Report 3: Factors that affect the viability of biomethane projects

FFCRC RP1.2-04

April 2024

Project number: RP1.2-04

Integrated model for bio-methane injection in gas networks

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Australian Government
Department of Industry, Science and Resources
AusIndustry
Cooperative Research Centres Program

This work is funded by the Future Fuels CRC, supported through the Australian Government's Cooperative Research Centres Program. We gratefully acknowledge the cash and in-kind support from all our research, government and industry participants.

IMPORTANT DISCLAIMER

PROJECT INFORMATION	
Project number	RP1.2-04
Project title	Integrated model for bio-methane injection in gas networks
Research Program	RP1
Milestone	Report 3: Factors that affect viability
Description	The scope, methodology and findings of a sensitivity analysis to determine which factors have the largest effect on biomethane project viability
Research Provider	University of Adelaide (SET)
Project Leader and Team	Project Leader: Holger Maier Project Team: Holger Maier, Peter Ashman, Aaron Zecchin, Tara Hosseini, Sam Culley, Olivia Smith, Sandra Kentish
Industry Proponent and Advisor Team	Proponent: Patrick Lowry (AGIG) Advisor Team: AGIG: Jarrod Irving Jemena: Alhoush Elshahomi Energy Networks Australia: Dennis R Van Puyvelde GHD Group: Craig Clarke APA: Bart Calvert DMIRS: Mohamed Hammad
Related Commonwealth Schedule	RP1.2.2 Techno-economic models and software for future fuel production technology completed. RP1.5.3 Feasibility studies for new demonstration project(s) in Australia delivered.
Project start/completion date	May 2021/Oct 2024
IP Access	**Open** – available publicly to all parties outside the CRC.
Approved by	Patrick Lowry (AGIG)
Date of approval	17/4/24

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Glossary of Terms

LCOE	The LCOE is estimated by calculating the total discounted lifetime costs (or, the net present value), divided by the total discounted energy output.
LCOE*	In some scenarios where a revenue stream is present (from selling byproducts or a government policy etc.), we adjust the standard measurement of LCOE to include the net project costs, not total project costs. The primary reason for this is to acknowledge that revenue streams reduce the gap between the LCOE and the market price of natural gas so that projects can be profitable, allowing for a consistent comparison across the analysis. But it is important to note in these cases that the inherent cost of the biomethane is not changed. This adjusted measure of LCOE will be denoted in the report using LCOE*.
Carbon saved	The net carbon saved from operation of the AD biomethane project, in terms of tCO_2e/year.
Energy density	The energy content of gas produced per tonne of feedstock input, i.e. gravimetric energy density in GJ/tonne.
Fugitive emissions from gas networks	Fugitive emissions in the transport and consumption of gas outside of the biomethane projects themselves (i.e. gas networks and consumption in consumer appliances).
Digestate profit	The profit that is received from selling 1 tonne of processed solid digestate ($/tonne).
Gate fee	The income from charging to dispose of waste at the plant ($/tonne).
CO_2 gas sale	The profit from processing and selling food grade CO_2 ($/tonne).
RGGOs	A renewable gas guarantee of origin scheme ($/MWh).
Feed in Tariff	The average Feed in Tariff amount over a 20-year project lifetime ($/GJ).
Green Gas Support Scheme	A tiered support scheme from the UK that provides a tariff based on biomethane production ($/GJ), represented here as the average level over the project life.
ACCU	Australian Carbon Credit Units
Displacement ACCU	The ACCU from a tonne of carbon emissions displaced by a biomethane project injecting into the grid ($/tonne CO_2-e).
Conversion ACCU	The ACCU from a tonne of carbon emissions avoided by a biomethane project capturing organic feedstock ($/tonne CO_2-e).
Direct grant funding	The offset to CAPEX of the AD plant (i.e. excluding cost of connection to grid) as supplied from a government grant ($).
CAPEX	Capital expenses of a project ($)
OPEX	Operational expenses of project ($/year)
AD	Anerobic digestion plant

Summary of Report

Now that biomethane projects are receiving more attention and momentum across Australia, there is a need to understand the significant variability in the potential techno-economic viability of such projects. This variability can arise due to a combination of factors; some that are within the control of project stakeholders and others that are not, as they are caused by external forces. The former include type and location of plant, feedstock source etc., which should be optimised to maximise the chances of project viability. The latter include factors such as government support/policy, geopolitical instabilities, demand for gas from consumers, natural hazards such as droughts/floods and other market forcings, which need to be managed, especially if they have a significant impact on project viability. The purpose of this report is to provide a better understanding of the relative impact the above factors have on the viability of biomethane grid injection projects in Australia. This is achieved by applying a sensitivity analysis to the integrated biomethane project assessment model developed as part of this project (Culley et al. 2023). The metrics for project viability used in this assessment are the levelised cost of energy (LCOE, $/GJ) and the net carbon saved (tCO_2-e).

As an example of the assessment performed, Figure i shows the sensitivity of both LCOE and net carbon saved to factors that relate to the source of feedstock and distance from the anerobic digestion (AD) plant. Full descriptions of these factors, as well the ranges of values considered for each of these factors as part of the sensitivity analysis, can be found in Section 3 of this report. As can be seen from Figure i, the factors related to feedstock have a far bigger impact on both LCOE and net carbon saved than the factors related to distance from the plant. Feedstock availability has the largest impact on LCOE and net carbon saved, as this affects operational costs associated with transport and biogas upgrading, biomethane produced, and also the CAPEX of the required plant size (estimated from peak biogas flow rate). The second most significant factor affecting LCOE is feedstock availability throughout the year, as this is essentially a proxy for feedstock storage, highlighting that fully utilising agricultural feedstock that is only available for one to two months a year is likely to be prohibitively expensive.

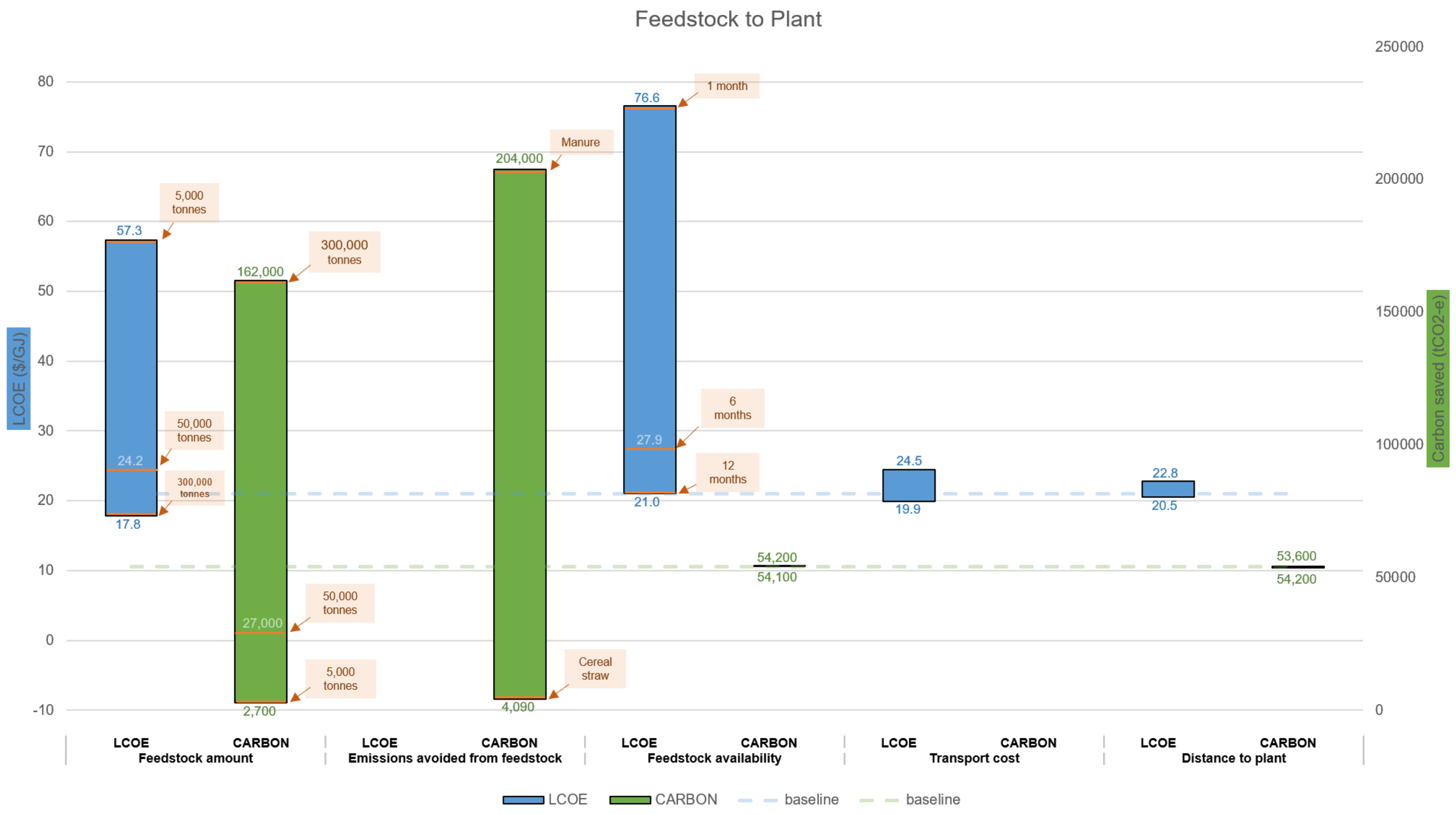

Figure i – The sensitivity of LCOE and Net carbon saved to factors related to feedstock selection and distance from plant.

A summary of the relative influence of all of the factors considered in this study on LCOE and carbon saved, ordered from most to least influential, is given in Figures ii and iii, respectively. As can be seen from Figure ii, the factor LCOE is most sensitive to overall is energy density of the feedstock. This factor controls the biomethane injected to the grid per tonne of feedstock transported to the plant and also determines the size of the plant for a fixed feedstock amount. As a result, smaller energy density values result in a lower plant capacity (with a relatively larger capital cost) and less biomethane offset for a fixed transport cost. The second and third most significant factors affecting LCOE are feedstock availability and feedstock amount (also shown in Figure i), which both also affect the size of the biomethane plant. In the case of feedstock availability, this is because the plant is sized to process all the annual feedstock, which can be either over all twelve months of the year (if the feedstock is available all year round) or in just one month (if feedstock supply is only available for a single month), resulting in plant underutilisation and prohibitively high costs, as mentioned above.

For net carbon saved, the two most significant factors by far are the emissions avoided from feedstock and the feedstock amount (Figure iii). These two factors inform conversion and displacement ACCU calculations, respectively. Both of these factors provide a strong motivation for biomethane projects with respect to waste re-use as part of creating a more circular economy, with the potential to save tens of thousands more carbon emissions depending on the feedstock type used. The third most significant factor affecting carbon emissions saved is the amount of biomethane injected vs flared (given network constraints), which has the effect of displacing less natural gas, as well as leading to bio-methane slippage into the atmosphere, and so the increase of flaring has a negative impact on the amount of GHG emissions that can be avoided.

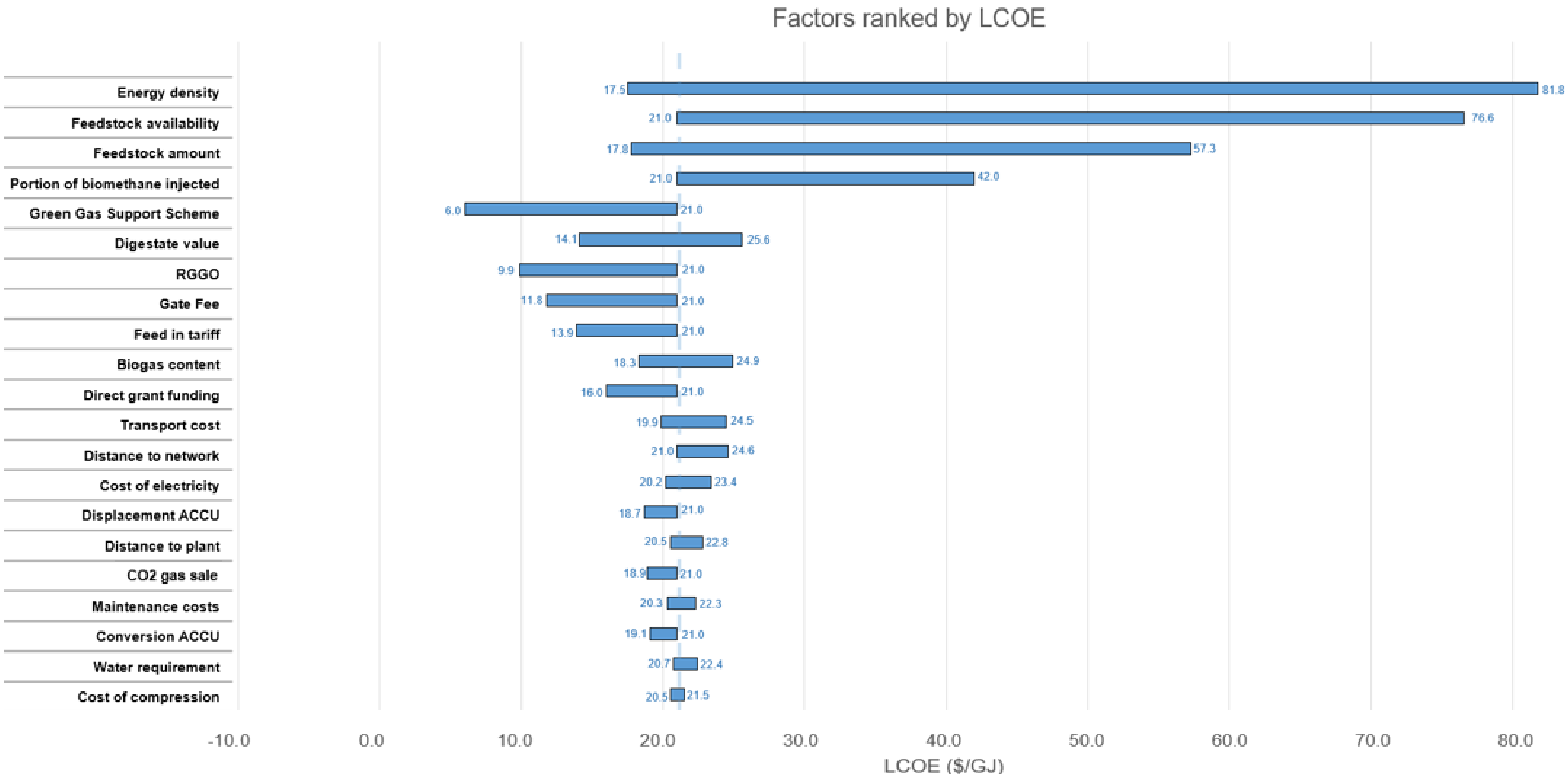

Figure ii – A ranking of how factors impact LCOE, with change presented relative to the baseline (the range taken for each factor can be found in Section 3)

