RACE for 2030
RELIABLE AFFORDABLE CLEAN ENERGY

B5: Opportunity Assessment

Anaerobic digestion for electricity, transport and gas

Final Report

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An Opportunity Assessment for RACE for 2030 CRC

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Although the IRG members and partners have provided valuable inputs and feedback throughout the project, the findings and recommendation included in this report do not necessarily reflect the views of each individual member or their organisation. The views expressed herein which are associated with, or refer to, ARENA are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained in this regard.

Acknowledgement of Country

The authors of this report would like to respectfully acknowledge the Traditional Owners of the ancestral lands throughout Australia and their connection to land, sea and community. We recognise their continuing connection to the land, waters and culture and pay our respects to them, their cultures and to their Elders past, present, and emerging.

What is RACE for 2030?

RACE for 2030 CRC is a 10-year cooperative research centre with AUD350 million of resources to fund research towards a reliable, affordable, and clean energy future. https://www.racefor2030.com.au

Disclaimer

The authors have used all due care and skill to ensure the material is accurate as at the date of this report. The authors do not accept any responsibility for any loss that may arise by anyone relying upon its contents.

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Abbreviations

€	Euro
ACCUs	Australian Carbon Credit Units
AD	anaerobic digestion
AnMBR	anaerobic membrane bioreactor
AUD	Australian dollar
Bio-CNG	biological compressed natural gas
Bio-CO_2	carbon dioxide
Bio-LNG	biological liquefied natural gas
BOD	biological oxygen demand
CAL	covered anaerobic lagoon
CapEx	capital expenditures
CFI	Carbon Farming Initiative
CH_4	methane
CHP	combined heat and power, also known as cogeneration
CO_2-e	carbon dioxide equivalent
COD	chemical oxygen demand
CSTR	continuously stirred tank reactors
DM	dry matter
EPA	Environment Protection Authority
ERF	Emission Reduction Fund
EU	European Union
FOGO	food organics and garden organics
GHG	greenhouse gas
GJ	gigajoules
GWh	gigawatt-hour
H_2	hydrogen
ICC	initial capital cost
LCOE	levelised cost of electricity
Nm^3	normalised cubic meter
Mt	million tonnes
MWOO	mixed waste organic outputs
NSW	New South Wales
OpEx	operating expenses
PJ	petajoules
PPA	power purchase agreement
P2G	power to gas
QLD	Queensland
SA	South Australia
TRL	Technical Readiness Level

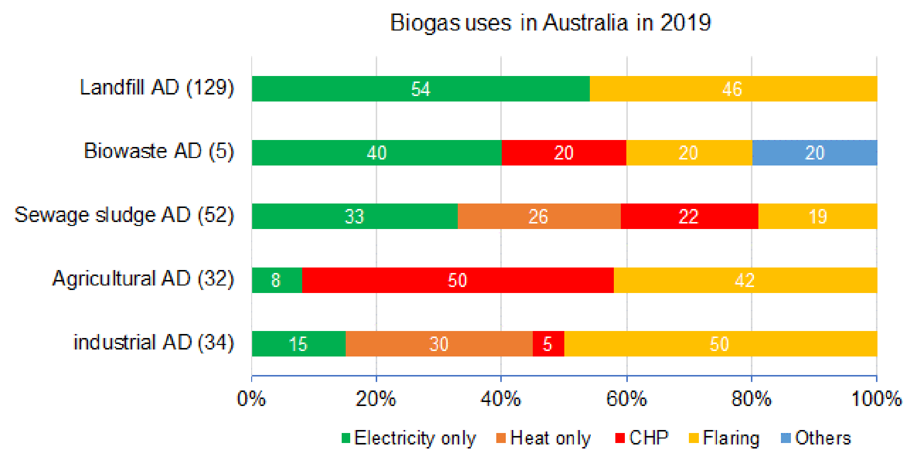
TS	total solids
TWh	terawatt-hour
UK	United Kingdom
VIC	Victoria
WA	Western Australia
yr	year

EXECUTIVE SUMMARY

The aim of this *Opportunity Assessment for Anaerobic Digestion (AD) in Australia* is to deliver a research roadmap that identifies the most impactful projects to 2030 that create new markets and scale-up the biogas industry in Australia. As a part of this project, a rapid review was carried out to establish the state-of-the-art of AD in Australia, sustainable feedstock availability, reactor technology, market status, and technical and economic barriers to the current industry. The review examines the potential of the biogas market for electricity, transport and gas including opportunities in biogas upgrading and grid injection as well as applications of the beneficial use of digestate and the use of biogenic carbon dioxide ($BioCO_2$).

Market status and potential

As of March 2019, there were 242 AD facilities in operation in Australia as outlined in the figure below (Carlu, Truong, & Kundevski, 2019) However, there are no commercial biogas upgrading plants operating in Australia. The literature suggests that this may be due to barriers in realising the full financial value of biomethane for onsite usage and/or gas grid injection. Landfills and wastewater plants accounted for most AD facilities in Australia, while there are a few agricultural AD facilities treating livestock manure and industrial AD facilities treating red meat processing and rendering wastewaters. Approximately 62 million tonnes dry matter (TS) of biomass is available in Australia, most of which is agricultural crop residue (69.5%), followed by biowaste and agro-industry waste.



Several types of AD technologies are used for biogas production in Australia and the choice is based on feedstock characteristics and volume. The most common AD reactor technology for treating animal effluent from piggery, dairy and red meat industry in Australia is anaerobic ponds, most often covered anaerobic lagoons (CAL). Despite higher initial infrastructure costs, CALs offer significant advantages over uncovered lagoons such as odour control, intensification of the decomposition process and biological oxygen demand (BOD) removal, an increase in feed rate and the potential for capturing methane-rich gas as a fuel source for bioenergy and the reduction in greenhouse gas emission (GHGs) (Pöschl et al., 2010). However, CALs are often operated at sub-optimal conditions operating under ambient conditions with little or no mixing and thus offer minimal ability to control the digestion performance and methane production.

