA 2022). It can be assumed that methane comprises 60% of biogas produced by ACoD, however this is only the case if good management of the plant is achieved, and highest quality biogas is produced (Rajendran et al. 2014).

The lower heating value of biomethane (LHV_{CH4}) is a measure of energy available per volume of the compound, which is constant and a chemical property of CH_4. This value is approximately 37 MJ/m^3 for energy rich methane (Rajendran et al. 2014).

The capacity factor of the ACoD plant (CF) accounts for the fact that the plant will not always be working at full capacity in the real world, and capacity is realistically likely to average out at about 86%, which is a number that has been slowly increasing as AD plants become more efficient countrywide (Grant et al. 2018). Inefficiency is usually due to several factors discussed previously, such as biomass supply problems, limited bacterial performance/poor reactor conditions, sudden temperature change, management errors, unaccounted biogas leaks etc and so good management can potentially increase CF to the target minimum 90% in time.

3.11 Vehicle Fuel Replacement Potential

Biogas can be turned into usable biofuels, equivalent to LPG, diesel and jet fuels, via multiple processes, however one of the most common is the Fischer-Tropsch method (FT). This is a series of chemical reactions that uses the carbon monoxide and hydrogen in Syngas to create liquid hydrocarbons (Lau et al. 2011). Syngas is in turn created from raw biogas through methods such as dry reforming and steam reforming, and from biomethane with partial oxidative reforming (POR).

There are energy inputs required for dry/steam reforming, as they require temperatures of 700-900°C, and this energy can be supplied by a proportion of the generated biogas. This does however mean energy conversion efficiency of the biofuels synthesis is relatively low at around 30%. Ashraf et al. (2015) found that for every 4000 kg/h of biomethane fed into the FT process, 1602 kg/h of liquid biofuel could be produced. This means an estimate of biofuel generated (BF) from the ACoD process is calculated as follows, assuming biogas is comprised of 60% biomethane:

$$BF\ (kg) = \frac{1602}{4000}(0.6 \times BPV\ (kg)) \qquad (5)$$

3.12 GHG Emission Reduction Potential

The only emission saving potential considered here is via the replacing of a fossil fuel with biogas and doesn't consider savings through collection methods (mining vs waste collection etc.), production of the fuel, or refinement processes necessary to make the resulting fuel useable.

The GHG emissions avoided via replacement of fossil fuel electricity (AEE) source is calculated in equation 6, where SCE is the specific CO_2 emission factor of coal in relation to primary energy content (93.9 g CO_2/MJ) (Juhrich 2022) and E_p is the calculated energy potential of ACoD methane potentially replacing burning coal.

$$AEE\ (kg\ CO2) = E_P\ (PJ/year) \times SCE \qquad (6)$$

The GHG emissions avoided by using biofuels instead of traditional fossil fuels (AEF) can be calculated with equation 7, where SEF is the special emissions factor of CO_2 per litre of burnt fuel. An SEF of 2.3-2.7 kg/litre is typical for hydrocarbon fuels, with diesels at the higher emissions range and petrol lower (Ayodele et al. 2018).

$$AEF\ (kg\ CO_2) = BF\ (litres) \times SEF \qquad (7)$$

These emission reductions also depend on the use of the final produced biofuel and what proportion is used for upgrade to vehicle fuel, used as gas grid injection or used to generate electricity. This report will not go into detail estimating this, and instead GHG reduction potentials are assuming the entire volume of produced biogas is used for the particular energy application.

3.13 Biofertilizer Production Potential

Biofertilizer produced from the leftover digestate of anaerobic digestion is a useful source of nutrients which can be used as fertiliser. The potential to replace the extensive use of chemical fertilisers in Australia is promising and could be a significant cost saver for the agricultural industry. The amount of digestate produced (DP) in the AD process is a function of the total solids (dry matter) (TS) and volatile solids (VS) of the feedstock, as per equation 8 (Halder et al. 2016).

$$DP = (TS - VS) + 40\%\ of\ VS \qquad (8)$$

3.14 Greenhouse Gas Emissions from AD Plants

There are several sources of possible emissions from the AD process from transport to processing power requirements. However, biomethane leaks specifically are environmentally harmful, unintentional, and difficult to offset, so estimating their amount is important for good reactor management. Methane emissions (ME) are estimated in equation 9, where an estimated 5% of all processed biomethane is assumed to escape the system through leaks (Mohareb et al. 2011), methane produced is estimated as 60% of total biogas volume (BPV_T), and methane density (d_M) is taken as 0.717 kg/m^3. These methane emissions can be converted to equivalent CO_2 emissions by multiplying a global warming potential (GWP) index constant for methane, which is equal to 29.8 (Brander & Davis 2012).

$$CO_2e\ \ (kg) = 0.05 \times 0.6 \times BPV_T \times d_M \times 29.8 \qquad (9)$$

CHAPTER 4 – RESULTS

4.1 Introduction

The results presented in tables 6-8 below are calculated with equations 1-9 using the values presented in tables 3-5. An excel spreadsheet was used to perform these calculations as per the methodology. Additional assumptions and simplifications that need to be considered are also mentioned below, and these seriously affect the applicability of the results.

4.2 Assumptions and Simplifications

In collecting the data required for biogas estimates, there were several assumptions and simplifications made due to the generalising effect of the variables required. These assumptions are outlined below. Having made these simplifications means results achieved by this study are estimates only, and as stated previously, should only be used as a guide to determine potential future biogas development opportunity in Australia.

4.2.1 Manure Assumptions and Simplifications

For most manure sources an estimate is made for each data point by averaging a range of values. This is because in reality, variability gives a range of possible values due to the following factors:

- Variations in manure quality due to individuals/population diet, conditions, and proportion of livestock ages/maturity/breeding purposes.
- Availability of manure and variation in farming methods across the country meaning manure quality/dryness is not universal and it may be mixed with other material such as water or bedding.