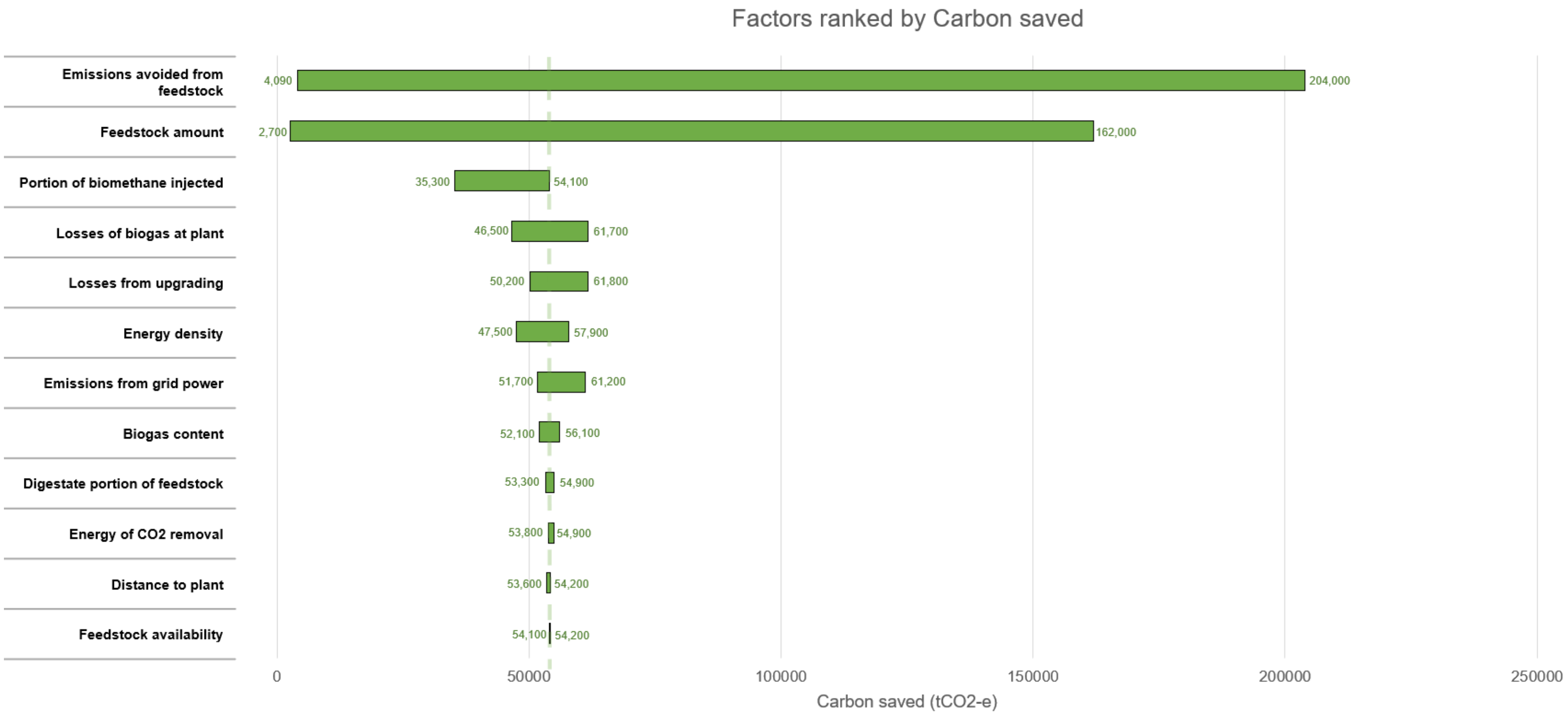

Figure iii - A ranking of how factors impact net carbon saved, with change presented relative to the baseline (the range taken for each factor can be found in Section 3)

Finally, a series of joint sensitivities are considered to explore how closely the LCOE can approach the price of natural gas, when revenue streams and/or various favorable Government policies are in place, (Figure iv) such as:

- **Renewable Gas Guarantees of Origin (RGGOs) + digestate profit**: This combination demonstrates the effects of a single policy support and revenue source, to compare with the price of natural gas.
- **Feed in Tarrif (FiT) + grant**: This combination represents a policy scheme that is not solely reliant on FiTs but also includes capital support.
- **RGGOs + ACCU conversion**: This combination represents a carbon market with organisations purchasing RGGOs and also biomethane projects ACCUs.
- **CO_2 revenue + ACCU conversion + ACCU displacement**: This combination represents a biomethane project that has an emphasis on capturing CO_2.
- **CO_2 revenue + digestate profit + gate fee**: This combination represents the revenue streams that would be relevant with a strong circular economy focus.

The joint sensitivities of policies and revenue streams were investigated to examine which combinations lead the LCOE* to approach the price of natural gas (Figure iv). Of the five combinations examined, four resulted in LCOE* values that were less than the price of natural gas (taken as $11/GJ). Two of these include a RGGO scheme, which provides a heavy price offset, given the amount of biomethane produced ($40/MWh). The only policy combination to not reduce the LCOE* to values that are less than the price of natural gas is the one that focuses only on a carbon economy, where a credit of $60/tCO_2e$ for the conversion and displacement abatement, and sale of food grade CO_2, are not enough of a revenue stream for projects to have a positive NPV when selling biomethane at the price of natural gas.

When considering combinations of government policy and revenue support, the two lowest LCOE* combinations (at $2.97/GJ and $2.79/GJ) both consider a revenue stream from the selling of the digestate by-product. It is important to note that the profit available from digestate is highly uncertain due to several factors (e.g. limitations of use of digestate, market competition, and potentially having to dispose of the digestate at cost). When considering the values of a circular economy and combining the digestate profit with revenue from captured food grade CO_2, as well as the imposition of a gate fee, the LCOE* reduces to a value of $2.79/GJ. Alternatively, a FiT based on values from the Netherlands and other countries in the EU, when combined with a once off $28,000,000 grant from Government agency funding (50% of CAPEX), reduces LCOE* values to $8.92/GJ, which is below the price of natural gas. If applied in Australia, this would increase the viability of large-scale agricultural projects, like the one modelled in the baseline of this assessment.

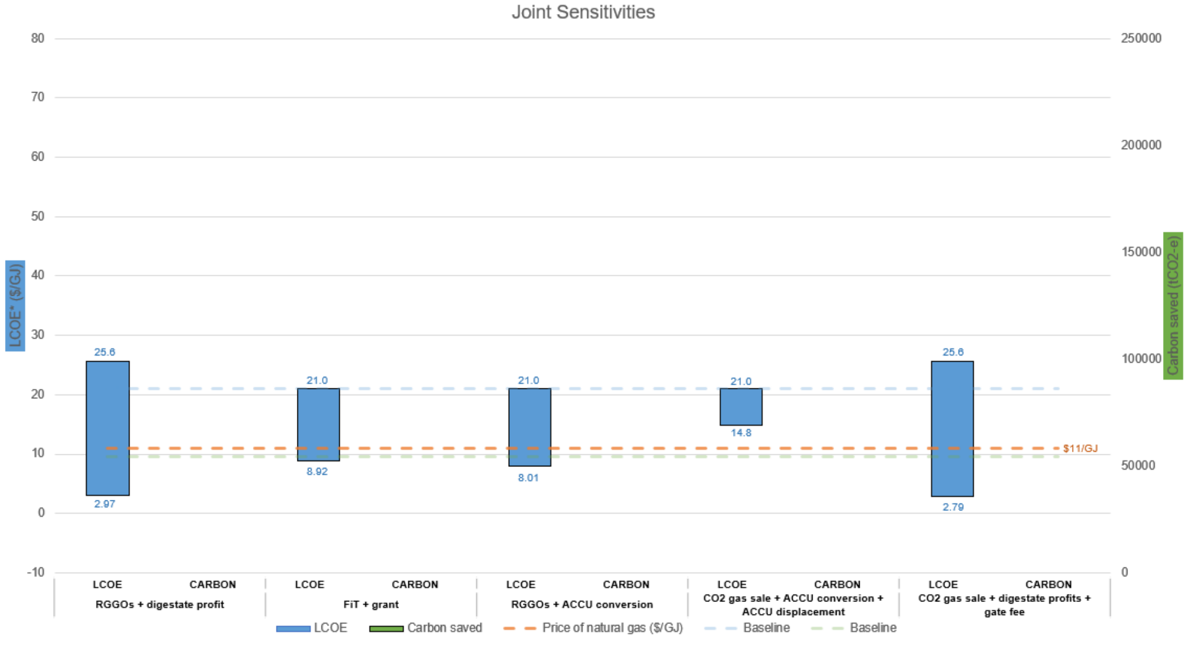

Figure iv – Joint sensitivity of LCOE to combinations of revenue and policies. Results are presented as change in LCOE from the baseline

1. INTRODUCTION

1.1 Background

The conversion of waste to bioenergy is regarded as an emerging opportunity to decarbonise energy systems in Australia, capable of meeting up to 20% of Australia's energy requirements by 2050 (Carlu et al., 2019; ENEA and Deloitte, 2021). As gas delivers 44% of Australia's household energy, there is a significant opportunity to reduce greenhouse gas emissions while utilising existing gas networks with waste-to-gas schemes - specifically the production and injection of biomethane. Europe is the world's leading producer of biomethane, with 350 plants feeding into the gas grid in 2015 (Scarlat et al., 2018). Despite the opportunity and the significant commercial success in Europe, the production of biomethane and its injection into existing gas networks is currently almost non-existent in Australia.

The Future Fuel CRC's Project RP1.2-03 took the first steps towards providing the information needed by gas network owners to assess the viability of injecting biomethane into their networks in an Australian context by co-developing a high-level framework outlining the steps that need to be considered in such assessments, how they relate to each other and what appropriate data sources are required (Culley et al., 2021b). While the high-level framework is able to provide guidance on how to perform the desired viability assessments and what potential data sources might be, it does not enable quantitative assessments to be performed. Consequently, the overarching objective of this project (RP1.2-04) is to develop a user-friendly integrated assessment model that enables the high-level framework developed in project RP1.2-03 to be applied easily and reliably by end users to perform pre-feasibility techno-economic viability assessments at locations of interest across Australia.

1.2 Purpose of this report

Biomethane grid injection projects are being recognised as a promising technology with the potential to contribute significantly to Australia's renewable energy transition, especially 2030 decarbonisation targets. However, it is also understood that compared to the implementation in other countries, there are a number of barriers in Australia, resulting in a significant variability in the viability of projects (Culley et al., 2021a). This can arise due to a combination of factors, including available feedstocks, larger distances, policy positions and cost of energy. The purpose of this report is to identify and understand the key factors that significantly impact project viability through conducting a sensitivity analysis on biomethane grid injection projects in Australia, using the integrated assessment model developed as part of this project (Culley et al., 2023). This analysis can aid end users of this project to either: further optimise projects to decrease the cost of biomethane production so it comes closer to the price of natural gas, or, be aware of key uncertainties beyond immediate control (such as government policies) and understand the opportunities and risks this poses to the viability of a project.

An overview of the approach used to identify the factors that have the biggest effect on viability is shown in Figure 1. A series of factors that influence the techno-economic viability of biomethane projects will be changed, and a quantitative system model will be used to estimate the impact on both cost and carbon emissions saved for a typical biomethane project. The quantitative system model used is the integrated assessment model developed as part of this research project (RP1.2-04 Report 2) (Culley et al., 2023).

This report is structured as follows. First, the framing of the sensitivity analysis, including the metrics assessed and an overview of the assessment model, are presented in Section 2. Then, the methods, case study, and factors considered in the assessment are described in Section 3. Results of the assessment are then presented in Section 4, with conclusions provided in Section 5.

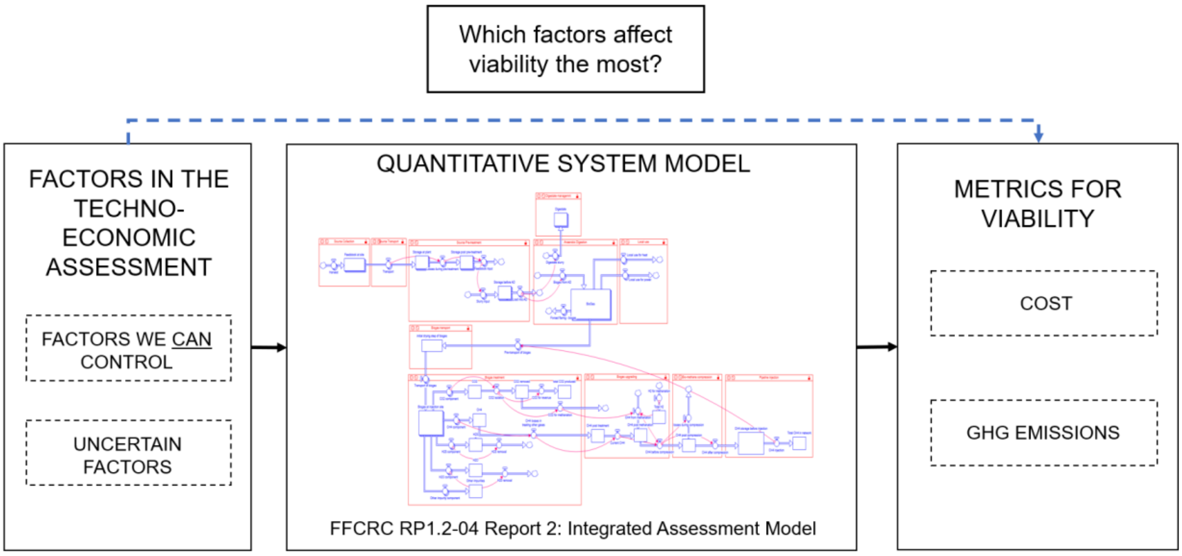

Figure 1 – Framework illustrating the approach used to identify the relative influence of factors affecting the viability of biomethane projects.