Australia has an estimated biogas potential of 371 PJ/yr (103 TWh/yr), which is almost 9% of Australia's total energy consumption (Carlu, Truong, & Kundevski, 2019). Thus, biogas can play a major role in the future zero emission economy. However, as of 2019, electricity generation from biogas was only 4.74 PJ or 1.3% of the estimated available potential. The economic value of biogas is context-dependent since financial outcomes of biogas projects are governed by the interactions between supply and demand within the energy market.

Behind-the-meter operation is an established biogas market and is financially viable where there is the co-location of high energy biomass and high energy demand. Although behind-the-meter operation has limited market size and scalability, there are several large opportunities for new near-term projects. Two steps are recommended to unlock this potential. First, standardisation and improvement in AD process design, operation, and maintenance by adapting new technologies (including digital technologies) will reduce the capital and operating expenditure (CapEx and OpEx) of biogas projects and increase the market size. Second, the transition from combustion engines to fuel cells could further expand the market while simultaneously reducing maintenance and servicing costs of biogas plants.

Once the behind-the-meter market has been saturated, other options for biogas can be pursued. For example, biogas (specifically biomethane) injection to the gas pipeline network, bio-alternatives for liquid natural gas (LNG) and compressed natural gas (CNG), and power to gas (P2G) exchange for energy storage could significantly increase the market size of AD. These emerging markets are already being demonstrated at commercial scale in Europe, North America, and other countries. In the Australian context, biomethane can already be injected into the existing gas grid without major infrastructure upgrade. Technologies for purifying biogas to biomethane and grid injection are readily available but are still expensive compared to conventional fossil gas, especially for small scale operations. Significant research and capacity development is required to support biomethane for grid injection including to develop; gas storage and the transfer of biogas from small-scale biogas facilities to a centralised location; technologies for biogas upgrading, quality monitoring, compressing, bottling and dispensing; and network optimisation to maximise the viable injection capacity. P2G exchange for energy storage also offers a new and significant market for the Australian biogas industry, however much more investment in research and development (R&D) and pilot testing will be needed for this option to reach technological maturity.

Barriers to market potential

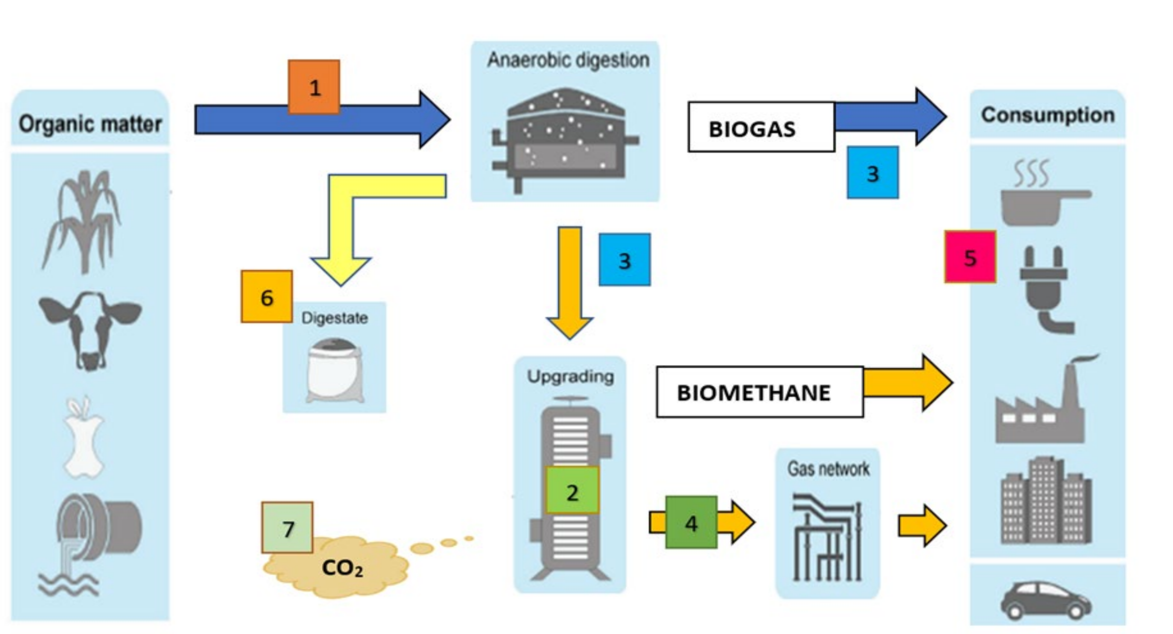
Barriers to the adoption of AD technology in Australia can be categorised as social, technical, economic, and regulatory. Social barriers relate to an ongoing and persistent negative public perception (even as far as stigma) of AD technology. However, this stigma is not as severe as has been experienced in other countries and has sometimes been used in positive marketing. For example, the NSW Treasurer stated at announcement of a renewable gas plant at the Malabar Waste Treatment site, "we're using your 'business', to power our business" (Sydney Morning Herald, 2022). Technical barriers, such as infrastructure, feedstock supply and characteristics of gas and digestate represent some of the more significant challenges preventing the deployment of AD technology in Australia. The economic barriers, or market failures and market barriers, relate to knowledge and uncertainty. Market barriers relate to uncertainty over the economic benefits of AD technology adoption including comparing costs with other (often less expensive) technologies and fuels. Knowledge-related barriers relate to both leveraging the technology for generating and capturing value, and to an understanding of the technology itself. Similarly, to other regions around the world, the lack of a stable and favourable policy making environment significantly undermines the economic success of AD technology. Thus, profound business and market transformation is needed in the longer term to support a successful biogas industry.