Cattle

Several assumptions are required to achieve a single availability factor for beef cattle manure. Assuming animals are fed in a feedlot setting, meat cattle only have manure collected during this time, as collection from a paddock is impractical. This means that only 1 000kg TS/head/year could be collected, however this value could also be as low as 400-420kg TS/head/year depending on industry practice/decomposition rates (Tucker et al. 2015). Examples of these industry practices to consider include whether feedlots retain an 'interface layer' in the bedding. If they do not, collection rates could be increased to up to 2000kg TS/head/year of manure mixed with gravel and other bedding material. The value chosen in this study is the smaller range for pure manure (to be conservative) and assumes bedding material impurities would be undesirable in the ACoD process.

Dairy cattle manure collection is assumed to only occur 10-15% of the time, as manure must be deposited on surfaces that have effluent runoff collected (Birchall et al. 2008), however in reality this value may be slightly higher depending on cow behaviour and farm routines.

Lamb and Sheep

The manure generation rate stated in the data collection assumes sheep and lamb generate the same amount, however this is not realistic. As with cattle, manure availability factor is dependent on the farming method and duration of time spent on areas where manure is available for collection.

Swine

In Australia there are four main methods of farming pigs, including ‘conventional housing’, ‘deep litter housing’, ‘feedlot outdoor piggery’ and ‘rotational outdoor piggery’ (Australian Pork Limited 2015). Depending on which method is used, availability factor for pig manure may vary widely (from 1 for conventional housing to 0 for rotational outdoor piggeries). In this study, an average value of 0.5 representative of all farming methods is used. The quality of the manure collected also varies depending on the farming method, with anything from liquid effluent runoff generated from feedlot outdoor piggeries and spent litter mixed with manure from deep litter piggeries. Compared with other livestock types, piggeries are also more likely to have on site manure treatment methods, and so manure is of limited availability for AD collection for this reason. For example, rotational piggeries use manure as direct fertiliser to paddocks that will be used for crop growth after removal of the animals.

Manure generation rate of swine is dependent on the weight of the animals being kept and the feed type, as it is highly variable. The range can be anywhere from 2.7-3.6 kg of manure per day for 23-79kg pigs, or in other studies, a 60kg finisher pig produced 3.5-5kg of manure per day (Ngwabie et al. 2018). In this study, the manure generation rate is taken as an average 3.1kg per day, to generalise for all sizes of pig. The total solids and volatile solids of the manure is dependent on the digestibility of feed as well as presence of impurities. Chastain et al. (1999) found that between all farm types, (e.g. Farrow-to-wean, feeder-to-finish, nursery etc.), the average total solid of swine manure is 11.7% and average volatile solids is 77% of the TS.

Chickens

As with piggeries, the farming method used for poultry greatly affects availability factor and the quality of the manure. Free range farms will have much lower availability than caged farms, and barn environments will have litter mixed with manure at varying levels of moisture and quantity, meaning AD plants will need to be designed to enable digestion of litter if this biomass is used. The proportion of laying hens kept in cages (where all manure is collected, availability of 1) to hens kept in cage-free environments is about half (Department of Primary Industries NSW nd), and so availability factor for Australian poultry manure is estimated at 0.5.

4.2.2 Agricultural Residue Assumption and Simplifications

The types of crops considered in the estimate were determined from the Australian Bureau of Statistics Agricultural Commodities Australia 2021-2022 'Agricultural commodity estimates by Australia, states, and territories' report data. This report is a nation-wide governmental estimate of Australia's agricultural commodities, and so is a reliable source of information of crop yield.

Crop Availability Factors

A representative availability factor of Australian crop residues is particularly difficult to determine due to high variability in farming/tillage practice between various regions of Australia. Also important to consider is the weather at harvest time, crop rotation patterns, soil fertility and land slope of the particular farm (Kim & Dale 2004). After collection, availability is also dependant on the use of residues for other purposes. For example, sugarcane bagasse is already commonly used for energy production through combustion at sugar mills, or for production of sustainable papers/food packaging, and so availability is greatly reduced. Residues are also commonly used for carbon sequestration/erosion protection in poor Australian soils and so left in paddocks/tilled into soils, or can even be used as livestock feed etc.

Availability also varies with residue type of a particular crop, as some crops have more than one residue that is created during harevest/processing. For example, corn (or maize) has stalks residue, resuting directly from harvest, while cobs and husks can be generated as by-product of processing the product.

Given these uncertainties, the availability factors chosen are only representative, and not applicable to every Australian farm. They are mostly sourced from studies investigating single farms or regions, and in the furture it would be beneficial to perform calculations with data from individual states or farming regions of Australia to increase accuracy.

Biogas Potential

Biogas potential of each residue type is determined from published literature specifically for each type, except for pulses (chickpeas, faba beans, field peas, lentils, lupins) and soybean as there was no existing research found for these specific feedstocks. Instead, the average production of 0.35 m^3 biogas/kg VS from 'all agricultural residues' from range 0.2-0.5 m^3 biogas/kg VS (Vasco-Correa et al. 2018) was selected.

Vegetables Definition

Due to the wide variety of vegetables grown in Australia, it would be impractical to consider them all individually in biogas estimates. Instead, an average value is taken, including vegetables such as artichoke, peas, rhubarb, turnip, kale, potatoes, sugar beet and fodder beet, as per Murphy et al. (2011).

4.2.3 OFMSW Assumption and Simplifications

Population Values

Population values are recorded from the Australian Bureau of Statistics data for 2021 and includes only cities and their greater areas. This means regional areas are not counted in this estimate, and the final values of biogas are simplified and representative only. Further study is required to determine if MSW collection in rural areas is worth the biogas return. This study is only considering municipal solid waste (not industrial or otherwise), and so waste generation rate for each state include per capita estimations of household wastes only.

Total Solids and Volatile Solids

More so than any other residue type, the properties (TS and VS) of MSW and biogas yield is dependent on the pretreatment methods and the type of AD method employed. Total solids and volatile solids data could not be located for any other city besides Brisbane, Qld. Therefore, it is assumed that OFMSW has relatively uniform levels of TS and VS across Australia, and 29.4% TS and 77.2% VS is applied universally (Campuzano & González-Martínez 2016). Another simplification is made where biogas potential is assumed to be universal for each OFMSW collection region, and 0.45 m^3 biogas /kg VS is used based on experimental values from Kigozi et al. (2013) and Vasco-Correa et al. (2018).