2. FRAMING OF THE ASSESSMENT

Now that biomethane projects are receiving more attention and momentum across Australia, there is a need to understand the potential reasons for the significant variability in the viability of such projects, which can arise due to a combination of factors. In this section, we provide a framing for the assessment to determine the most significant factors that affect the viability of biomethane grid injection projects in Australia. We first describe the two key metrics that are used to characterise the performance of a biomethane project, as it is the sensitivity of these metrics to the project factors that is of key concern within this report. The metrics are: cost as characterised by the LCOE and greenhouse gas (GHG) emissions (Section 2.1). We then provide a summary of the integrated assessment model used in this assessment (Section 2.2).

2.1 What is sensitivity measured to?

In order to consider a more rounded business case, as mentioned, two metrics are considered as part of this assessment, one for cost and one for GHG emissions. The cost metric used is the Levelised Cost of Energy (LCOE), and the carbon metric is a measure of net Greenhouse Gas (GHG) reduction from the European Biogas Association (EBA, 2020).

LCOE

The LCOE (measured in $/GJ) is estimated by calculating the total discounted lifetime costs (or, the net present value), divided by the total discounted energy output. In select scenarios where a revenue stream is present (from selling byproducts or a government policy etc.), we adjust the standard calculation of LCOE to include the annualised net project costs, not total project costs. The primary reason for this is to acknowledge that revenue streams reduce the gap between the LCOE and the market price of natural gas so that projects can be profitable, allowing for a consistent comparison across the analysis. But it is important to note in these cases that the inherent cost of the biomethane production is not changed. This modified LCOE metric will be denoted in the report using LCOE* and is measured in $/GJ, allowing for comparison with the purchase price of traditional fuels such as the price of natural gas. LCOE is calculated using the following equation:

Equation 1 – Levelised Cost of Energy

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where, n = lifetime (years), r = discount rate (%), t = project year, I_0 = CAPEX (Capital Expenditure, $) amount, M_t = net cost in year t ($, note that in some relevant scenarios, we subtract revenue from costs), and, E_t = energy produced in year t (GJ). In this assessment, the sensitivity of LCOE to a range of factors will therefore be determined by their impact on the CAPEX and OPEX (Operational Expenditure) of running a biomethane project. However, the discount rate and project lifetime will also have a significant effect on the LCOE metric. This is explored more in Section 3.2.1, where the effect of these parameters on the baseline LCOE breakdown is demonstrated.

Net Carbon Saved

The method of estimating the carbon emissions adopted in this assessment is based on both the European Biogas Association (Figure 2), and the Australia emissions reduction fund calculations (Regulator;, 2022). The greenhouse gas emissions reduction potential is estimated by taking the net difference between emissions caused from the project (transport of feedstock, flaring/leakage of gas, and emissions from grid power), and the carbon abatement (displacement of natural gas, avoidance of feedstock emissions and any avoidance from byproducts). In this study, the emissions tracked are as follows:

Carbon emissions:

- Transport;
- Carbon from electricity grid;
- Leakage from AD reactors;
- Leakage from biogas upgrading;
- Scope 3 fugitive emissions from gas networks;

- Leakage from incomplete combustion through flares (not in the baseline case, only when demand is limited).

Carbon abatement:

- Avoided from feedstock decomposition/prior use;
- Net abatement from digestate use instead of fertiliser;
- Displaced natural gas from grid.

A breakdown of this metric is provided in Section 3.2.2, using the baseline case study defined as part of this assessment (Section 3.2).

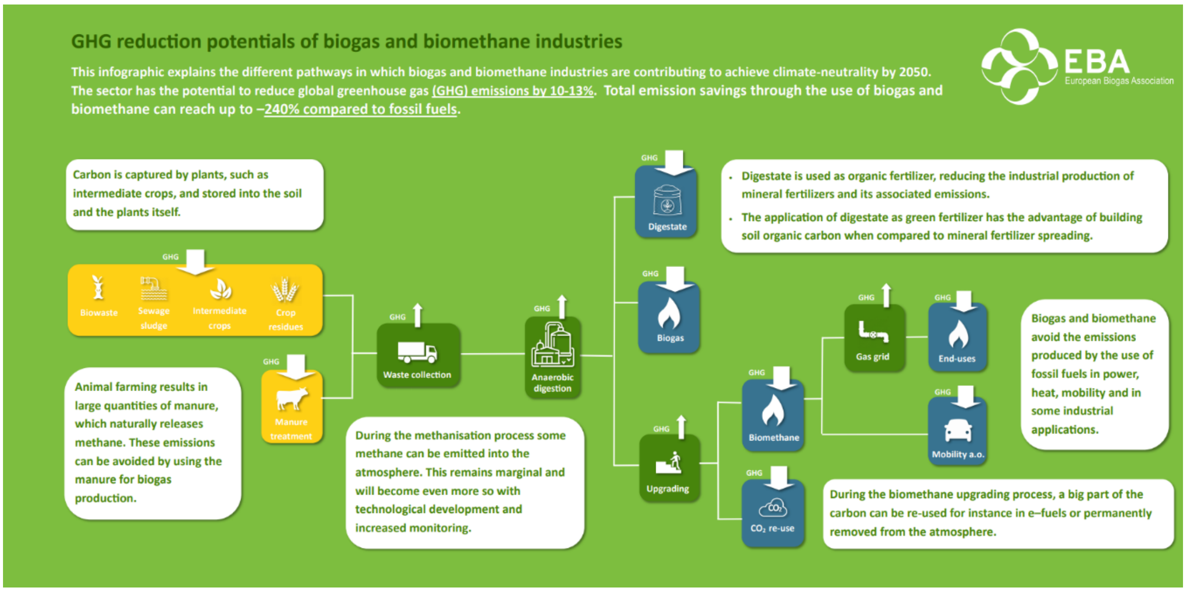

Figure 2 – GHG reduction potentials of biogas and biomethane industries ((EBA, 2020)).

2.2 How is the impact estimated?

A high-level description of the processes modelled by the quantitative system model is shown in Figure 3. The first product is the feedstock, which is collected, and transported to the biogas plant (processes 1-2, Figure 3). At the biogas plant, the feedstock is pre-treated to form a slurry (process 3), which mixes all available feedstocks with water. At the AD stage, this slurry produces both biogas and digestate (process 5, products 21 and 22). The digestate is dewatered, where it can be refined and sold as fertilizer (processes 6 and 7). The biogas is then treated to remove the CO_2, water vapour, and H_2S (processes 8 and 11). There is also an optional process of upgrading the removed residual CO_2 to CH_4 via methanation (process 12), which occurs before the biomethane is compressed and injected into the transmission pipeline (processes 13-14) (Culley et al., 2023).

Throughout all these processes, the techno-economic metrics from Section 2 (LCOE and net carbon saved) are calculated for each, and then totalled at the end of all the processes. Note that in the case of LCOE, it is only the operational costs that are calculated in each section. For the capital costs, the size of the biomethane plant is estimated based on the peak biogas flows at the stage of anaerobic digestion, which includes the equipment required for pre-treatment, digestate management and biogas upgrading. Note that the digestate modelling is high level i.e. net revenue and net emissions avoided are assumed, and the transport of the digestate is not modelled in detail. The CAPEX for gas compression and storage are the only elements calculated independently, as this will depend on the gas pipeline constraints more than the AD plant. More details are provided in Report 2 of this project (Culley et al., 2023).

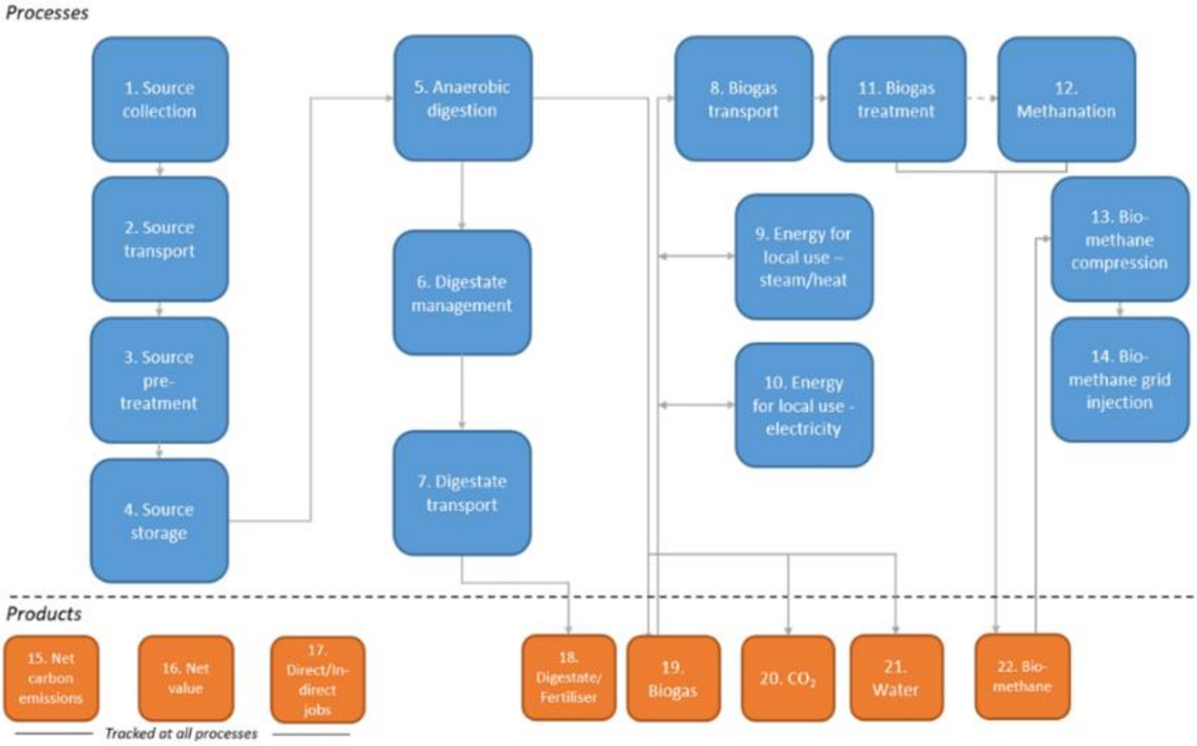

Figure 3 – Draft framework illustrating the end-to-end process and products to consider in a viability assessment of biomethane grid injection projects (Culley et al. 2023).

3. METHOD FOR DETERMINING FACTORS THAT AFFECT VIABILITY

In this section we describe the approach used to determine the factors that have the most significant effect on the viability of biomethane projects. Section 3.1 first describes the general approach of the assessment. Section 3.2 details the case study used throughout the assessment, and also presents a baseline for both of the metrics used in this assessment. The list of factors selected, including the minimum and maximum values they can take, and the value when held constant, are detailed in Section 3.3. Finally, to explore the extent to which the cost of a biomethane project can approach the price of natural gas by considering a set of combined effects of policy and revenue factors, as described in Section 3.4.

3.1 General approach

The objective of this assessment is to identify which factors have the biggest impact on the viability of biomethane grid injection projects in Australia (Figure 4). As discussed in Section 2, the metrics used to measure viability are LCOE and net carbon emissions.

The approach adopted to determine which factors have the biggest effect on viability is to 1) select a series of factors, 2) vary them one at a time, and then 3) examine combined effects. When considering the factors that can potentially influence the two viability metrics (Figure 4, factors shown on left side), both factors that are within and beyond the control of stakeholders of a biomethane project are considered. Examples of the latter include government support/policy, geopolitical instabilities, demand for gas from consumers, natural hazards such as droughts/floods and other market forcings. In this assessment, we have sorted these factors into revenues, policies and external costs (i.e. carbon accounts factors, price of utilities etc). Examples of the former include type of plant, location of plant, size of plant and feedstock source. These factors are generally optimised to maximise project viability. In this project, we have arranged these factors into the following categories: "Feedstock to plant" (Figure 3, processes 1-4), "Biogas Plant" (Figure 3, processes 5-8), and "Upgrading and grid connection" (Figure 3, processes 11-14).

When deciding on which ranges to consider for each of the above factors as part of the sensitivity analysis, two main approaches were taken. If there was little data available for a factor, a range was taken to indicate the uncertainty in the value. Examples of these factors include potential government policies or potential revenues from by-products. For factors that are much more certain as they are an established part of a biomethane project, or a factor that stakeholders may even have control over, a range was taken to show how this value can change across case studies in Australia. Examples of these parameters include distances (feedstock to plant, and plant to pipeline), feedstock types, and technologies for upgrading biogas.