Significant information gaps exist, creating another barrier to future Australian biogas projects. There is insufficient data on sustainable collection and use of AgWaste and manure from feedlots as feedstocks for biogas production, how pre-treatments, co-digestion and different reactor types can improve process performance and methane yields. Finally, there is also no information on improving the biogas productivity from existing CALs and landfills. Co-digestion of manure or sewage sludge with other high energy density co-substrates such as food waste, crop residues and/or food organics and garden organics (FOGO) needs to be explored. New AD processes such as dry AD and reactor technologies such as anaerobic membrane bioreactor (AnMBR), continuously stirred tank reactors (CSTR) and up-flow sludge blanket (UASB) reactors with heating should be introduced to match the feedstock characteristics and solids content. Economic benefits of heated and insulated AD reactor technologies can be realised through improved biogas yields from biomass pretreatment and/or co-digestion. Further, scale of production and market for both digestate and biomethane uses, if developed, can improve the overall economics of biogas production in Australia. In addition, AD technology will ensure decarbonising the energy and transport sector by use of biogas in a combined heat and power (CHP)/co/trigeneration plant to produce electrical power and heating/cooling, directly in boilers or upgraded for biomethane production for grid injection or vehicle fuel use. Although biogas projects should ideally be feasible based on energy value alone, on-going and future policy incentives would greatly encourage biogas projects to generate more revenue through Australian Carbon Credit Units (ACCUs) for greenhouse gas emissions abatement and carbon sequestration.

Three broad categories of regulatory barriers are identified: (i) missing regulation to support the development of an AD biogas industry, (ii) inadequate or not fit for purpose regulation and (iii) regulatory complexity and confusion. Missing regulations include: the lack of a national renewable gas target; the lack of an effective and comprehensive carbon pricing mechanism; and the lack of clear and mandated sustainability criteria for bioenergy production. Inadequate regulation barriers include: the previous narrow interpretation of "natural gas" in the National Gas Laws, which was amended in 2022 to cover natural (fossil) gas, hydrogen, biomethane, synthetic methane and blends; natural gas Australian Standards; the application of economic regulations of gas pipeline infrastructure and distribution networks to include upgrading/blending that facilitates grid injection processes. Barriers related to regulatory complexity and confusion include: the complex regulatory instruments relating to energy sector stakeholder authorities, including permissions, licenses and permitted or prohibited activities; multiple environmental, water, and land use constraints and protections, arising from different levels of government; complex safety and technical regulation, including multiple industry codes and transport and storage regulation; and policy and statutory changes to end-use applications, such as emerging mandates against gas connections to new residential developments.

Market opportunities

This Opportunity Assessment has also investigated several potential valuable market opportunities for a number of agents in the AD value chain. A simplified AD process with areas of opportunities for future research and industry development has been discussed. In doing so, the research has highlighted not only specific opportunities for value chain partners to create and capture value from AD operations, but has also outlined some innovative business models that help boost the market potential of AD. Mainly, the market opportunities addressed have been grouped according to five major areas as: (i) feedstock supply and security (ii) biogas upgrading and cleaning (iii) grid injection (iv) digestate and (v) Bio-CO_2. These are represented in the schematic below.



From the input side, *feedstock supply and security* has proven to be both a challenging exercise and a source of considerable opportunities for further value creation when it comes to participants in an AD value chain. Here, the review of scientific and grey literature, complemented by a discussion with key agents has highlighted that formalised contracts to guarantee a stable supply of feedstock in AD operations should be favoured as they could partially reduce the uncertainty over the inflows. However, a wider engagement with the local community in which operations are proposed as well as their partners in the value chain could smooth some of the extant barriers related to social acceptance. Thus, informal contracts are also a critical component in capturing value from feedstock supply where mutually beneficial engagements (sharing technical knowledge and other arrangements) seem to bolster more effective supply and foster collaborative behaviour amongst value chain participants. Given the geographically distributed nature of feedstock, another opportunity was identified to develop specific technologies for feedstock aggregation and transfer.

More opportunities emerged relating to processing and related outputs. *Biogas upgrading* has emerged as one such opportunity from the increased interest of biogas output. Biogas upgrading technologies are well established, with many variations in existence – though such technologies generally require significant capital outlay to design, install, operate, and maintain. *Upgrading-as-a-service* is exemplified as a novel business model opportunity stemming from the increased interest in upgraded and cleaned biogas uncovered in this report.

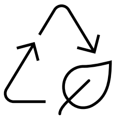
On the other hand, *grid injection* forms another significant opportunity, given the primary output of AD is biogas. The following key priority areas have been identified: technology, regulations, economics and consumers. Technology opportunities stemmed from the need to build local capabilities in the development of large-scale biomethane projects. From a regulatory standpoint, there is a need for Australia to learn from the international community to urgently develop policy and regulation for certifying renewable gas. In the economics/market realm, significant opportunities for a biogas market exist to provide pricing incentives and investment mechanisms to support biomethane projects. From the consumer point of view, the project highlighted a need to educate the public and consumers about the distinction between biomethane as a renewable gas and fossil gas. For large scale commercial gas users, there is an opportunity for collaboration amongst biowaste generators, biomethane producers and end-users to co-invest, de-risk upstream investment, secure a reliable energy supply, and achieve decarbonisation. Lastly, the use of blockchain renewable gas certification is also discussed as a potential opportunity.