4.3 Tables of Results

Table 6 - Biogas production potential volume from each individual biomass source

Biogas Volume Estimate Results (June 2021 – June 2022)					
Manure		**Agricultural Residue**		**OFMSW**	
Source	***BPV_i***	***Source***	***BPV_j***	***Source***	***BPV_k***
	(Mil. m^3/year)		*(Mil. m^3/year)*		*(Mil. m^3/year)*
Cattle (Dairy)	88.416	**Wheat (Straws)**	1,151.678	**Brisbane**	20.597
Cattle (Meat)	1,496.116	**Canola (Stalks)**	294.819	**Sydney**	99.852
Sheep/Lambs	355.392	**Barley (Straws)**	376.179	**Melbourne**	95.200
Pig	33.245	**Oats (Straws)**	63.022	**Adelaide**	26.008
Poultry (Meat)	124.015	**Sorghum (Straws)**	104.704	**Hobart**	2.384
Poultry (Layers)	18.691	**Cottonseed (Stalks)**	119.560	**Perth**	26.080
		Rice (Straws)	93.305	**Canberra**	12.350
		Rice (Bran)	2.225	**Darwin**	0.365
		Chickpeas (straws)	19.774		
		Faba beans	12.029		
		Field Peas	4.860		
		Lentils (Straws)	18.601		
		Lupins	17.838		
		Maize (Stalks)	311.467		
		Maize (Cobs)	106.329		
		Maize (Husks)	27.101		
		Soybean (Straws)	1.065		
		Sunflower (Stalks)	1.109		
		Vegetables (Wastage)	33.796		
		Sugarcane (Bagasse)	157.915		
		Sugarcane (Tops)	437.995		
Total	**2, 115.876**		**3, 355.370**		**282.836**

Table 7- Energy/Electricity potential of upgraded methane depending on generator used.

	Generator type	**Internal combustion**	**Gas turbine**	**Combined heat and power**
	Energy Efficiency, E_{ff} [a]	35%	50%	67.5%
Manure	*(TJ/year)*	14,139	20,198	27,268
	(GWh)	3,927	5,611	7,574
Ag. residue	*(TJ/year)*	22,421	32,030	43,241
	(GWh)	6,228	8,897	12,011
OFMSW	*(TJ/year)*	1,890	2,700	3,645
	(GWh)	525	750	1,012
Total	*(TJ/year)*	38,450	54,928	74,153
	(GWh)	10,681	15,258	20,598

Sources: [a] (Patterson et al. 2013; US EPA 2022)

Table 8 - Summary table of total data calculated for each biomass source

Biomass Source	Units	Manure	Agricultural residue	OFMSW	Totals
Biogas Total	*(Mil. m^3/year)*	2,116	3,355	283	5,754
Methane Total	*(Mil. m^3/year)*	1,270	2,013	170	3,452
Energy Potential	*(TJ/year)*	27,268	43,241	3,645	74,153
Electricity Generation	*(GWh)*	7,574	12,011	1,012	20,598
Biofuel Potential	*(Mil. L/year)*	380	602	51	1,032
GHG Reduction (fuel) [1]	*(Mil. kg CO_2e/year)*	949	1505	127	2,581
GHG Reduction (coal) [2]	*(Mil. kg CO_2e/year)*	2,560	4,060	342	6,963
Biofertilizer Produced	*(Mil. kg/year)*	6,346	9,371	437	16,154
Leaked Methane	*(Mil. kg CO_2e/year)*	1,356	2,151	181	3,688

[1] Assuming all biomethane is used for vehicle fuel replacement.

[2] Assuming all biomethane is used for replacing coal in electricity production.

CHAPTER 5 – DISCUSSION

5.1 Introduction

This discussion will investigate the results calculated to determine key points, recommendations and address the project objectives. Specifically, biogas/methane generated, electricity, biofuel and digestate estimates will be discussed. Net GHG reduction, recommendations, and further research will also be investigated, and conclusions reached based on the research results.

5.2 Biogas and Methane Potential

Biogas produced in potential ACoD of the three waste streams in June 2021 - June 22 is presented in Table 6 and Figure 10. The most productive source of biogas was agricultural residue by far, potentially producing 3, 355 million m^3/year. This is almost 1.5 more productive than livestock manure (2, 116 million m^3 biogas/year) and about 12 times more productive than MSW (283 million m^3 biogas/year). A clear comparison of the contributions can be seen in Figure 10 below.