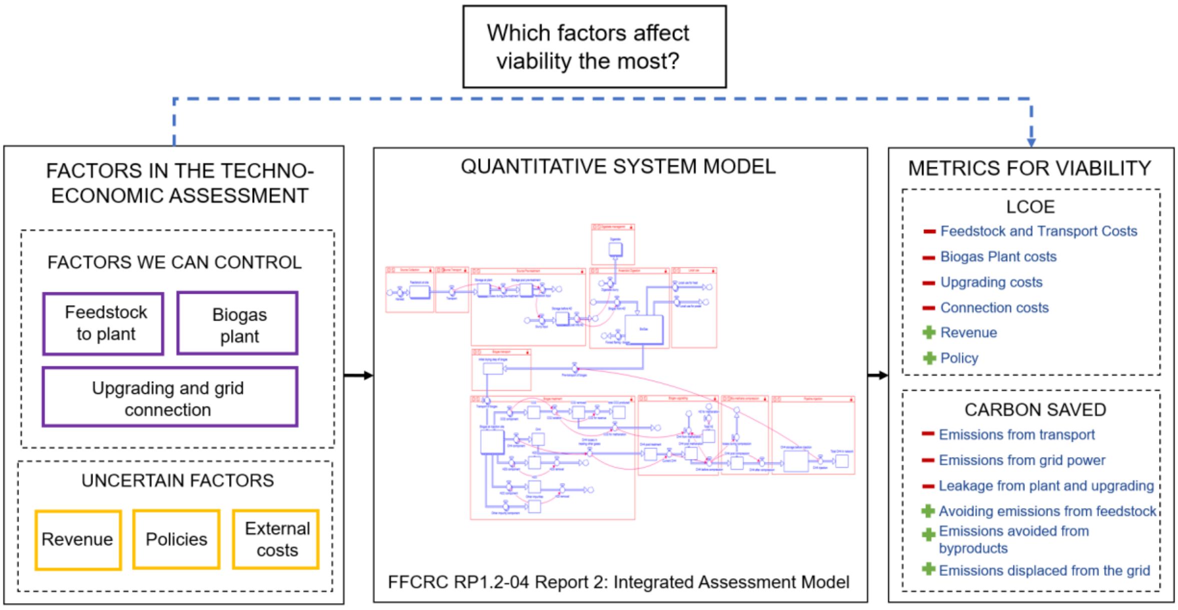

Figure 4 – Detailed framework to identify which factors have the biggest impact on the viability of biomethane grid injection projects in Australia.

3.2 Case study and Baseline Metrics

To understand the effect variability in the factors considered has on biomethane project viability, it is necessary to first establish a baseline project scenario by configuring the integrated assessment model to a case study. The case study chosen in this assessment is selected to be indicative of a typical large scale biomethane hub, located rurally in Australia, akin to the case study of Griffith NSW (from project RP1.2-03) (Culley et al., 2020). While this baseline represents a typical agricultural biomethane hub, the structure of the sensitivity analysis and parameter variations allows for the exploration of a greater range of projects across Australia, including feedstock types from wastewater treatment plants to sugarcane waste; urban environments, plants that are located a significant distance from the gas grid and different pricing and carbon accounts factors for utilities, that vary state by state. This is all reflected in the range of values parameters are allowed to take (Section 3.3). Further, as part of this baseline project scenario, it is assumed that there are no revenue streams or policy support, but these are all investigated as part of the sensitivity analysis (Section 3.3).

As a baseline scenario, the case study has the following key configurations:

- 100,000 tonnes a year of feedstock: a mix of cereal straw, organic municipal solid waste and manure;
- The sources of feedstock are 20km from the anaerobic digestion (AD) plant, transported by trucks;
- The plant is sized assuming the feedstock is evenly available through the year;
- Digestate is processed, but in the baseline is not sold for profit, but given away (digestate profit is explored in other parts of this assessment, as is the cost of disposal);
- The biogas is 60% methane;
- The CO_2 from the biogas is separated using membrane technology;
- The biogas plant is located next to a transmission gas pipeline, where the gas is injected (assuming a 3000 kPa inline pressure);
- Carbon accounting values are taken as the national average.

Full details on the assumptions made in the case study modelling can be found in Section 3.3. The baseline metrics (i.e. values for the baseline scenario case study), and a breakdown of the costs and carbon emissions (as outlined in Figure 4), are explored in the following subsections. This will serve as a basis for comparison within the sensitivity analysis, where all changes are presented relative to this baseline.

3.2.1 Current framing and breakdown of LCOE

The LCOE of the case study used in this assessment is $21.0/GJ, when no additional revenue streams or policy support is considered. A breakdown of costs is shown in Figure 5 (blue colour), separated into the major supply chain components as per Figure 4. The most significant cost component is the biogas plant, which is primarily due to this being the most expensive CAPEX cost. The second largest cost – in this case study – are the transport costs, which are categorised as OPEX costs, followed by upgrading and then compression. As an indication of how this project could become economically viable (with an LCOE approaching the price of natural gas), select revenue streams available to biomethane projects are also considered (Figure 5, green colour). These include a Gate fee (priced competitively to existing waste levees), digestate profit and CO_2 profit, and when all are present the LCOE can reduce to $9.7/GJ (yellow colour). Note that the parameters behind these revenue streams are explained in Section 3.3, Table 4.

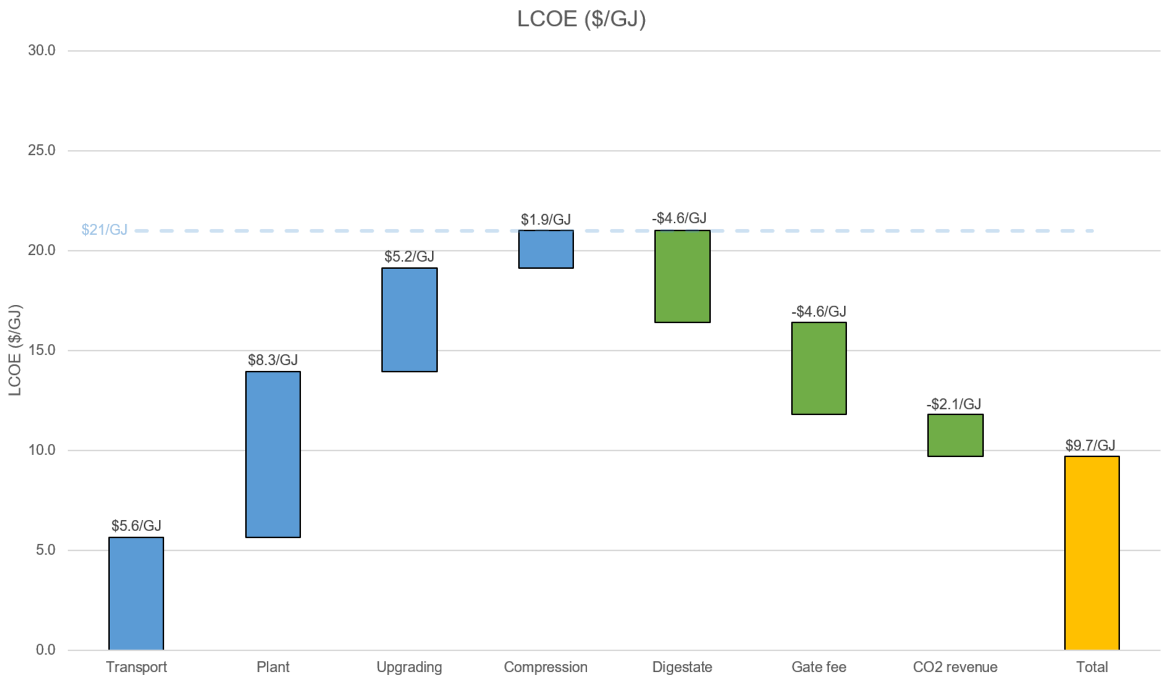

Figure 5: Breakdown of the case study costs using the LCOE metric.

The LCOE as a metric is not just sensitive to changes in costs of running a biomethane project, but also the discount rate and project life that are assumed. Figure 6 shows the change in LCOE that can be obtained from only a small change in discount rate (~$3/GJ) and also changes to the assumed project life ($4/GJ). These parameters primarily affect the relative importance of CAPEX against OPEX, with smaller discount rates and longer project lives diminishing the relative contributions of CAPEX costs to LCOE. This can be seen clearly in Figure 7, where the baseline LCOE is reproduced with a 3%, 40-year project life assumption and a 10%, 10-year project life assumption. Notably, the relative importance of transport costs vs plant costs changes significantly (due to transport being OPEX and the biogas plant being CAPEX). The impact of discount rate and project life are, in a way, second order factors affecting the LCOE metric, when compared to actual physical configurations of a case study or revenues and policy amounts. In other words, whichever factors are found to have the most impact on the LCOE, a change in discount rate can produce a further $/GJ change. For the remainder of this study, the discount rate will be taken at 7% and the project life at 20 years, for the results of the sensitivity analysis to be comparable.

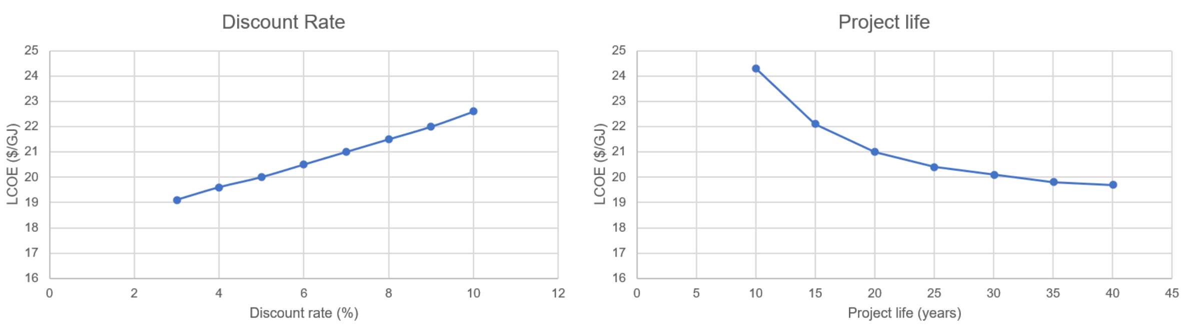

Figure 6 –The effect discount rate and project life assumptions can have on the LCOE metric.

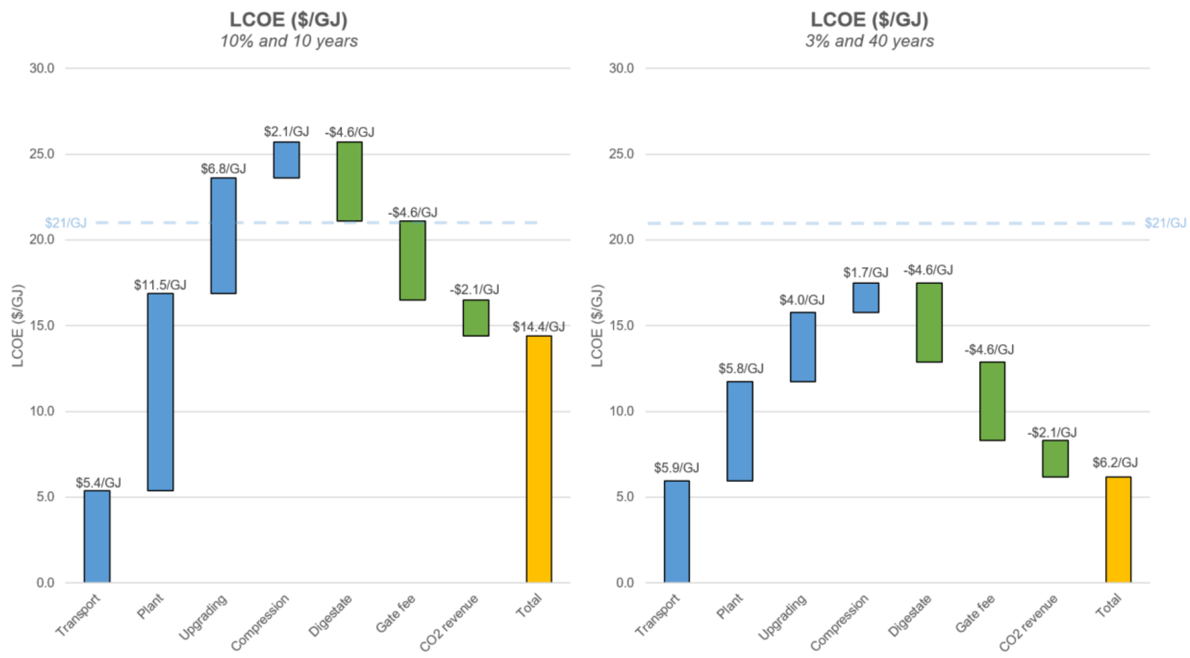

Figure 7 – Breakdown of cost using the LCOE metric with a case study of 10 years and 10% discount rate, and a case study of 40 years and 3% discount rate.

3.2.2 Current framing and breakdown of Carbon emissions

A breakdown of the method of estimating net carbon saved in this assessment is shown in Figure 8. The major sources of carbon emissions include leaking from the biogas plant and upgrading process, drawing power from the grid, and fugitive emissions from the gas grid. The emissions from transport are quite low, relative to those from the other sources. When considering carbon abatement (Figure 8, emissions avoided), the two most significant contributions are the avoided emissions from feedstock decomposition and the displacement of natural gas. The avoided emissions from feedstock are significant, as this is a large-scale agricultural project, and otherwise the waste would be decomposing. The emissions avoided by use of the digestate are less significant, but are still an order of magnitude larger than the transport emissions.

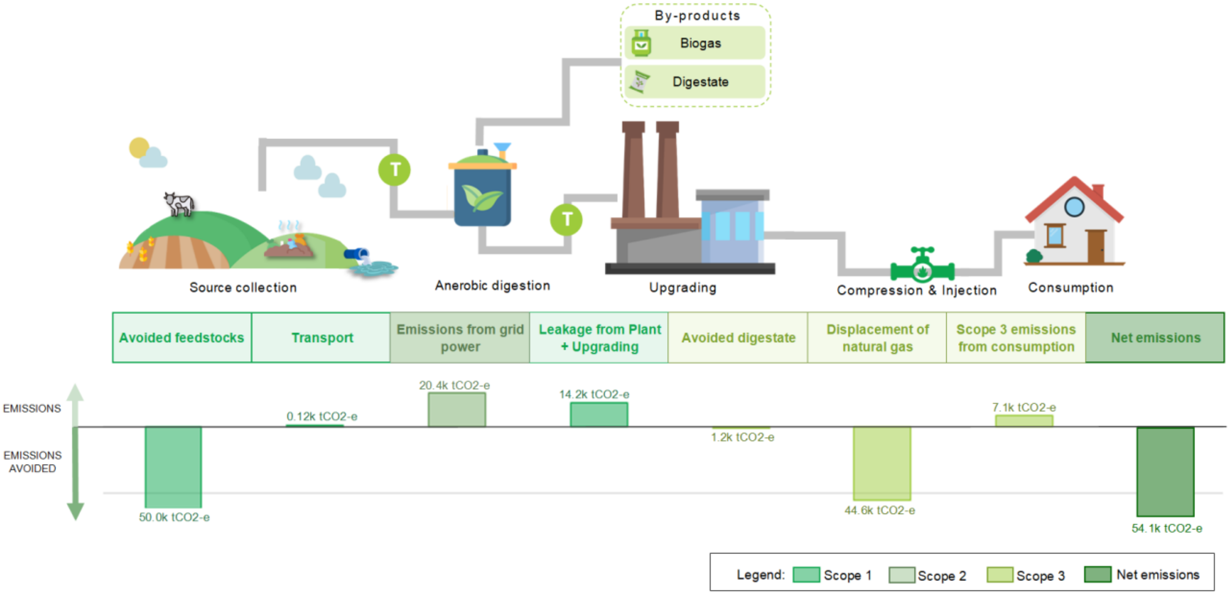

Figure 8 – Breakdown of the case study net carbon saved metric.