Such an increased interest in biogas also brings forth opportunities for generating value from *digestate*, which is a secondary output. In this area, a wide range of opportunities has been discussed, including fertiliser production, animal bedding, the production of fuel pellets and a host of other options. The motivation to make use of digestate is also a key consideration in this report where, for example, digestate was viewed as a significant contributing factor for value generation in rural settings. Indeed, digestate can help reduce overproduction, return nutrients to the soil, avoid GHG emissions, and, perhaps more prominently, reduce the purchase of inorganic fossil fuel-based fertilisers, whose price has increased considerably. Interestingly, different stakeholder perspectives are also discussed in terms of the potential to create and capture value from digestate. Government organisations, energy providers, agri-businesses and other stakeholders presented different insights. Key enablers in the context of leverage the value creation potential of digestate likewise present a key concern in this section where technological, commercial, regulatory, economic and social enablers are discussed.

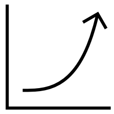
Lastly, and in addition to the digestate, another secondary coproduct of the AD process is *CO_2 extraction* after the biogas upgrading and cleaning process. Common opportunities stemming from the use of Bio-CO_2 from on-premises AD are discussed, and some implications of these opportunities are provided.

Research priorities

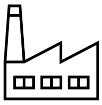
There are several research opportunities to overcome the barriers to a vibrant biogas industry in Australia. The major research opportunities are categorised as: growing the feedstock supply; scaling-up and increasing efficiency of existing AD; improving the economics for new AD-ready infrastructure; and developing markets for new AD products.



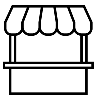
Grow the feedstock supply



Scaling up and increasing efficiency



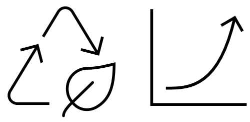
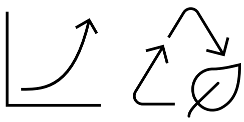
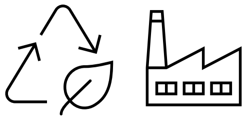
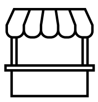
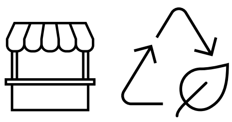
Improve economics for new infrastructure

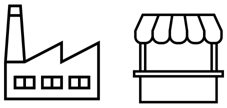
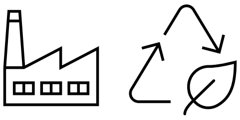
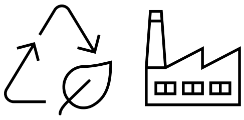
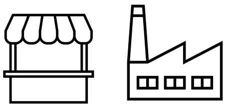
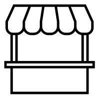
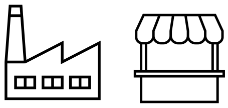
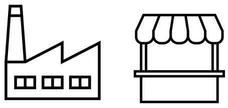
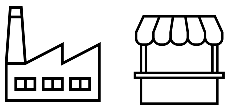
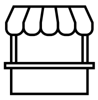
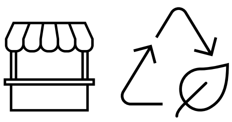


Markets for new AD products

In the next decade, direct research investment of at least $10 million per year will be needed to support projects in the following table, representing less than 1% of the potential revenue. These research projects will also provide training to create the necessary workforce for the biogas industry in Australia. These findings have been widely discussed with industry stakeholders via an Industry Reference Group (IRG) established for the project. Information gathered from these discussions were useful in the development of this research roadmap.

Research roadmap to foster a vibrant Australian biogas industry by 2030

No	Project title	Description	Themes	Market value* PJ/yr	$mil/yr
1	Food waste co-digestion at wastewater treatment plants	New tools to assess the viability of co-digestion, ways to collect and manage food waste, co-digestion demonstration projects		8.2	82
2	Demonstrating advanced AD technologies	AnMBR and CSTR technologies for dairy, food processing wastewater and municipal waste industries to increase biogas production and reduce cost		10	100
3	Manure collection at feedlots	Techniques to collect manure and new pen design to minimise contamination and improve biogas production		0.3	3
4	Biomethane quality specification	Standardising biomethane specification for common behind-the-meter applications (20 Mt TS of biomass = 6.0 billion Nm³ of biogas)		10.9	109
5	Digestate assessment and standardisation	Standards to manage digestate from specific feedstocks and for specific beneficial reuse options (digestate 33 Mt @$20/t)		na	660