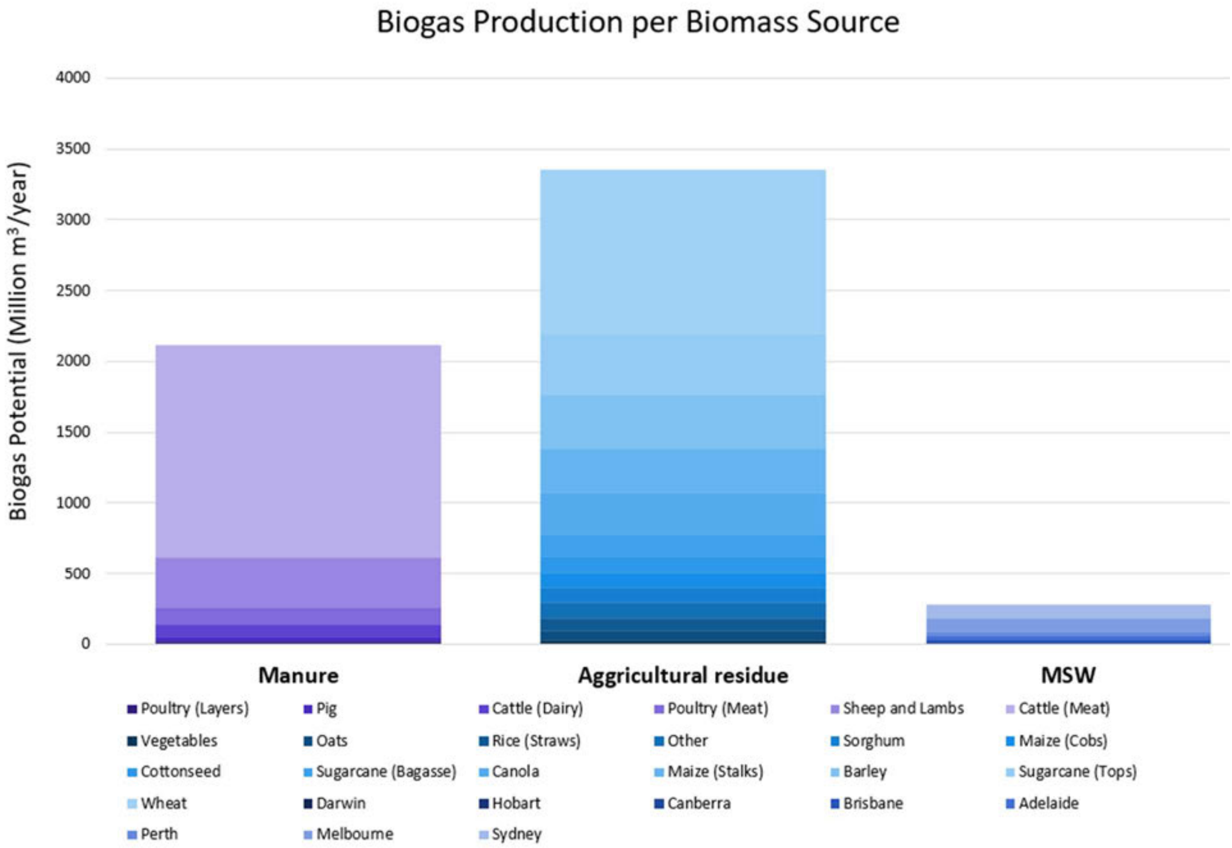

Figure 10 - Graph comparing biogas produced from each biomass and sector.

Of the agricultural residues considered, the most productive are wheat straws, producing up to 34% of total biogas from agricultural residue (Figure 11). This is followed by sugarcane tops (13%) and barley straws (11%). There were several residue sources that provided less than 1% of total biogas production each, including maize husks, chickpeas, lentils, and soybean etc, and these are all grouped in the 'Other' category in Figure 11. From these proportions, it is clear which residues to focus on collecting and using in ACoD, and which are of less importance and lower biogas capacity.

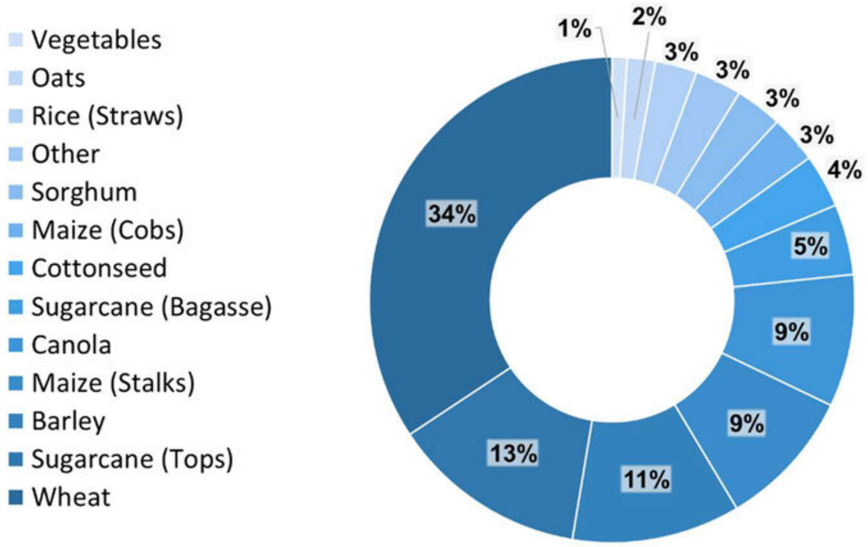

Figure 11 - Proportion of 3 355 million m^3/year biogas produced by each agricultural residue.

The large proportion of biogas sourced from agricultural residue and the promising 12 TWh electricity potential is good evidence for the need to better manage stubble Australia wide. However, there are also conflicting interests of use and availability difficulties to consider. Agricultural residues are not simply a waste product like MSW or manure, and are often used by farmers for carbon sequestration etc., reducing their availability and possibly introducing negative attitudes towards their collection for AD. To avoid this, farmers would need to see direct personal gain from giving up residue for AD, as well as the option of whether to participate at all in the process. Agricultural residues are also arguably the most spatially spread out and seasonal of the three biomass, as they are only consolidated during harvests, if at all, and are only available for most crops at certain times of year (unlike manure or household wastes).

Manure has the next largest biogas potential, with the overwhelming majority of it sourced from meat cattle (71%) as per Figure 12 below. This is due to the large population, higher availability from feedlot farming and higher manure production rate of the animals. The next most productive manure is sheep/lambs (17%) and meat chickens (6%). There is very little contribution from laying chickens (1%), due to relatively low population, and pig manure only contributes 2% due to low population and relatively low total solids content in manure. Dairy manure is at only 4% contribution, and so along with layers and pigs, would be almost not worth transporting offsite, and instead is more suited for onsite use where emissions from transport are less likely to outweigh the savings from offset.

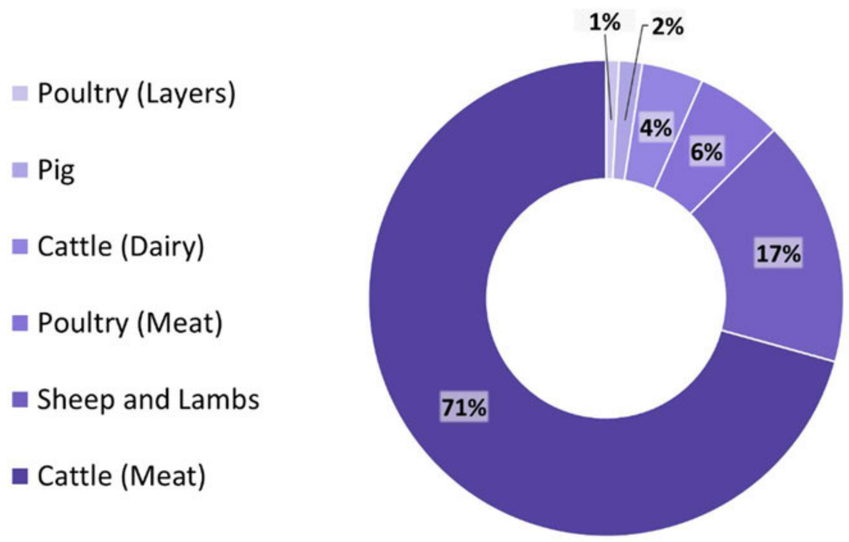

Figure 12- Proportion of 2 116 million m^3/year biogas production by each manure source.