3.3 Factors for the sensitivity analysis

The factors that are included as part of the sensitivity analysis are detailed in Tables 1-5. Each table contains the name of the factor, a description of its role in the model, the default value when held constant based on the case study, the range it is changed over, and sources used to inform these values. The set of factors presented were chosen in consultation with end users of this project. The first three tables represent the factors stakeholders of a project can control, whereas the final two tables represent the uncertain factors (Figure 4).

The first table lists the factors from the point of feedstock collection to the AD plant. The parameters feedstock amount and emissions avoided from feedstock are typical to a techno-economic assessment of biomethane and are expected to have a significant impact on the results. The factor of feedstock availability was added to the underlying system dynamics model to explore the effect of storage of feedstock on viability (Table 1). Feedstock availability would typically be specified directly by the end-users of the tool, but this parameter was added to generalise the duration in the year that feedstock is available. The effect of this factor relates to the need to size a biogas plant for the peak gas rate, which is then underutilised through the rest of the year, instead of a smaller plant that produces gas evenly all year-round. Transport cost and distance to plant relate to the cost of transporting the feedstock (with distance to plant adding a scaling factor to a base assumption of cost).

Table 1 – Factors considered as part of feedstock selection to plant

Factor	Description	Default Value	Min	Max	Source
Feedstock amount	Feedstock amount (tonnes/year)	100,000	5,000	300,000	Default value – used in Culley et al. (2023) Max value from https://araratbio.com.au/
Emissions avoided from feedstock	Carbon emissions avoided by capturing the feedstock source (tCO_2-e/tonne).	0.5	0	2	Table 8.4 of IPCC report (Smith et al., 2007), Waste calculator: (Watch My Waste, 2020) https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/wasteregulation/fogo/22p4163-emissions-impacts-landfilling-food-waste.pdf
Feedstock availability	This allows the exploration of availability and storage time of the feedstock (% available through the year)	100	8.3	100	Developed for this assessment to represent a range of 1 – 12 months of availability (a value of 8.3% indicates all the feedstock is available for one month).
Transport cost	The cost of transporting feedstock via truck to the plant ($/tonne)	40	30	70	Biotransformation of Agricultural Waste and By-Products (Poltronieri and D'Urso, 2016) Headline economic value for waste and materials efficiency in Australia (CIE, 2017)
Distance to plant	A scaling factor for transport costs, and also carbon emissions, based on distance.	20	0	100	Developed for this assessment to represent a range across Australia

Table 2 lists the factors that influence the anaerobic digestion plant settings. The factor 'feedstock energy density' is used to represent the biogas yield for a range of feedstock types. This is more approximate than considering moisture content, total solids and volatile solids individually, but the main mechanism in the model is the amount of biomethane that can be obtained from the tonne of feedstock that was transported at a fixed $/tonne. The range of energy density values is varied to represent the high end of transporting co-digestated material versus the low end of transporting manure, which is high in water content. The remaining parameters affect the water required, byproducts recovered and losses at the plant (which have an impact on carbon emissions).

Table 2 – Factors considered that relate to the biogas plant

Factor	Description	Default Value	Min	Max	Source
Water requirement	The amount of water needed to add to the feedstock slurry to make the desired moisture content (kL/tonne)	1	0	5	(Basumatary et al., 2021)
Biogas content	The percent of methane in the biogas (%)	60	50	70	Table 1, (Chen et al., 2015)
Energy density	The energy content of the feedstock in m^3/tonne.	400	50	600	Biogas opportunities for Australia
Digestate recovered	The percentage of feedstock that is recovered as solid digestate (%).	40	0	80	Chemical process modelling software (aspentech, 2020) (Logan and Visvanathan, 2019)
Loss of biogas at plant	The leakage of biogas from the plant (%)	2	0	4	Biogas to bio-methane review, Table 3 (Ardolino et al., 2021)

Table 3 lists the factors that affect the integrated assessment model in the estimates of upgrading costs and compression and injection costs. The factors energy and water for CO_2 removal reflect the range of technologies available; membrane separation, water scrubbing, pressure swing absorption and amine scrubbing. The baseline case study assumes membrane separation is used. These technologies also have associated methane slippage, represented by loss from upgrading. The cost of grid connection is represented by two parameters: the cost of compression, and the distance from the plant. When combined, total connection costs reach a maximum of $25,000,000. The final factor was included to explore the demand for biogas, to represent conditions where the demand is lower than the produced biomethane and the biomethane is instead flared.

Table 3 – Factors considered as part of upgrading and grid injection

Factor	Description	Default Value	Min	Max	Source
Energy for CO_2 removal	The energy required to remove the CO_2, with ranges taken to reflect water scrubbing, PSA, and membrane separation (kWh/Nm^3)	0.22	0.1	0.265	Economic assessment of biomethane supply system (Paturska et al., 2015)
Water for CO_2 removal	The water required to remove the CO_2 (kL/Nm^3)	0	0	0.00003	Economic assessment of biomethane supply system (Paturska et al., 2015)
Losses from upgrading	The leakage of CO_2 and methane during the CO_2 removal and other upgrading processes (%)	2	0	3	Default value from the ACCU methodology (Department of the Environment and Energy, 2017)
Cost of compression	The cost of connecting to the grid and purchasing compression units ($)	3,000,000	0	6,000,000	(BECA, 2021)
Distance to network	Addition costs for connection to the grid depending on distance to the plant (km)	0	0	50	Assumed that pipeline construction is only viable for <50km
Portion of biomethane injected	The percentage of produced biomethane that is injected into the grid, instead of flared due to low demand (%)	100	50	100	Developed for this assessment to represent grid constraints limiting biomethane injection down to 50% of plant capacity

Table 4 presents the revenue options included in the assessment, and the potential policies considered. As shown in Section 3, the revenue options include: charging a gate free for the disposal of the feedstock, selling the digestate byproduct for profit, and selling the CO_2 captured during biomethane upgrading. Some of the policies selected are modelled from existing tariffs and schemes from the EU/UK and US, while others (grant funding and carbon abatements) are selected based on activity in Australia to date.

Table 4 – Factors considered that represent revenues and policies

Factor	Description	Default Value	Min	Max	Source
Digestate profit	The profit that is received from selling 1 tonne of processed solid digestate ($/tonne)	0	-100	150	The profit from selling digestate, with an upper range based on digestate from manure (Index Mundi, 2020), (BECA, 2021). A negative minimum value was taken to explore the additional cost of disposal.
Gate fee	The income from charging to dispose of waste at the plant ($/tonne)	0	0	80	From Griffith case study - The cost of landfill starts at $40/tonne in Australia (BDA Group, 2009). This is applied to cereal straw, silage, winery waste and poultry bedding (not the MSW).
CO_2 gas sale	The profit from processing and selling food grade CO_2 ($/tonne)	0	0	200	(BECA, 2021)
RGGOs	A renewable gas guarantee of origin scheme ($/MWh)	0	0	40	From an EU study of prices in UK and Demark https://www.prnewswire.com/news-releases/argus-launches-biomethane-guarantee-of-origin-price-assessments-301461026.html
Feed in Tariff	The average Feed in Tariff amount over a 20-year lifetime project ($/GJ). Note this is kept constant across project life.	0	0	7.1	From a FiT scheme in France https://assets.sustainability.vic.gov.au/susvic/Report-Energy-Government-measures-interventions-for-biogas.pdf
Green Gas Support Scheme	A tiered support scheme from the UK that provides a tariff based on biomethane production ($/GJ). Note the average effect over 20-year project life was used.	0	0	15	https://hsfnotes.com/energy/tag/green-gas-levy/
Displacement ACCU	The ACCU from a tonne of carbon emissions displaced by a	0	0	60	Taken from RepuTex report for Australia to reach emissions

	biomethane project injecting into the grid ($/tonne CO_2-e)				targets by 2050 (RepuTex Energy, 2020)
Conversion ACCU	The ACCU from a tonne of carbon emissions avoided by a biomethane project capturing organic feedstock ($/tonne CO_2-e)	0	0	60	Taken from RepuTex report for Australia to reach emissions targets by 2050 (RepuTex Energy, 2020)
Direct grant funding	The offset to CAPEX as supplied from a government grant ($)	0	0	28,000,000	From ARENA (using a grant award of 50% of AD plant CAPEX) https://arena.gov.au/projects/?project-value-start=0&project-value-end=200000000&technology=bioenergy&page=2

Table 5 presents the factors that affect the costs of both carbon emissions and LCOE, globally throughout the assessment. The factors that represent the utility costs include the price of water, electricity, and the carbon cost of drawing electricity from the grid in Australia. Also included are two factors that are known to affect the operational cost of a biomethane plant, which are the cost of wages and the annual maintenance costs. Finally, the carbon cost of transport (via truck) is also included.

Table 5 – Factors considered that relate to general costs

Factor	Description	Default Value	Min	Max	Source
Transport emissions	The emissions factor for road transport via truck (kgCO_2/tonne-km)	0.062	0.04	0.07	ECTA guidelines for measuring CO_2 emissions (McKinnon, 2007)
Emissions from grid power	The emissions factor for using grid electricity in Australia (tCO_2-e/kWh)	0.00068	0.00017	0.00085	Table 1 from Australian National Greenhouse accounts factors – (Department of the Environment and Energy, 2017)
Wages	The hourly rate for wages ($/hour)	40	35	50	Aspen plus software (aspentech, 2020)
Cost of electricity	The cost of electricity from the grid ($/kWh)	0.2	0.15	0.35	State providers
Cost of water	The cost of water for use in the biogas plant ($/kL)	3.035	2	3.035	State providers Max value was from SA Water

Maintenance cost	The percentage of capital costs that are required for annual maintenance (%)	3	2	5	Range reported across case studies

3.4 Combined effects of factors

As the baseline case study only examines costs, without consideration of potential revenue streams or supportive policies, a series of joint sensitivities are considered to explore the extent to which the LCOE can approach the price of natural gas and what factors have the biggest influence on this. The following combinations will be explored in Section 4.

- **RGGOs + digestate profit**: This combination demonstrates the effects of a single policy support and revenue source, to compare with the price of natural gas.

- **FiT + grant**: This combination represents a policy scheme that is not solely reliant on FiTs but also includes capital support.

- **RGGOs + ACCU conversion**: This combination represents a carbon market with organisations purchasing RGGOs and also biomethane projects earning Australian Carbon ACCUs for conversion, incentivising those producing biogas.

- **CO_2 revenue + ACCU conversion + ACCU displacement**: This combination represents a biomethane project that has an emphasis on capturing CO_2 and being credited for the reduction in GHG emissions.

- **CO_2 revenue + digestate profit + gate fee**: This combination represents the revenue streams that would be relevant with in an environment with a strong circular economy focus, namely re-use of waste and by products.

4. RESULTS AND DISCUSSION

This section presents the results of the sensitivity analysis framed in Section 3, with respect to the levelised cost of energy (LCOE) and net carbon emissions saved. At a glance, the effect of change in all these factors can be seen in Figure 9, divided into the categories corresponding to Tables 1 – 5. A description of these results is provided in Section 4.1, first focussing on the factors a project can control, and then the uncertain factors (Figure 4). A summary of the most significant factors for both LCOE and net carbon saved is provided in Section 4.2. The results of the joint sensitivity analysis (Section 3.4) are described in Section 4.3. A table summarising all simulation results can be found in Appendix A.