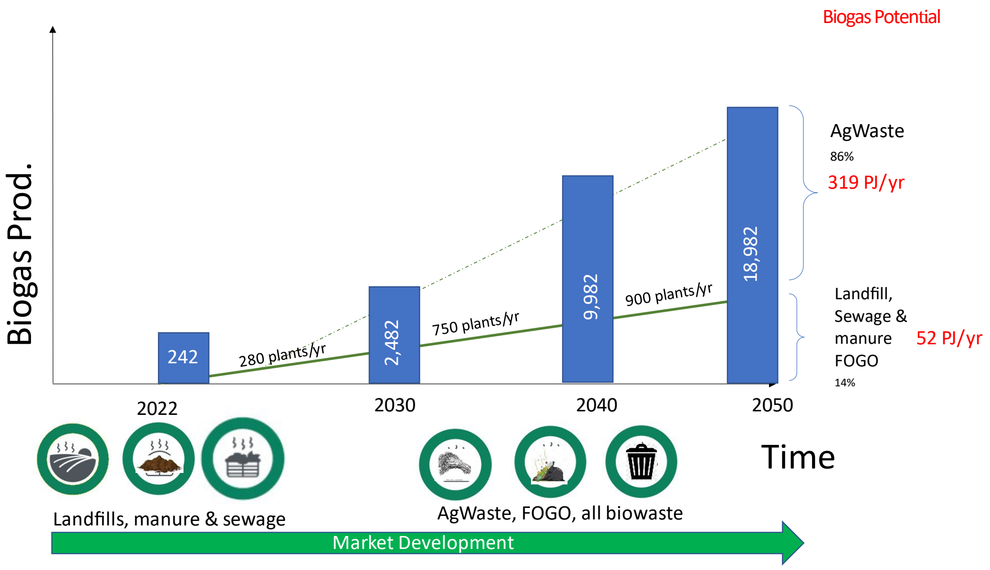
No	Project title	Description	Themes	Market value* PJ/yr	$mil/yr
6	Demonstration of small-scale partial biogas upgrading	Technology demonstration and techno-economic assessment of partial biogas upgrading, storage and transfer		15.5	155
7	Techniques to enhance landfill gas production	Techniques to enhance gas production and accelerate landfill maturity (1 t OF-MSW = 50 Nm^3 CH_4)		8.5	85
8	Biogas production from FOGO	Technology development and demonstration of biogas production from FOGO in the Australian context including source separation, collection, and mechanical bioreactor for high-rate and high-solid AD (Dry AD)		3.5	35
9	Integrating AD to microgrids	Integration of AD to a microgrid for energy reliability and efficiency		--	--
10	$BioCO_2$ utilisation	Assessing new options for utilising $BioCO_2$ from biogas upgrade (e.g. green-house operation, animal slaughtering @$200/t $BioCO_2$)		--	1.2
11	Biological methanation using existing AD facility	Biomethanation to enhance biogas production and enrich CH_4 content in biogas by using RE-H_2 (Power to gas)		--	--
12	Biomethane standards as transport fuel	Economic assessment and fuel standard testing for trucks and farm machineries to operate on biogas/B85/biomethane		--	--
13	Demonstration of small-scale BioCNG, BioLNG, and grid injection	Techno-economic demonstration of BioCNG, BioLNG, and grid injection at commercial scale		--	--
14	New business model to finance and support biogas project	New financial model to allow for long-term and large capital investment to biogas projects		--	--
15	National framework to regulate AD material flows	A framework to promote the most beneficial use of feedstock, digestate, and biogas		--	--

No	Project title	Description	Themes	Market value* PJ/yr	$mil/yr
16	Inclusive renewable energy market	A framework to acknowledge the role and value of renewable biomethane in the national energy mix through renewable gas target, renewable gas certificate and the interchangeability between biomethane and other forms of energy		--	--
17	National sustainability criteria	A national framework to assess and evaluate the sustainability of AD projects against specific criteria considering carbon credit, soil organic carbon, and land use regulation		--	--
18	Social licensing and system transition	Public engagement to gain social and regulatory support for a biomethane market		--	--

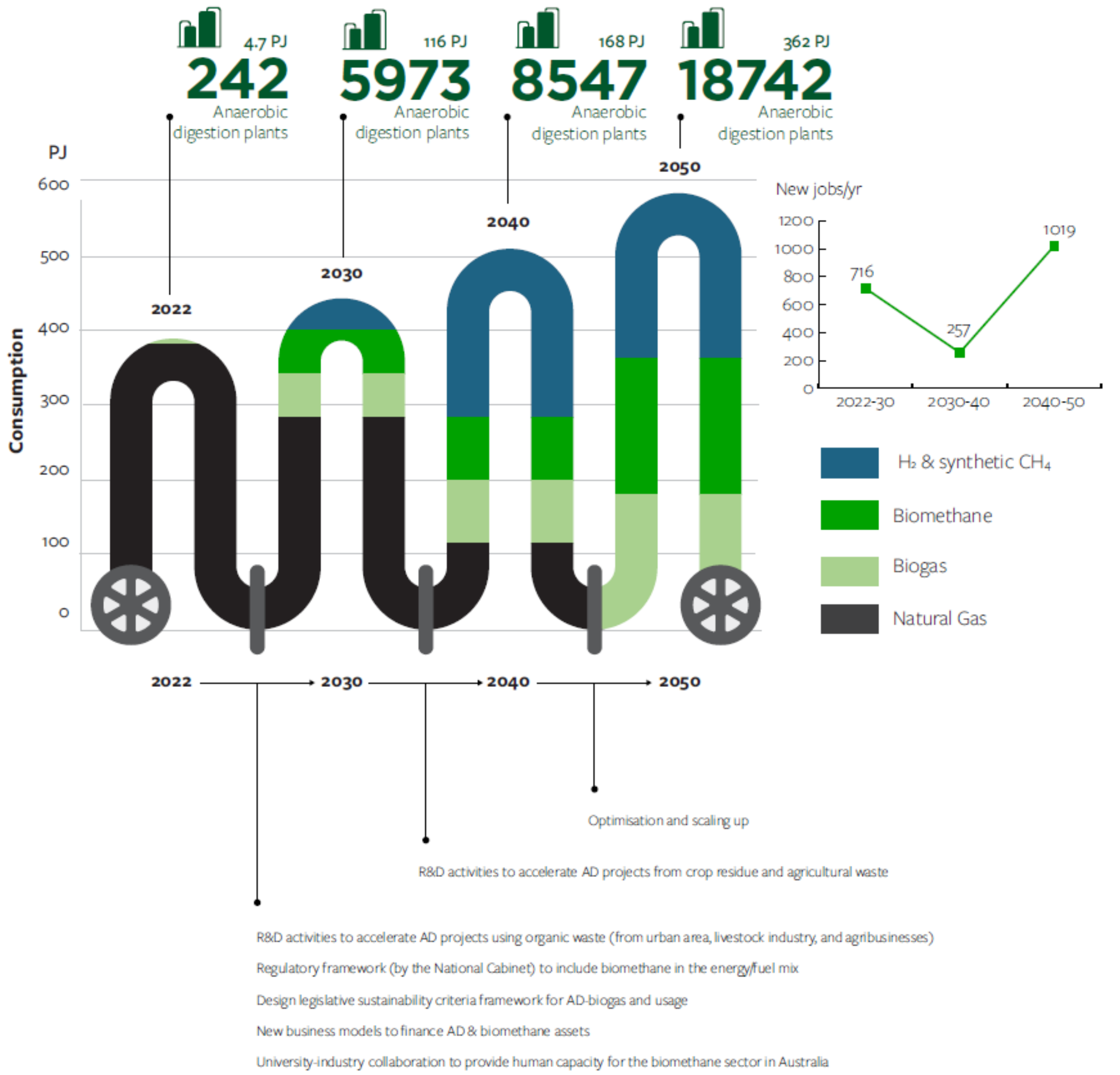
Note: AnMBR: Anaerobic Membrane Bioreactor; CSTR: Continuously stirred tank reactor; $BioCO_2$: Carbon dioxide from biogas upgrading; BioLNG: Liquefaction of biomethane. Assume current market price of biomethane at $10/GJ; Digestate value is assumed at $20/t (33 million tons/yr); current market price of $bioCO_2$ is $200/t. *Market value has been estimated where possible.