The smallest potential is from municipal solid waste of major Australian cities, with Sydney and Melbourne contributing approximately a third each (35% and 34%), and Perth and Adelaide tied at 9% each (Figure 13). Darwin and Hobart contribute very little, due to low population, and in Darwin's case this is mostly due to low population and low availability factor. In reality, there should be regional areas included in the estimate as they may contribute a significant amount, especially into the future as Australia's population grows and moves towards regional centres. Of the three biomasses investigated, organic fraction of municipal solid waste contributes significantly less overall due to relatively low levels of dry matter and as only a portion of the available mass is organic and available for digestion.

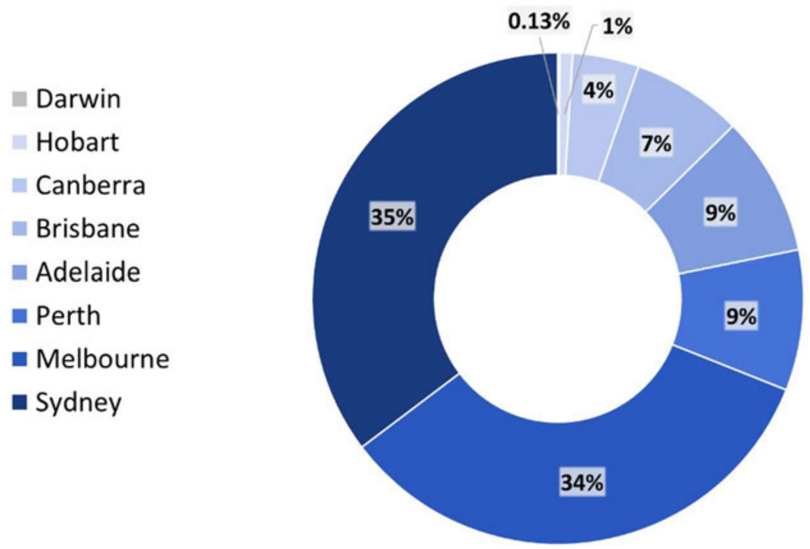

Figure 13 - Proportion of 283 million m^3/year biogas production by each OFMSW city region source

According to Deloitte (2017), residential and commercial (not including industrial) gas demand Australia wide was 160.5 PJ/year in 2016. This means the 74 PJ biogas production estimated in this study could potentially supply almost half (46.2%) of gas demand. This is a significant proportion and indicates the viability of developing the biogas sector in Australia.

5.3 Electricity Generated

Total Australian electricity usage in the financial year of 2022 was 189 TWh (Australian Energy Regulator 2022). The energy potential estimated from the three biomasses (Figure 14Table 7) could supply approximately 10% of this (20 TWh). However, the application of biogas would be more beneficial in 'hard-to-abate' sectors of domestic gas network supply, where it is not possible to directly substitute with green electricity generated by other renewables.

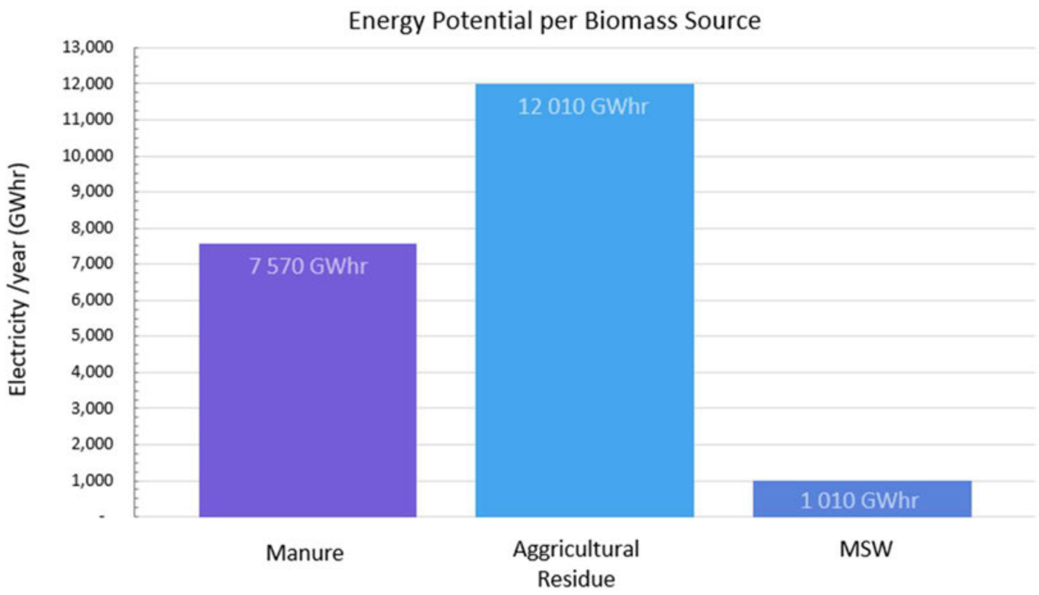

Figure 14 - Total electricity potential of each biomass source sector using combined heat and power generators

The study 'Decarbonising Australia's gas distribution networks' by (Deloitte 2017) is the most relevant study to compare to biogas estimates of this study. They found total Australian agricultural residue potentially generates 319.4 PJ/year, livestock residue generates 29.3 PJ/year and urban waste generates 19.9 PJ/year. This can be directly compared to results of this study, where agricultural residue energy supply is 43.2 PJ/year, livestock residue generates 27.3 PJ/year and MSW generates 3.64 PJ/year. Comparing the most to least productive biomass sources between the studies shows them to be the same, with both having most productive source be agricultural residue, then manure, then MSW as lowest. Comparing the values themselves however reveals discrepancies. Agricultural residue especially has much higher energy production from the Deloitte (2017) study, at approximately seven times more. MSW is approximately five times more productive compared to this study, however livestock residue generation is very similar.