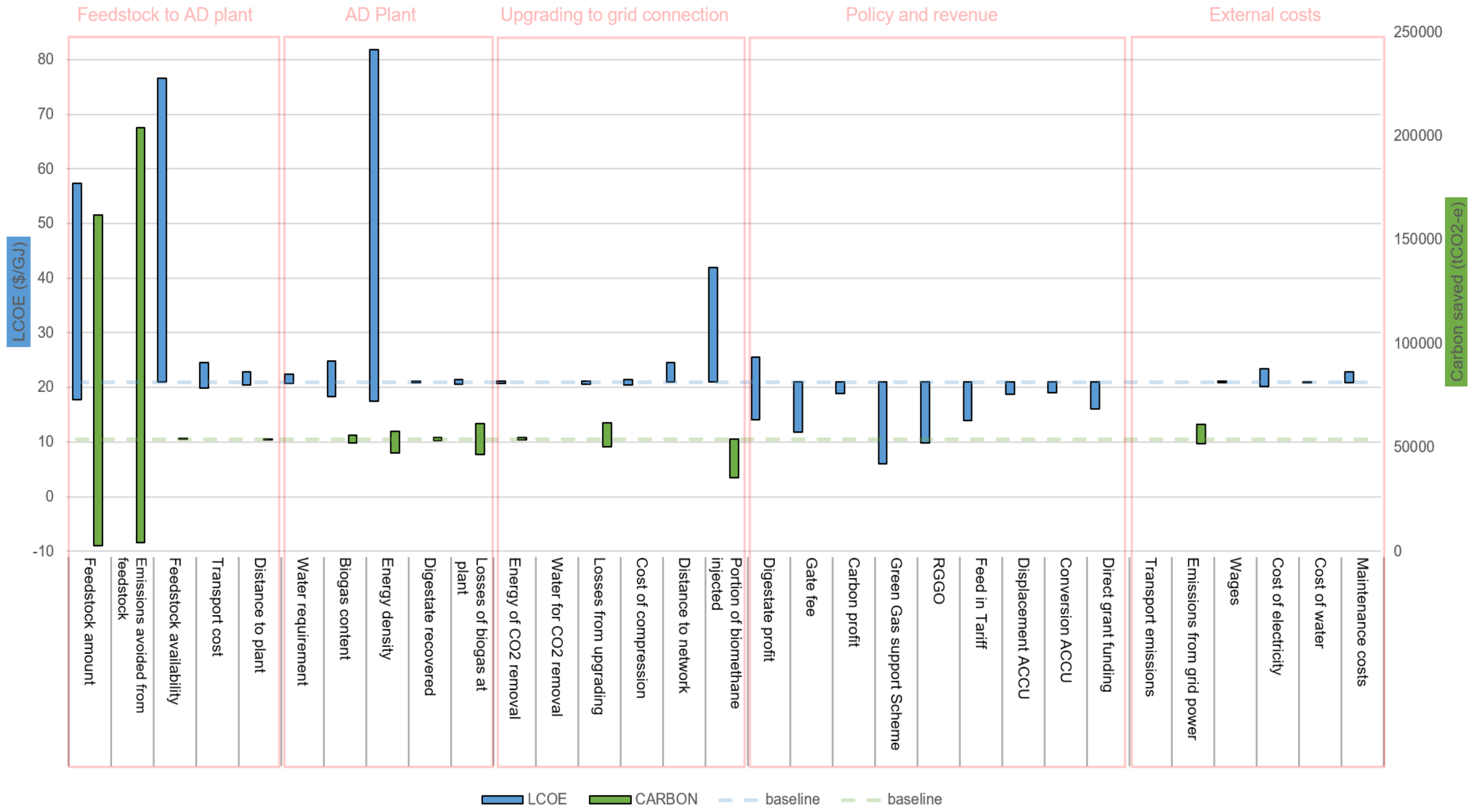

Figure 9 – Effects of all the factors in this assessment on LCOE and Carbon saved. The dashed lines represent the baseline project scenario values.

4.1 Influence of varying factors individually

The first factors considered were those that influence the collection of feedstock, up until the AD plant (Table 1, Section 3.3). From both a carbon saved and LCOE perspective, the factor that most affected viability was, unsurprisingly, the feedstock quality (Figure 10). The total feedstock amount was expected to be a significant factor on LCOE as it affects both OPEX costs (from transport and biogas upgrading) and the total biomethane produced. However, in this model formulation, it also affects the CAPEX of the plant as the plant is sized based on peak gas flow rate. The second most significant factor affecting LCOE was feedstock availability throughout the year. This factor represents feedstock storage, and shows that if feedstock can only be stored for 1-2 months a year, costs become very high. Transport cost has a much-reduced impact on LCOE compared with factors affecting feedstock availability, while distance to plant has a very minimal effect.

Regarding carbon saved, the second most significant factor after feedstock amount was the carbon avoided from the prior use of feedstock. The reason this factor is so significant is twofold: first, the default plant size is quite large, at 100,000 tonnes per year, and second, the range of uncertainty around this feedstock is very large. For example, for food waste in landfill, the amount of carbon saved is up to 2 tCO_2-e/tonne, whereas for cereal straw this value is close to zero. Therefore, the relative influence of carbon abatement on project viability is significantly dependent on feedstock type.

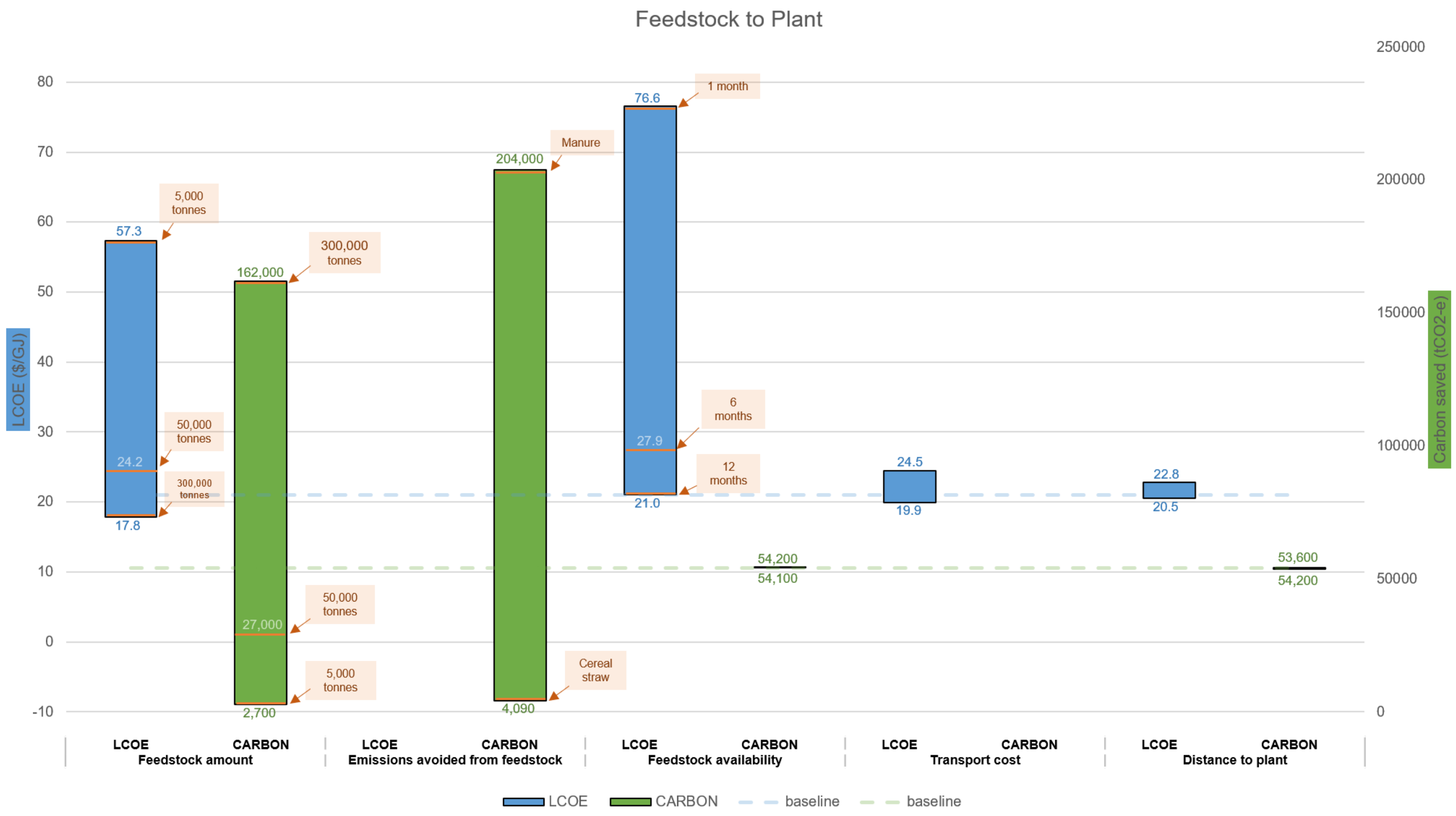

Figure 10 - Effects of factors from “Feedstock to AD Plant” subset on LCOE and carbon saved.

The next set of factors considered relate to the operation of an Anaerobic Digestion plant. The factor with the largest influence on both LCOE and net carbon saved was the energy density of the feedstock (Figure 11). This is to be expected, given that the transport costs per tonne of feedstock are held constant, and so the biogas produced per tonne will have a large effect on the amount of biomethane injected into the grid. The range of this factor is also quite large, given it represents a wide selection of feedstocks in this assessment. Another consideration is that the CAPEX costs of the plant scale with the maximum biogas rate, and as the biogas produced decreases, the CAPEX costs of the plant become relatively more expensive (following a cost curve). The second largest impact on LCOE was the percentage methane content of the biogas, which has a similar effect as the biomethane injected into the grid, but across a smaller range. This is often just taken as an assumed value of 60%, but literature suggests this can change from 50-70% (Basumatary et al., 2021), and for larger projects this has a significant effect on LCOE. The second biggest effect on net carbon saved after energy density was the losses of methane at the plant, as this is venting CO_2 and methane into the atmosphere. The water requirement factor has little to no effect on LCOE and carbon saved. However, it is important to note that in water scarce regions, the quantity of water required could have a significant effect on the local community and/or ecosystem.

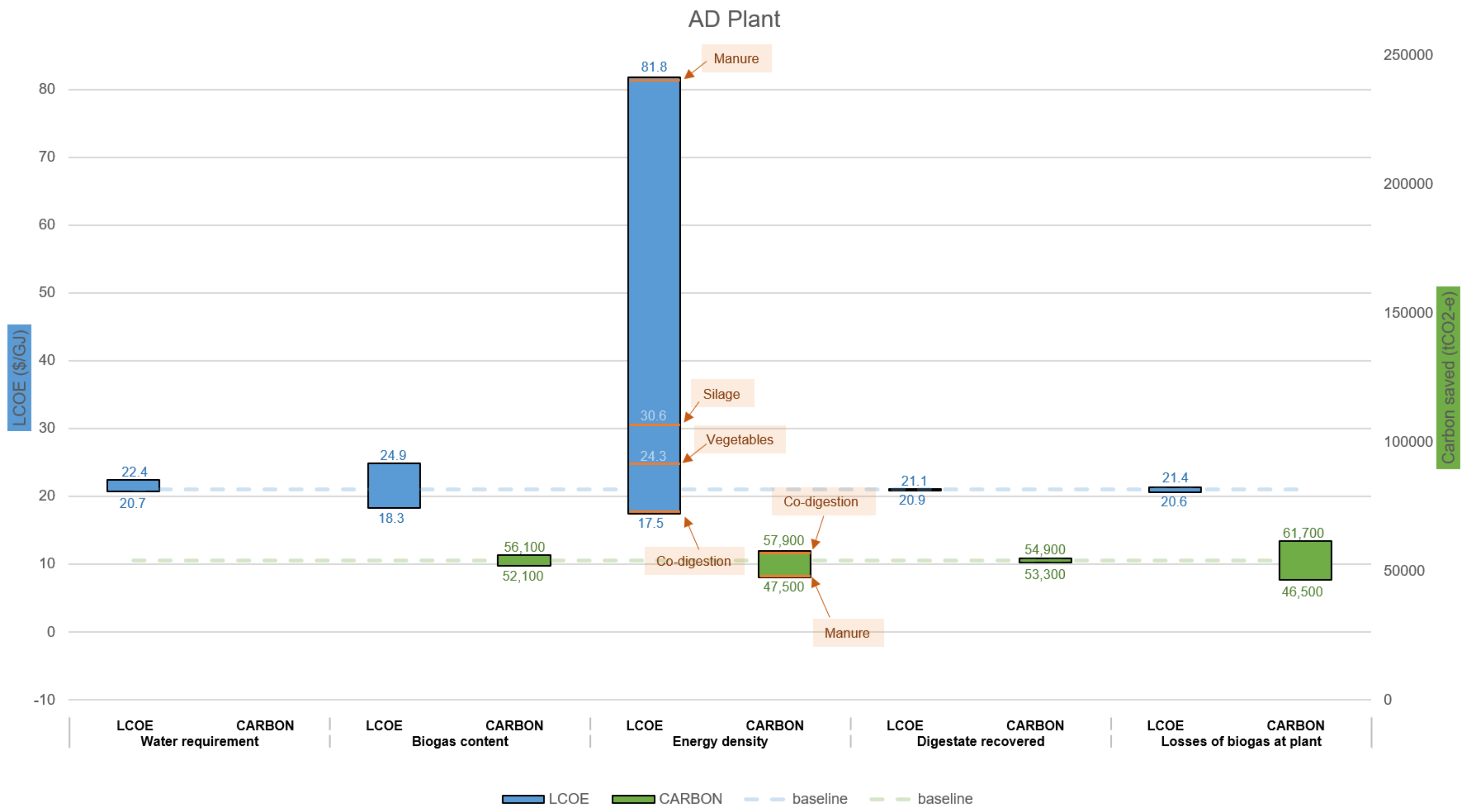

Figure 11 - Effects of factors from AD Plant on LCOE and carbon saved.

The final set of factors that a project can control is the factors relating to upgrading the biogas to biomethane and then injection into the grid. The factor with the largest effect on both LCOE and net carbon saved is the portion of biomethane injected (Figure 12). This factor represents grid constraints limiting biomethane injection down to 50% of plant capacity (Section 3.3 Table 3), which causes (i) the LCOE to increase as the costs are fixed but biomethane is flared, and (ii) the net carbon saved to decrease as significantly less natural gas is displaced. The total cost of connection also presents a large change to the LCOE, represented by both cost of connection to the grid (which changes based on distribution lines and transmission lines) and also the distance from the grid, where a pipeline is constructed. The final three factors relate to which upgrading technology is used: membrane separation, water scrubbing or pressure swing absorption. The results indicate that the type of technology has a minimal effect on the water and power needed, however, it should be noted that in some cases the type of upgrading technology might negate the need to compress the biomethane further before injection (as it reaches pipeline pressure). In this case, the choice of upgrading could have the effect of an LCOE reduction similar to that of the cost of compression.

Figure 12 - Effects of factors from Upgrading to Grid Connection on LCOE and carbon saved.

The first set of uncertain factors relate to general costs associated with a biomethane project, including utilities, maintenance and wages. The only factors that have a moderate effect (>$1/GJ) on LCOE are cost of electricity and maintenance costs, and the only factor to have any major effect on carbon saved was the emissions from grid power (Figure 13). The range taken for the emissions from grid power and cost of electricity factors represents the variance across the states in Australia. Hence these results indicate that the location of case study alone can have an effect on LCOE, aside from the expected case study factors that vary by location like feedstock type availability and distance to plant. In other words, the same project, undertaken in both Tasmania and NSW, could see a ~10,000 tCO_2-e /year difference in carbon accounting.

Figure 13 - Effects of factors from External Factors section on LCOE and carbon saved.