BIOGAS POTENTIAL

This section outlines the expected development of the biogas industry in Australia from 2022 to 2050, depending on the quantity of sustainable biomass available. Agricultural waste accounted for 319 PJ/yr of the overall biogas potential of 371 PJ/yr in 2050, whereas landfills, sewage sludge, livestock manure, and FOGO accounted for the remaining 52 PJ/yr. Biogas has the possibility of supplying up to 6.2% of Australia's total energy consumption of 6,013 PJ by 2050, or to replace 22.5% of the nation's current fossil gas usage of 1,647 PJ. Adoption of biogas technology for organic waste management might add $50 billion to Australia's GDP by 2050 and provide 18,100 full-time positions, primarily in regional areas.



A quantitative analysis of an accelerated scenario for Australia suggests that biogas and biomethane can contribute to more than half of all gaseous consumption in Australia by 2050 as presented in the infographic below. To completely phase out of fossil gas in the network, the remaining balance is projected to be provided by green H_2 and synthetic methane (produced from H_2 and CO_2).



Note:
Assume average plant size of 0.66 MW.
New direct jobs with specialised technical skills in biogas/biomethane technologies.

1 Technology review

Anaerobic digestion (AD) is a biological process where organic matter is degraded by micro-organisms under anaerobic conditions, that is in the absence of oxygen, to produce biogas (40-70% methane, CH_4 and 30-60% carbon dioxide, CO_2). The produced biogas can be used for production of heat alone in boilers or for electricity and heat generation in combined heat and power (CHP)/cogeneration plants. Biogas can also be cleaned and upgraded to biomethane for injection into the gas pipeline network ($BioCH_4$) or compressed and used as vehicle fuel (BioCNG). The AD process also produces a nutrient-rich by-product called digestate. Digestate is comprised of water, nutrients and approximately half of the carbon from the feedstock materials, can be used as organic fertiliser and/or separated into solid and liquid fractions for subsequent use in primary production.

Australia has a vast potential for AD. Waste management, climate change initiatives, and renewable energy targets are driving the adoption of biogas technology in Australia, which is currently dominated by landfills and sewage biogas plants. With intensive livestock and food-processing industries looking to valorise their waste and landfill gate fees and electricity costs rising, the Australian biogas industry is expected to grow.

1.1 Current status

- Australian energy consumption in 2019-20 was 6,014 petajoules (PJ). Renewables accounted for 7% of total energy consumption (418.8 PJ). Approximately, 16.7 PJ of energy was produced by biogas in Australia. The biogas sector reported an annual growth rate of 2.1% over the previous year. Solar and wind energy had an average annual growth rate of 41.7 and 15.2%, respectively. Over the last decade, biogas reported the lowest growth (1.9%) when compared to solar (33.8%) and wind (14.4%) (Department of Industry Science Energy and Resources, 2021a).

- As of March 2019, there are an estimated 242 AD facilities operating in Australia (Carlu, Truong, & Kundevski, 2019). Most of these AD facilities are landfills (129) and sewage biogas plants (52). The agricultural AD facilities (22) mainly digest livestock manure e.g. pig, cattle or poultry manure while a number of the industrial AD facilities (34) use red meat processing and rendering wastewaters (Figure 1). Interestingly, there are only five AD facilities that utilise food waste, suggesting that the biogas sector requires significant national policy towards organic waste diversion from landfills. Moreover, these AD facilities are heavily concentrated in the relatively densely populated south-east coast of Australia. On the other hand, broadacre crop residues and agro-industry wastes are not explored while energy crops are not currently grown for biogas production in Australia. Introduction of biogas plants to regional areas by developing biomass supply chain infrastructure for broadacre agricultural crop residues and agro-industry wastes would increase the number of agricultural AD plants.

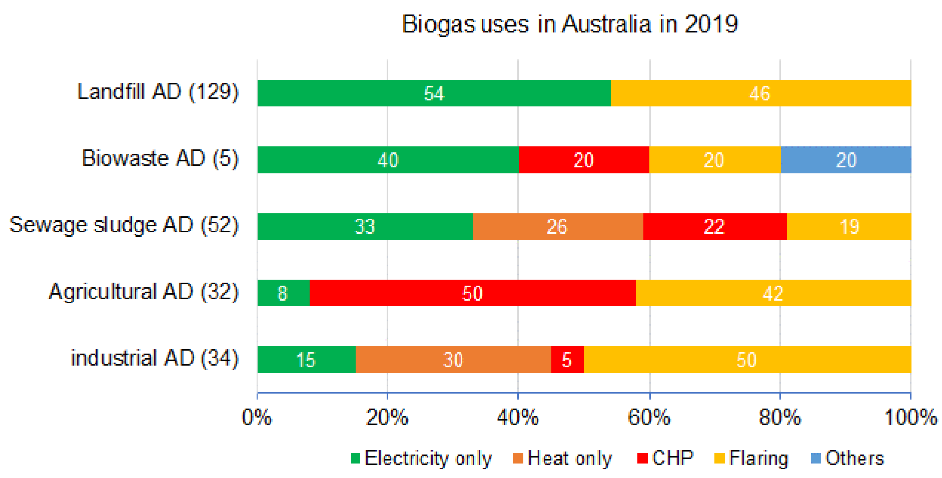


Figure 1. Number of biogas plants by feedstocks and biogas uses (%) in Australia in 2019 (Carlu, Truong, & Kundevski, 2019).