Reasons for these differences are likely due to different estimation methods, as well as the Deloitte (2017) study being more in depth. For example, the small difference in manure energy estimate is likely due to Deloitte having included litter in the estimation for manure biomass, where this study assumed ACoD could not facilitate bedding digestion. The 'Urban waste' portion of Deloitte's estimate also includes commercial and industrial waste, construction and demolition waste, wastewater, and food wastage from production/retail. This study did not include any of these sources and this explains the large discrepancy. It is however unclear why the agricultural estimate of this study is so low in comparison, as there is no indication from Deloitte's paper that they considered additional sources for this category.

Zaman & Reynolds (2015) found that food waste could produce 265 m^3 biogas/tonne and using the masses of food waste found in this study, is equivalent to 6.128 million m^3 biogas/year. This is only about 2% of the biogas estimated from OFMSW in this study. The reason for such a dramatic reduction is unclear and most likely to do with the properties of food waste used by this study differing from Zaman & Reynolds (2015). Mahmudul, Akbar, et al. (2022) found that in 2022, considering only 10% of all of Australia's food waste could potentially generate 35.4 GWh/year. Only 10% is used as it assumes this is the actual amount of food waste collected for AD. Scaling this up to include the other 90%, this estimate comes to about 35% of the estimate made in this research. This is again likely due to different properties or amounts used for food waste, as well as different calculation methods.

The motor used to generate electricity is very important, and efficiency varies from 35-67.5% depending on which method is chosen. This study assumes the most efficient (67.5%) combined heat and power generator is always available and suitable for use. However, it also means there may be difficulties comparing results of other studies directly if they do not use the same generator or state what type. Dastjerdi et al. (2019) assumes 37% generator conversion efficiency and found that food waste in NSW only could produce 280 GWh/year from 940 791 tonnes of biomass. This study estimates about 360 GWh/year from 977 506 kg NSW MSW using a more efficient generator. These results are therefore very similar and are good support for the findings,

5.4 Biofuel Potential

Results from this study estimate biofuel produced from AD is approximately 1 032 megalitres/year from June 2021-June 2022. This amount of fuel could have offset about 3% of Australia's 34 170 megalitres used by road registered vehicles in 2018 (Australian Bureau of Statistics 2018). This isn't a very large proportion and suggests the biogas generated in AD would be more beneficial as gas supply and would also have less conversion losses.

5.5 Digestate Potential

The biomass sources investigated in this study could potentially supply 16 million tonnes of fertiliser every year (Figure 15), which could potentially supply the entire demand for imported fertiliser in Australia three times over (5 million tonnes in 2016-2017) (Australian Bureau of Statistics 2017). This would have saved the Australian agricultural industry $4.9 billion in 2021-22, and so is very good incentive to not only increase digestate production, but ensure proper management and distribution is achieved. Depending on where reactors are located in relation to farms requiring fertiliser, there might be problems with distribution and costs would need to be negotiated. This is also a possible incentive for farmers to collect and supply crop residues, as they could receive fertiliser back for reduced rate or for free.

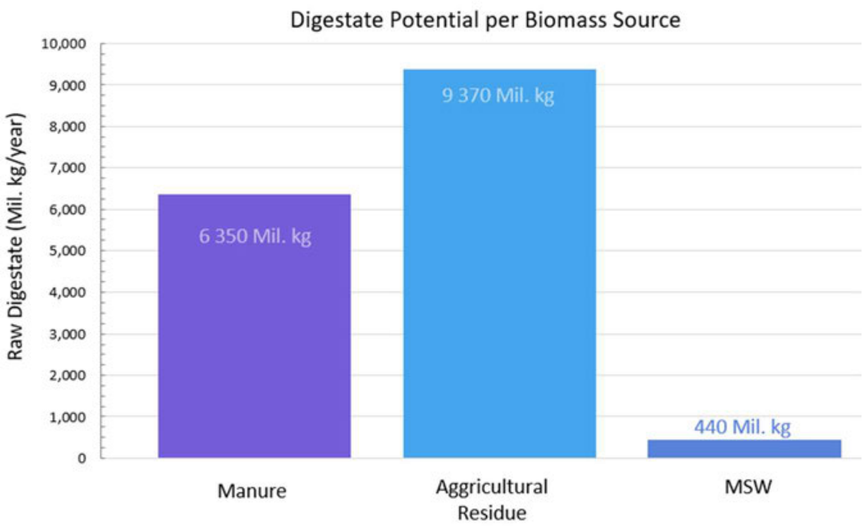

Figure 15 - Raw digestate potentially generated from AD of each biomass source.

Another important factor is not only the volume of fertiliser provided, but that it is the right kind needed for most Australian soils. Due to their age and high amounts of weathering, most Australian soils are carbon and nitrogen deficient, and commonly lack micronutrients such as Molybdenum (Mo) and Zinc (Zn) (Alloway et al. 2008). Most areas, especially in sandy soils, also lack micronutrient cations including Iron (Fe), Manganese (Mn), Copper (Cu) and Cobalt (Co). Digestates from all biomass sources have high proportion of carbon and nitrogen nutrients, generally around 30-50% C and 1-6% N for mixes of manure, agricultural residue, and food waste (Wang & Lee 2021).

Other common components of these digestate include Phosphorus (P), Sulphur (S), Sodium (Na), Magnesium (Mg), Potassium (K) and Calcium (Ca). There tends to be a greater mix of nutrients when ACoD includes a wide variety of feedstocks, which is beneficial for soils and the application of ACoD as well. Specialised fertilisers may still need to be applied for micronutrients that won't be common in digestate for poor Australian soils, and Na concentrations will need to be minimised to avoid worsening risk of saline soils.