The effects that revenue streams and potential policies have on LCOE* (note that costs are offset by revenue streams in the LCOE estimation, as defined earlier) are shown in Figure 14. Note that none of these policies have a direct impact on the net carbon saved given the framing of this assessment, as they do not change emission factors. In reality, Government policies that incentivise biomethane production would have a significant impact on the national reduction of GHGs, as more projects become economically viable and are implemented. The first three factors focus on the revenue available to biomethane projects; digestate value, gate fee and CO_2 revenue. These revenue streams have a moderate impact on LCOE*, with a reduction of 6.1, 9.2 and 2.1 $/GJ, respectively. Note that of the three streams, digestate value had the largest overall effect, but also caused an increase in LCOE* due to the uncertainty in the key profit parameter. In many cases, digestate will need to be disposed of presenting an additional cost, increasing the LCOE to $25.6/GJ.

The remaining factors relate to potential government policies. The policy with the largest impact on LCOE* was the green gas support scheme (as adopted in the UK), followed by the renewable gas guarantee of origin scheme and a feed-in tariff based on policy in the Netherlands (Section 3.3). The difference in impact between these factors is primarily due to the level of support they provide; all three factors are built around rewarding the injection of biomethane into the grid and so rely on the same component of the underlying techno-economic model, just with different $/GJ support. When considering carbon abatement under the emissions reduction fund, the displacement abatement provided more LCOE offset than the conversion abatement, although only by ~$0.5/GJ. However, the conversion abatement carbon savings will be much more impacted by the type of feedstock (due to its assumed prior GHG emissions). The emissions factor used in the baseline is similar in magnitude to the burning of crop residues; emissions from other feedstock types are reported as being higher. The resulting effect on ACCUs will be further explored as part of Project RP1.2-06. Direct grant funding had a larger impact than the ACCUs, although less of an impact than the other government policies. Note that this factor in particular is affected by discount rates and project life used in the LCOE calculation, as it relates to the capital cost of the project (Section 3.2).

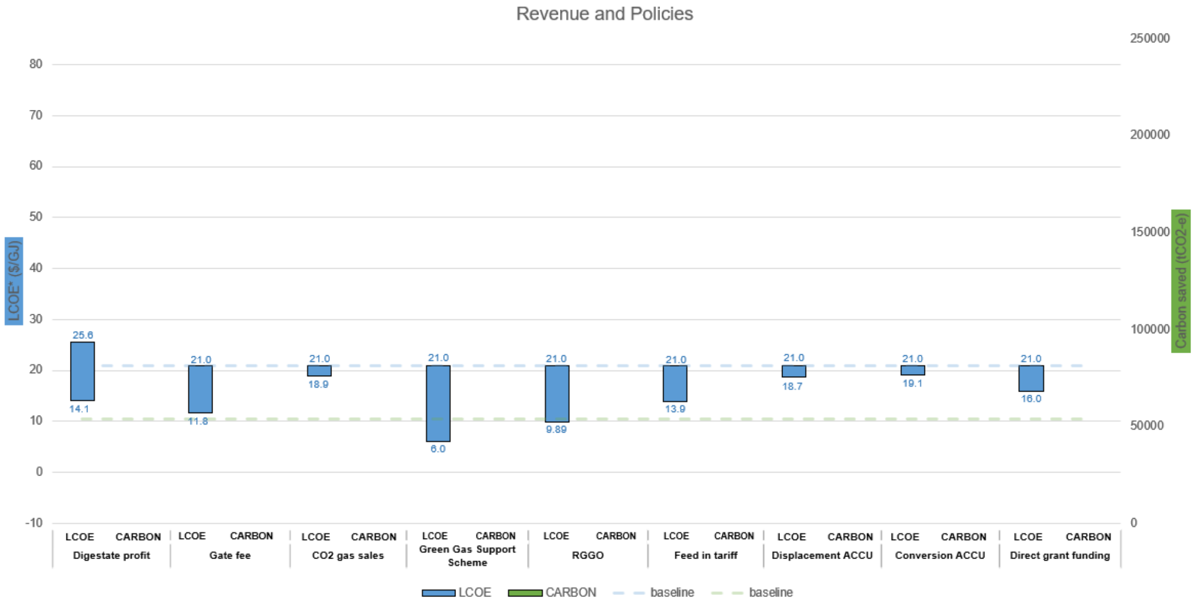

Figure 14 - Effects of factors from Revenue and Policies uncertainty factors on LCOE and carbon saved.

4.2 Summary of most significant factors

Figure 15 shows a summary of the factors with the largest effect on LCOE, ranking them from highest to lowest. Of the twenty-nine factors considered in this assessment, twenty-six had an impact on LCOE. Seven of these had a large impact (>$10/GJ), twelve had a moderate impact (between $1/GJ and $10/GJ) and seven had a low impact (<$1/GJ).

The factor the LCOE metric was the most sensitive to was energy density. This factor controls both the biomethane injected per tonne of feedstock transported, and also sizes the plant for a fixed feedstock amount. As a result, smaller energy density values result in a lower plant capacity (with a relatively larger CAPEX) and less biomethane yield for a fixed transport cost. The second and third most significant factors were feedstock availability and feedstock amount, which both also affect the size of the biomethane plant. In the case of feedstock availability, this is because the plant is sized to process all the annual feedstock, but either over all twelve months of the year or in just one, in which case the plant is underutilised. In relation to feedstock amount, the range considers very small plants of 5,000 tonnes/year, which, given a fixed cost of grid connection, is not economically viable. The portion of biomethane injected also has a significant impact, as for a fixed cost of production, up to half of the biomethane is flared instead of injected due to grid constraints.

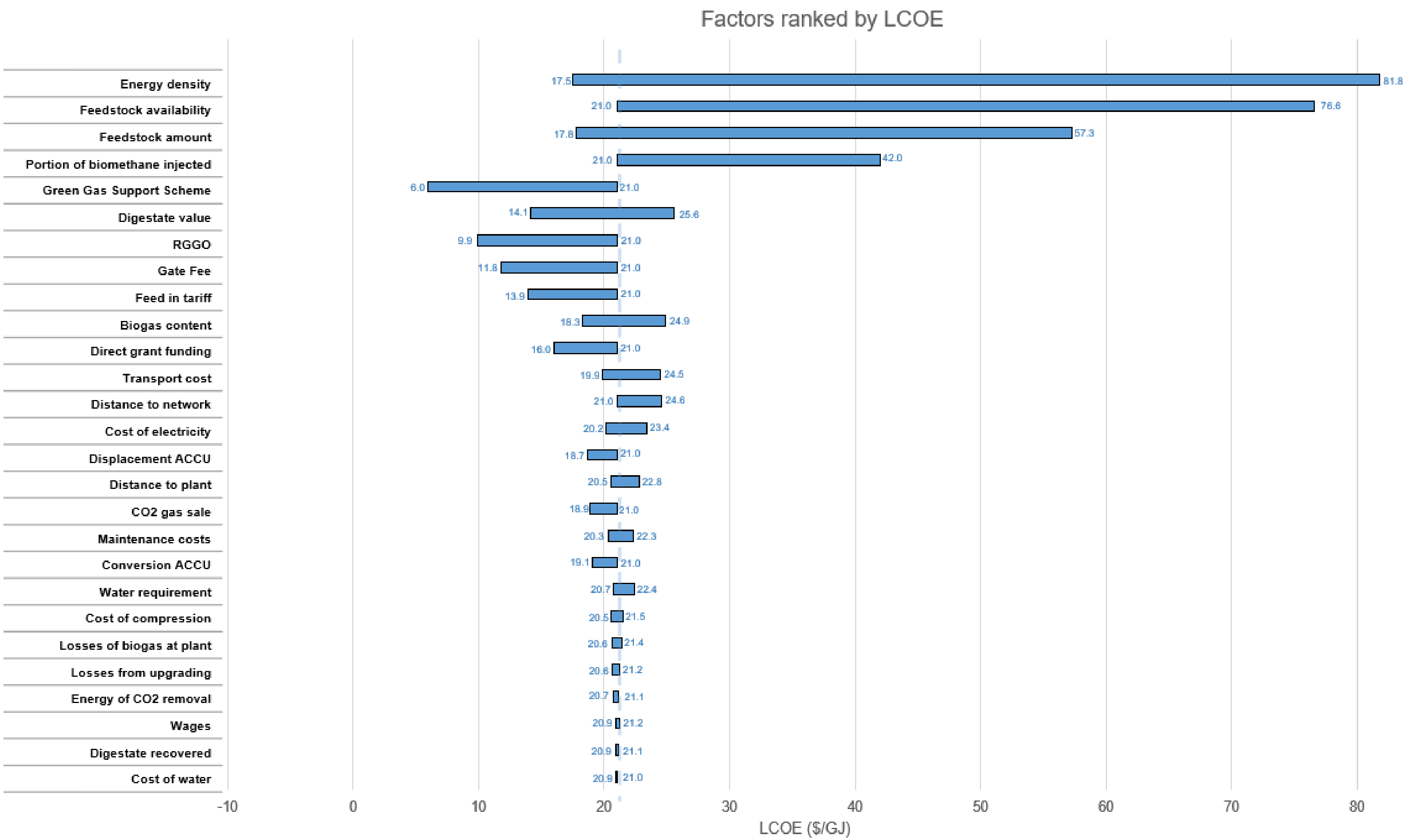

Figure 15 – A ranking of the factors that most impact LCOE

Figure 16 shows a summary of the factors with the largest effect on Net Carbon Saved, ranking them from highest to lowest. Only twelve of the factors have an impact on carbon emissions, which is primarily a function of our assessment framing and model – as many factors were included to determine their effect on cost (especially government policies). The two most significant factors by far are the emissions avoided from feedstock and the feedstock amount. These two factors inform the conversion and displacement ACCU estimates, respectively. Both of these factors provide a strong motivation for biomethane projects with respect to waste re-use as part of a movement towards an increasingly circular economy, with the potential to save tens of thousands more carbon emissions depending on the feedstock type used. The third most significant factor was the amount of biomethane injected versus flared – this has the effect of displacing significantly less natural gas, and so has a negative impact on the amount of GHG emissions that can be avoided.

When comparing the rankings in Figures 15 and 16, it can be seen that energy density has strong economic implications, but that this does not affect the carbon emissions as significantly. On the other hand, the factors surrounding electricity usage from the grid have stronger impacts on carbon emissions than LCOE.

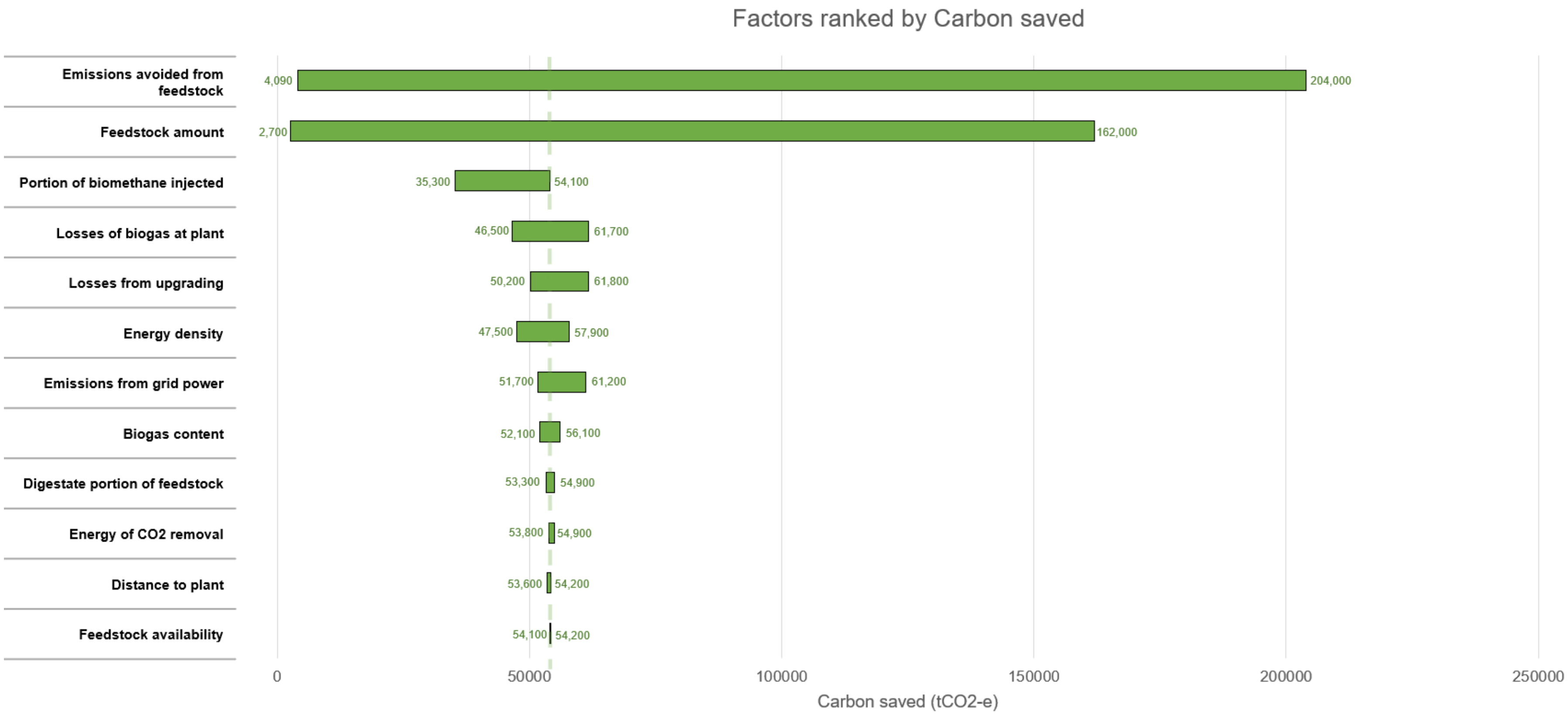

Figure 16 - A ranking of the factors that most impact net carbon saved

4.3 Combined effects

The joint sensitivities of policies and revenue streams were investigated to examine which combinations lead the LCOE* to approach the price of natural gas (Figure 17). Of the five combinations examined, four reduced the LCOE* of the biomethane project to less than the price of natural gas ($11/GJ). Two of these include the RGGO scheme, which provides a heavy price offset, given the amount of biomethane produced ($40/MWh). The only policy combination to not reach the price of natural gas is one that focuses only on a carbon economy, where a credit of $60/tCO$_2$-e for the conversion and displacement abatement, and sale of food grade CO_2, do not provide a sufficiently large revenue stream for projects to have a positive NPV when selling biomethane at the price of natural gas.