- The first large-scale biogas plant will start operating in Nowra, treating 150,000 t/yr of farm manure from 19 neighbouring dairy farms and 30 t/yr of food waste (to be commissioned in July-Sept 2022) (Henly, 2021). Another 20 such centralised biogas plants projects are in pipeline by Australian Government (WMW, 2021).

- Most of the biogas production in Australia is used for heat and electricity generation in CHP/cogeneration plants or is being flared at landfills (Figure 1). Total electricity generation in Australia in 2019–20 was 265 terawatt hours, TWh (955 PJ). Of which, biogas accounted for 0.5% of total electricity generation in 2019-20. Total electricity generated from landfill gas (1,105 gigawatt hours, GWh) and sewage biogas (248 GWh) was 1,353 GWh in 2019-20. Landfill biogas generation rose by 2% in 2019-20.

- There are currently no commercial biogas upgrading plants operating in Australia for biomethane production. The first pilot-scale biogas plant with biogas upgrading and compression to produced compressed biomethane (BioCNG) of 96% methane from AD of sugarcane bagasse/trash was reported (ARENA, 2016). In 2020, the first demonstration-scale project on biomethane production for grid injection was announced (ARENA, 2020).

- Landfills generated 1,105 GWh of electricity in 2019-20. A large proportion of biogas (941 GWh energy content) is flared at landfill due to uncertainty in gas quality and the lack of infrastructure for biogas cleaning. The estimated total biogas flared in 2019 was 2,394 GWh.

- Although there is information regarding the design and operation of anaerobic lagoons and upgrading these to covered anaerobic ponds within the dairy and Australian meat processing industries to minimise the greenhouse gas (GHG) emissions from wastewater treatment operations, there is a clear lack of published literature on the quantity and quality of biogas produced using this AD technology, especially in optimising the biogas production from CAL.

- The absence of suitable methods to monetise the full value of gas injection into the gas grid is responsible for the dearth of commercial upgrading facilities. For instance, lack of regulations on the digestate management and/or Australian Standards on digestate quality for land application restricts biogas project developers from maximising its utilisation. However, the development of Emission Reduction Fund (ERF) methods for biomethane, announced by the Australian Government in December 2020, being led by the Clean Energy Regulator, now allow biomethane from domestic, commercial and industrial wastewater treatment plants, animal effluent management systems, and landfills to reduce emissions and receive Australian carbon credit units (ACCUs). (Department of Industry Science Energy and Resources, 2022; ENEA & Deloitte, 2021).

1.2 Sustainable feedstock availability in Australia and its biogas potential

Figure 2 show the biomass availability for different feedstocks in Australia. The majority of dairy and beef is produced in VIC and QLD respectively, whilst sheep production occurs mostly in the southern states of NSW, SA and VIC and in the southern parts of WA (Figure 2). This has implications for the availability of organic waste as potential feedstocks for anaerobic mono- or codigestion. In contrast, pork production is evenly distributed across QLD, VIC, SA, NSW and WA (Figure 2).

Similarly, rice and sugarcane cultivation are mainly concentrated in NSW and QLD respectively, whilst cotton and grain sorghum production occur mostly in the QLD and NSW (Figure 2). These areas could be considered as potential high biomass density areas with pure organic waste available for farm-scale or centralised anaerobic codigestion. In contrast, canola, wheat and barley production areas were evenly distributed across VIC, SA, NSW and WA (Figure 2).

Table 1 presents the calculated annual quantities for 2022 of organic wastes as million tonnes (Mt) total solids (TS) generated from different economic activities for each Australian states and aggregated to a national total. Much of the data were sourced from the Australian Biomass for Bioenergy Assessment (ABBA) database (ARENA, 2020), available via the AREMI National Map platform (www.nationalmap.gov.au). However, the actual amounts feasible for biogas production will vary since the availability of biomass is dependent on the feasibility (costs and logistics) of collecting, processing and disposing of it.