5.6 Net GHG Emission Reduction

Emission reductions potential in this study were calculated based on what fossil fuel-based resources could be replaced by biogas derived fuels. The graph in Figure 16 compares the potential emissions offsets from replacing petroleum vehicle fuel or coal powered electricity. In this case, GHG reduction from liquified biofuel replacing diesel was found to be 2 581 million kg CO_2/year in total from the three sources. In comparison, the potential emissions avoided from replacing coal powered electricity with biogas generation is 6,963 million kg CO_2/year. Therefore, there is more than double the potential for carbon offsets from electricity generation than fuel replacement. Along with the low conversion efficiency discussed previously, this is another reason to discount converting biogas to biofuel to maximise emissions reduction effect of AD.

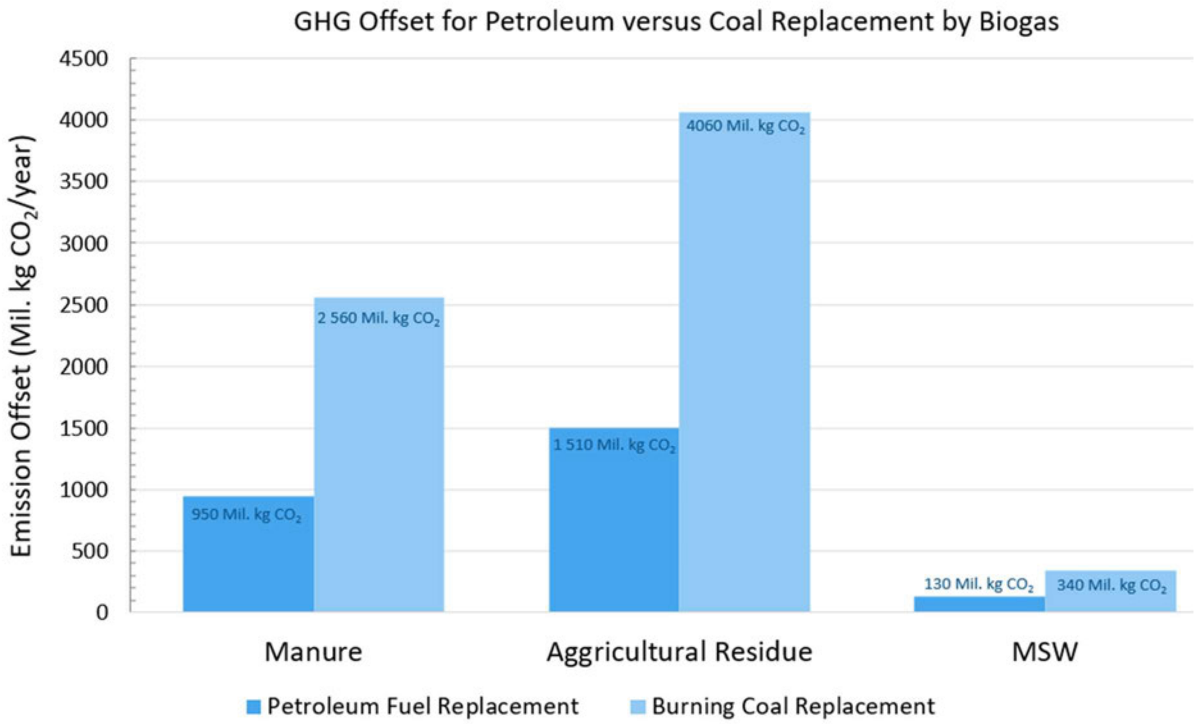

Figure 16 - Graph comparing the potential kg of CO_2 emission offset by converting biogas to liquid vehicle fuel or replacing coal powered electricity.

These values do not account for any emissions created in the biomass collection, reactor operation (heating, stirring, possible leaks etc.) or product distribution stages of AD. On the other hand, it also doesn't include the emissions saved by capturing methane emissions that would have occurred if food waste etc. was left to decay in landfill. All these positive and negative emission sources/savings must be considered in more detail to gain accurate estimate of net emission reduction and should be included in future studies/estimates.

Leaked methane equivalent carbon dioxide emissions were calculated in this study, so some idea can be gained of net emission reductions. Assuming 5% of methane produced is unintentionally leaked during the AD/conversion process, the potential leaked emissions estimated from digestion of biomasses in this study is 3 688 kg CO_2e/year. This can be directly compared to the potential emissions saved. When converting all biogas to electricity, there is a net carbon offset of 3 275 million kg CO_2e/year. When all biogas is converted to biofuel, there are not enough emissions offset by fuel replacement and there are potentially 1 108 million kg CO_2e/year of net emissions released. These emissions must be avoided for the GHG reduction promise of AD to be realised, and so liquid biofuels are again proven to be unjustified as a final product. This also highlights the importance of minimising methane leaks in the reactor/conversion processes, as due to its potency as a polluter, any offsets made by the green energy source of biogas will be very quickly reduced if any leaking occurs.

5.7 Recommendations

As discussed previously, there are significant opportunities offered from developing biogas in Australia overall. However, the results reveal there are some areas that are more beneficial in terms of net GHG emission reduction compared to others. Specifically, it was found that upgrading to biomethane to supply existing gas distribution networks was the pathway with the most offset potential. It was also found that digestate has significant potential in replacing almost all of Australia's imported synthetic fertiliser demand, especially carbon and nitrogen-based fertilisers. However, it may not contain all micronutrients needed by Australian soils so some specific fertilisers may still need to be synthesised. Generally, benefit in GHG reduction by synthesising liquid biofuels from biogas was not worth it, and the electricity supply from biogas potential was only a tenth of Australian demand.

It is recommended to focus on maximising agricultural residue harvest and collection for AD, as this is where most biogas was derived. Especially productive where wheat straws, sugarcane tops and barley straws, so harvest of these residues should be as efficient as possible, and farmers encouraged to collect and supply them. Some of the agricultural residues produced very little biogas, and so things like chickpea, sunflower or lentils may not be suitable for collection.