The two lowest LCOE* combinations (at $2.97/GJ and $2.79/GJ) both consider a revenue stream from selling the digestate by-product. It is important to note that the profit available from digestate is highly uncertain, due to a number of factors. First, there can be limitations in the use of the digestate due to the type of feedstock, for example, biohazard concerns from WWTP waste. There can also be limitations due to market competition for fertilizer and compost from other sources. And finally, given a sufficient lack of demand, in some cases the digestate will need to be disposed of at a further cost. This is when the options that include digestate profit, while the cheapest, can also potentially result in an increase in LCOE.

When considering the values of a circular economy and combining the digestate profit with revenue from captured food grade CO_2, as well as the imposition of a gate fee, the LCOE* reaches $2.79/GJ. Alternatively, a feed in tariff based on values from the Netherlands and other countries in the EU, when combined with a $28,000,000 grant from Government agency funding, reduces the price of biomethane below that of natural gas at $8.92/GJ. If applied in Australia, this would increase the viability of large-scale agricultural projects like the one modelled in the baseline of this assessment.

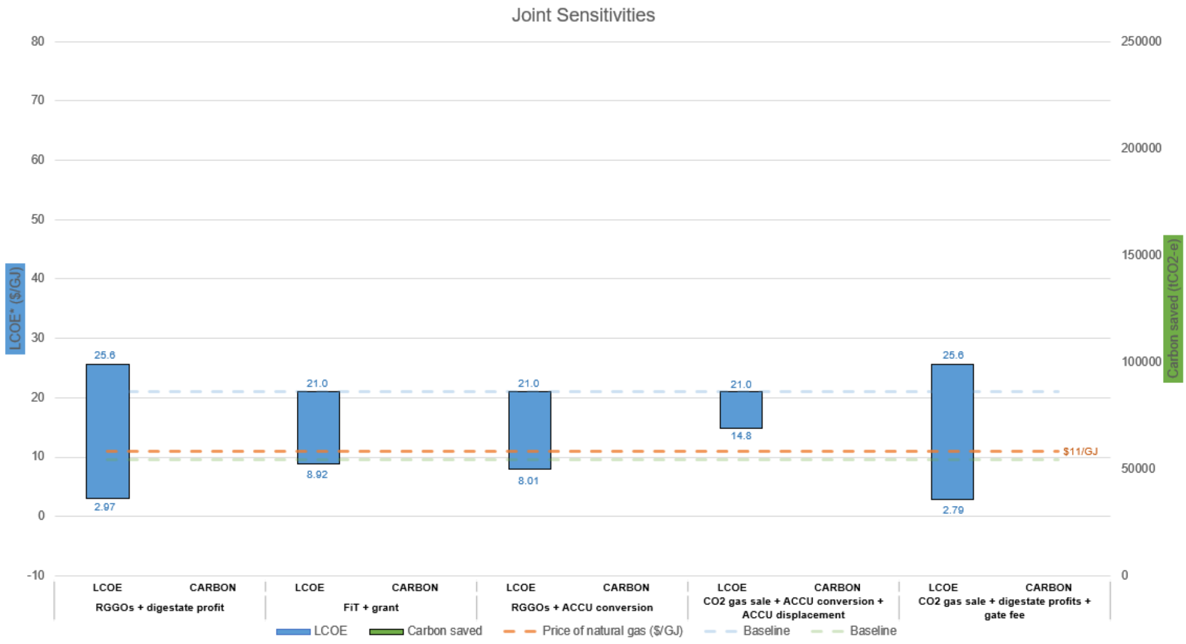

Figure 17 – Joint sensitivities of LCOE to revenues and policies

Table 6 – Results of the joint sensitivities of LCOE to combinations of policies and revenues. Change due to each single variable is also provided.

Joint sensitivity	LCOE value ($/GJ)			
	Combined effect	Variable 1	Variable 2	Variable 3
RGGOs + digestate profit	2.97	9.9 (*RGGOs*)	14.1 (Dig. Profit)	n/a
FiT + grant	8.92	13.9 (FiT)	16.0 (*Grant*)	n/a
RGGOs + Conversion ACCU	8.01	9.9 (RGGOs)	19.1 (Conversion ACCU)	n/a
CO_2 gas sale + Conversion ACCU + Displacement ACCU	14.8	18.9 (CO_2 gas sale)	19.1 (Conversion ACCU)	18.7 (Displacement ACCU)
CO_2 gas sale + digestate profit + gate fee	2.79	18.9 (CO_2 gas sale)	14.1 (Dig. Profit)	11.8 (Gate Fee)

5. CONCLUSIONS

This report presents a sensitivity analysis on factors that affect the viability of biomethane grid injection projects in Australia, using the integrated assessment model developed as part of this project (Culley et al. 2023). The aim here is to identify and understand the key factors that significantly impact their viability. This can aid end users of this project to either: further optimise projects to decrease the cost of biomethane production so it comes closer to the price of natural gas, or, be aware of key uncertainties beyond immediate control (such as government policies) and understand the risk this poses to the viability of a project.

In order to consider a more rounded business case, two essential metrics were considered as part of this assessment, one for cost and one for GHG emissions. The cost metric used is an estimate of the Levelised Cost of Energy (LCOE), and the carbon metric is a measure of net Greenhouse Gas (GHG) reduction from the European Biogas Association. It was demonstrated that the LCOE as a metric is not just sensitive to changes in costs of running a biomethane project, but also the discount rate and project life that are assumed. The change in LCOE that can be obtained from a small change in discount rate and also changes to the assumption of project life can have a significant impact on reported project performance, and hence viability. This means, with respect to conducting techno-economic assessments, the rates and project life assumptions need to be transparent - in this study a discount rate of 7% and project life of 20 years were used. However, more generally, this places an emphasis on reliably lengthening the life of a project, and/or reducing the cost of capital, which requires long term certainty in feedstock contracts and support/policy mechanisms.

The factor the LCOE metric was most sensitive to overall was energy density. This factor controls both the biomethane injected per tonne of feedstock transported, and also the size of the plant for a fixed feedstock amount. As a result, smaller energy density values result in a lower plant capacity (with a relatively larger capital cost) and less biomethane offset for a fixed transport cost. The second and third most significant factors were the feedstock availability and feedstock amount, which both also affect the size of the biomethane plant. In the case of feedstock availability, this is because the plant is sized to process all the annual feedstock, but either over all twelve months of the year or in just one, in which case the plant is underutilised. For net carbon saved, the two most significant factors by far are the emissions avoided from feedstock and the feedstock amount. These two factors inform the conversion and displacement ACCU calculations, respectively. Both of these factors provide a strong motivation for biomethane projects with respect to waste re-use as part of a more circular economy, with the potential to save tens of thousands more in carbon emissions depending on the feedstock type used. The third most significant factor was the amount of biomethane injected versus flared – this has the effect of displacing less natural gas, as well as some bio-methane slippage into the atmosphere, and so has a negative impact on the amount of GHG emissions that can be avoided.

When considering combinations of government policy and revenue support, the two lowest LCOE* combinations (at $2.97/GJ and $2.79/GJ) both consider a revenue stream from the selling of the digestate by-product. It is important to note that the profit available from digestate is highly uncertain, due to several factors (e.g. limitations of use of digestate, market competition, and potentially having to dispose of the digestate at cost). When considering the values of a circular economy and combining the digestate profit with revenue from captured food grade CO_2, as well as the imposition of a gate fee, the LCOE* reaches a value of $2.79/GJ. Alternatively, a Feed in tariff based on values from the Netherlands and other countries in the EU, when combined with a $28,000,000 grant from Government agency funding, drops the LCOE* value to $8.92/GJ, which is below the price of natural gas. If applied in Australia, this would increase the viability of large-scale agricultural projects like the one modelled in the baseline of this assessment.

6. IMPLICATIONS AND RECOMMENDATIONS FOR INDUSTRY

The following are the key findings of this research. Firstly, the key findings that relate to project development are:

- The factor the LCOE metric was most sensitive to was energy density, defined in this study as the gravimetric energy density i.e. the GJ biogas from a tonne of dry feedstock. Smaller energy density values result in reduced biomethane production for a fixed transport cost of feedstock. The second and third most significant factors were feedstock availability and feedstock amount, which both also affect the size of the biomethane plant. In the case of feedstock availability, this is because the plant is sized to process all the annual feedstock, but either equally over twelve months of the year or in just one month. The latter case would mean that the plant is underutilised.

- The energy content of the feedstock slurry is a key leverage point for projects, as relatively low -cost options such as pre-treatment and co-digestion can result in greater biomethane yields for the same fixed cost of feedstock transport.

- The percentage of biogas that is assumed to be methane affected the LCOE by almost $7/GJ when varied from 50-70%. This percentage is often just assumed to be 60%, but literature suggests that this value can change within that wider range, and for larger projects this has a significant effect on LCOE.

- Flaring biomethane due to insufficient network demand has a negative effect on both carbon emissions and LCOE. At an assumed flaring rate of 50% of gas produced, a project is still carbon negative due to captured emissions, but the LCOE is twice that of the baseline value.

Key findings that relate to policy support for biomethane are:

- For the net carbon emissions metric, the two most significant factors by far are the emissions avoided from feedstock and the feedstock amount. Both of these factors provide a strong motivation for biomethane projects with respect to waste re-use as part of a more circular economy, with the potential to save tens of thousands more carbon emissions depending on the feedstock type used.
    - Emissions avoided from the decomposition of feedstock will also vary widely depending on the prior use of feedstock (for example are crop residues burned, is OMSW being sent to landfill etc).

- When considering carbon abatement under the emissions reduction fund, the displacement abatement provided a greater LCOE offset than the conversion abatement, although only by

~$0.5/GJ. However, the conversion abatement carbon savings will be much more impacted by the type of feedstock (due to its assumed prior GHG emissions), whereas the displacement abatement is a function of the size of the project.

- The effect of feedstock type (and feedstock prior use) on conversion abatement is an ongoing area that needs additional research, as there are only very few methodologies currently used in Australia as part of the ERF. This will be further explored in FFCRC Project RP1.2-06.
- A Feed in tariff based on values from the Netherlands and other countries in the EU, when combined with a $28,000,000 grant from Government funding, would provide net profits when selling at the price of natural gas, with an LCOE* of $8.92/GJ. If applied in Australia, this would increase the viability of large-scale agricultural projects like the one modelled in the baseline project scenario of this assessment.

7. NEXT STEPS AND FUTURE WORK

This report is the final major milestone research report for Project RP1.2-04. The next steps of this project are to make current versions of the two models built as part of this assessment publicly available (as outlined in Culley et al 2023), and to submit the journal publications about this work. Finally, a summary report for RP1.2-04 will be produced.

Note that the tools built as part of this project will continue to be developed as part of Project RP1.2-06, where their scope will be expanded to focus on additional factors that affect the investability of biomethane projects.

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APPENDIX A

A full list of the sensitivity of LCOE and net carbon saved to the factors explored in this assessment

Variable	Parameter		Change in LCOE from baseline $21/GJ ($/GJ)		Change in Carbon saved from baseline 54.1k tCO_2-e (tCO_2-e)	
Variables	min	max	min	max	min	max
Feedstock amount (t/year)	5,000	300,000	36.3	-3.2	-51,400	107,900
Emissions avoided from feedstock (tCO_2-e/t)	0	2	0	0	-50,010	149,900
Feedstock availability (%)	8.3	100	55.6	0	100	0
Transport cost ($/t)	30	70	-1.1	3.5	0	0
Distance to plant (km)	0	100	-0.5	1.8	100	-500
Water requirement (kL/t)	0	5	-0.3	1.4	0	0
Biogas content (%)	0.5	0.7	3.9	-2.7	-2,000	2,000
Energy density (m^3/t)	50	600	60.8	-3.5	-6,600	3,800
Digestate recovered (%)	0	80	-0.1	0.1	-800	800
Losses of biogas at plant (%)	0	4	-0.4	0.4	7,600	-7,600
Energy of CO_2 removal (kW/Nm^3)	0.1	0.265	-0.3	0.1	800	-300
Water for CO_2 removal (kL/Nm^3)	0	0.00003	0	0	0	0
Losses from upgrading (%)	0	3	-0.4	0.2	7,700	-3,900
Cost of compression ($)	0	6,000,000	-0.5	0.5	0	0
Distance to network (km)	0	50	0	3.6	0	0
Portion of biomethane injected (%)	0.5	1	21	0	-18,800	0
Digestate profit ($/t)	-100	150	4.6	-6.9	0	0
Gate fee ($/t)	0	80	0	-9.2	0	0
CO_2 gas sale ($/t)	0	200	0	-2.1	0	0
GGSS ($/GJ)	0	15	0	-15.0	0	0

Renewable gas guarantee of origin (RGGOs) ($/GJ)	0	40	0	-11.1	0	0
Feed in tariff ($/GJ)	0	7.1	0	-7.1	0	0
Displacement ACCU ($/t)	0	60	0	-2.3	0	0
Conversion ACCU ($/t)	0	60	0	-1.9	0	0
Direct grant funding ($)	0	28,000,000	0	-5.0	0	0
Transport emissions (CO_2-e/t km**)**	0.04	0.07	0	0	0	0
Emissions from grid power **(**tCO_2-e/kWh**)**	0.00017	0.00085	0	0	7,100	-2,400
Wages ($/hr)	35	50	-0.1	0.2	0	0
Cost of electricity ($/kWh)	0.15	0.35	-0.8	2.4	0	0
Cost of water ($/kL)	2	3.035	-0.1	0	0	0
Maintenance costs (% CAPEX**)**	2	5	-0.7	1.3	0	0

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