Manure was the next most productive biomass and will be worth developing collection systems for. However, the type of manure used is important and sources such as layer chickens, pigs and dairy cows may be better kept as local, on-farm AD considering their small contributions. Although potential biogas from MSW was lowest, it was still a considerable amount and will be higher in practice when regional areas are included in the biomass collection. This research also did not account for emissions avoided by keeping organics out of landfill, which will contribute to increasing GHG offset from MSW biomass. Therefore, government policies surrounding landfilling organics should be unified Australia wide and levies increased to discourage unsorted dumping. Feed in tariffs may also be beneficial and should be researched further to determine when and how they are most effective.

5.8 Further Research

There is still discrepancy between literature and biogas potentials calculated in this study, so further study on this topic is recommended to verify results.

Specifically, the following needs further investigation:

- Most economic reactor locations, considering transport, redistribution, and maintenance of the biomass, digestors and biogas product.
- In-depth cost benefit analysis to determine if it is worth collecting/processing/pre-treating the biomass considering the energy it would take to do so.
- More detailed examination of GHG emissions from the entire ACoD process, especially emissions from collection, transportation, and processing of biomass, as well as those generated by operation of the anaerobic digesters. Must also considers emissions captured by keeping rotting organics out of landfill etc.

Future estimates of biomass also need to be more thorough, and go into finer detail when predicting biogas production potential, including factors such as:

- Details about animal populations including ages/weight ranges.
- Animal farming methods and different collection potentials from them.
- Include regional populations in estimate of MSW collection rates, potentially breaking up the collection areas and waste properties per council region.
- Find more detailed information on Australian MSW composition including possible seasonal variability.
- Agricultural residue availability factor should vary based on geographic location and possibly time of year. There is potential for far more level of detail, and it would be ideal to estimate collection rates for each farming region in Australia.

CHAPTER 6 – CONCLUSION

6.1 Conclusions

This research shows the considerable potential of biogas in Australia's carbon-neutral future and provides justification for more governmental and public attention for the technology. Of the three biomass sources investigated, agricultural residues have the most potential for generating biogas and offsetting GHG emissions, specifically using wheat straws, sugarcane tops and barley straws. However, the potential of manure and the organic fraction of municipal solid waste cannot be ignored, as these biomass sources are arguably more easily accessible. In total, based on 2021-22 numbers, the three sources combined could generate 5 700 million m^3 of biogas per year and could potentially avoid 7 million tonnes of CO_2 emissions by replacing coal powered electricity.

Overall, it was found that biogas is best utilised in hard-to-abate sectors and could potentially supply about half of Australia's residential and commercial LNG demand, after upgrading to biomethane. The benefits of digestate byproduct from anaerobic co-digestion was also found to be significant and could potentially fully replace the bulk of imported fertiliser in Australia's agricultural industry. There are however areas requiring further research, as questions around cost-benefit, more accurate net-GHG reduction estimation and logistical challenges are still unanswered by this study. All in all, biogas generated from ACoD of manure, MSW and agricultural residues was proven to be a viable opportunity for future development, with significant GHG reduction and biogas generation potential.

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Appendices

Appendix A – Project Specification

ENG4111/4112 Research Project

Project Specification

For:	Ella Chapman
Title:	Greenhouse gas reduction and biogas production potential through anaerobic digestion of biomass waste: an Australian perspective
Major:	Civil engineering
Supervisors:	Dr Antoine Trzcinski
Enrolment:	ENG4111 – EXT S1, 2023 ENG4112 – EXT S2, 2023
Project Aim:	Estimate the potential Australia-wide biogas supply and greenhouse gas emission reduction resulting from combined anaerobic digestion of livestock manure, agricultural residue and municipal solid waste.

Programme: Version 1, 15th March 2023

1. Review existing literature to understand AD in an Australian context, current biogas production, existing infrastructure, similar previous studies and research gap.
2. Research biomass sources and their availability in Australia to decide best options.
3. Collect data to determine variables for calculating biogas potential of each source.
4. Collect data for methane-energy conversion, expected loses from efficiency, polluting factors to include in calculations (transport, leaks) etc.
5. Process and summarise the collected data, excluding outliers to determine most representative final values.
6. Perform calculations for energy generated and net-GHG emission reduction.

If time permits:

7. Further research to make recommendations for small 'local' reactors as opposed to large 'regional' reactors and specify requirements for most efficient locations.
8. Rough cost-benefit analysis for the two AD plant options, efficiency comparisons and long-term management cost comparisons (e.g. benefits of refining to bio-methane, selling bio-fertiliser).

Appendix B – Risk Assessment

The risk assessment for this project was developed using the USQ Safety Risk Management System, with the ID 'Risk Assessment- Ref No: 2435'. The risk matrix is provided as Figure 17 and the risk register, and proposed controls is provided in Figure 18. The final residual risk level was determined to be 'very low' after the proposed controls were implemented and is approved by the project supervisor.

UniSQ **Risk Assessment [Ref Number: 2435]**

Date Printed: Wednesday, 17 May 2023

Appendix

Risk Matrix Level	
Very Low	Task can proceed upon approval of the risk assessment by the relevant supervisor, manager or higher delegate
Low	Task can proceed upon approval of the risk assessment by the relevant supervisor, manager or higher delegate
Medium	Task can proceed upon approval of the risk assessment by a Category 4 or higher delegate
High	Task can only proceed in extraordinary circumstances provided there is authorisation by the Vice Chancellor
Extreme	Task must not proceed. Appropriate and prompt action must be taken to reduce the risk to as low as reasonable practicable

Figure 17- Risk matrix level applicable to the project risk assessment

UniSQ **Risk Assessment [Ref Number: 2435]**

Date Printed: Wednesday, 17 May 2023

Low	Very Low		
Existing Controls	**Proposed Controls**		
	Description	Responsibility	Target Date
• No existing controls required: Usual study habits and workstation	Ensure regular breaks, hand/back/leg stretches, get up and move around periodically, ensure desk and chair arrangment as ergonomic as possible, give eyes a rest periodically to avoid eye strain.		14/10/2023

Figure 18 - Risk register and proposed controls approved by the project supervisor.

Appendix C – Timeline Gantt chart