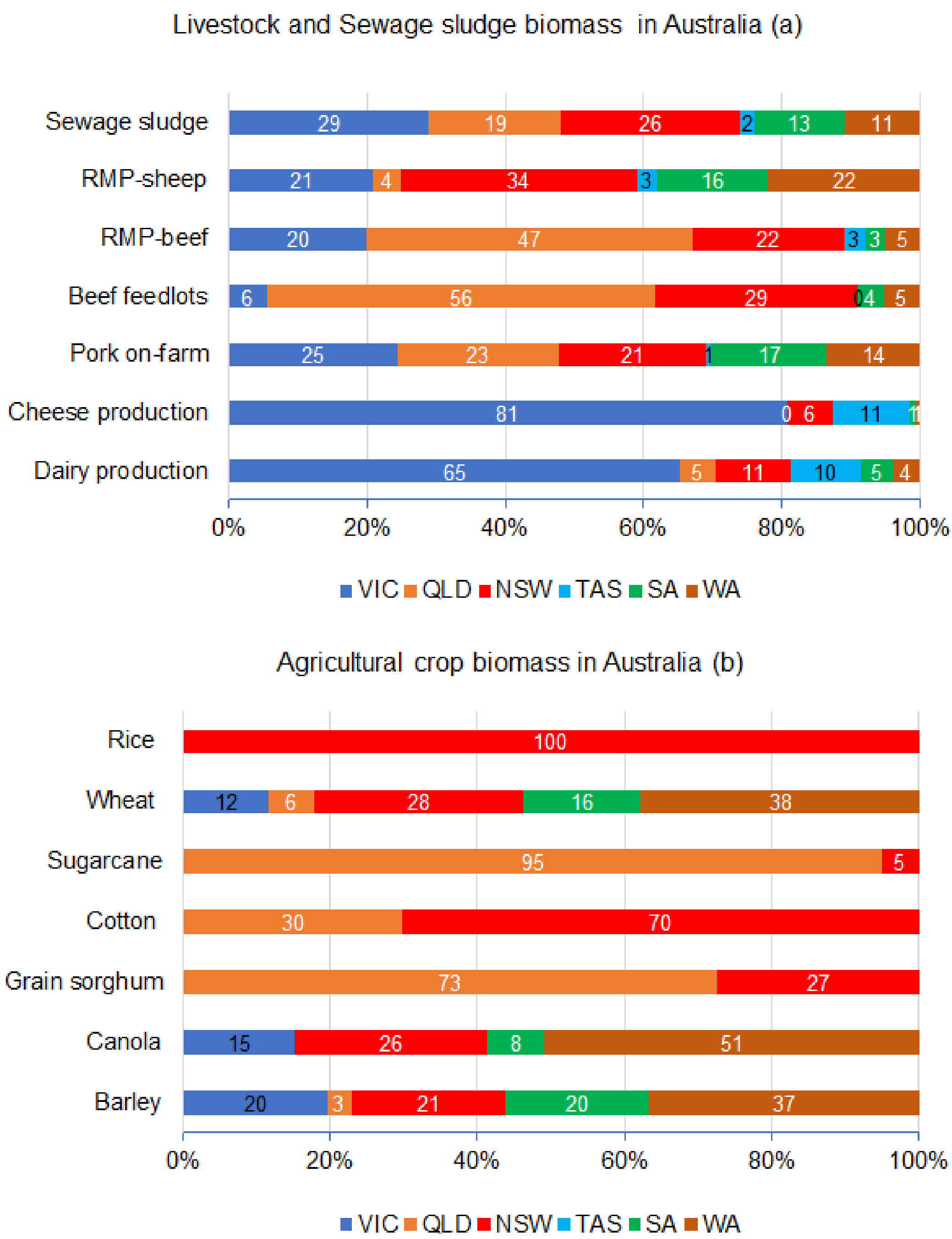


Figure 2. Distribution of biomass resources (a) livestock management, sewage and (b) agricultural crop production industries, across various states in Australia. RMP: Red Meat Processing. Adapted from data in the **Australian Biomass for Bioenergy Assessment (ABBA) database (ARENA, 2020), available via the AREMI National Map platform (www.nationalmap.gov.au).**

Table 1. Summary of annual organic waste amounts generated by feedstocks in Australia and their projected availability for biogas production.

Feedstock	Biomass production (Mt TS)	Percentage of total biomass	Collection rates		
			Low (Mt TS)	Medium (Mt TS)	High (Mt TS)
Agricultural crop residues	43.13	69.5	13.45	19.45	25.92
Livestock manure	2.98	4.8	2.08	2.38	2.98
Agro-industry wastes	6.92	11.2	3.46	5.19	6.23
Food processing wastes	0.73	1.2	0.55	0.58	0.65
Biowaste	7.91	12.8	2.37	3.56	4.75
Sewage sludge	0.37	0.6	0.37	0.37	0.37
Total	62.03	100	22.28	31.53	40.89

For the current biomass availability estimates, it was assumed that a minimum of 40% of crop residues was left in the field as soil mulch for maintaining sustainable agricultural practices and/or 5-10% of straw was burned. An estimated 70-100% of biomass availability was considered for organic wastes of high purity and available in a centralised location, for example, sugar industry, food processing industry, livestock manure, sewage sludge. For heterogenous and decentralised organic wastes such as food waste and garden waste, (FOGO), 40 to 70% of total waste collection rate was considered. These collection rates agreed with other international bodies. World Biogas Association has recommended about 45% collection rate for agricultural crop residues (WBA, 2021).

Results show that an estimated 62.03 Mt TS of biomass is available in Australia. Agricultural crop residues accounted for 69.5% of the total followed by biowaste and agro-industry wastes (Table 1). Livestock manure, the most reliable biomass source, accounted for 4.8% of total biomass. However, the actual biomass available for AD can range from a low 22.28 Mt TS per year to a high 40.89 Mt TS per year. This amount is dependent on the logistics and costs of biomass collection.

Table 2 presents the methane production potentials from each feedstock source and the energy produced from biogas use in CHP/cogeneration plants or for biogas upgrading biomethane. The biogas production potentials were derived from the projected low collection rate of annual waste quantities (Table 1) and the methane potential data from the literature and Griffith University research data (Data not shown).

Table 2. Methane production potential from the biomass and use of biogas in electricity and heat generation in CHP/cogeneration or biogas upgrading to biomethane.

Feedstock	Methane prod. (M Nm^3/yr)	Gross energy potential (GWh/yr)	Biogas use in CHP/Cogeneration		Biogas upgrading	
			Electricity production (GWh_e/yr)	Heat production (GWh_t/yr)	$BioCH_4$ (GJ/yr)*	$BioCO_2$ (Mt/yr)
Agricultural crop residues	2,504	24,912	10,563	10,613	8,742,286	4,745
Livestock manure	98.92	984	417	419	345,391	151
Agro-industry wastes	376	3,740	1,586	1,593	1,312,381	726
Food processing wastes	44.69	445	189	189	156,053	58
Biowaste	154.47	1,537	652	655	539,380	214
Sewage sludge	3.43	34	14	15	11,975	6
Total	3,181	31,652	13,420	13,484	11,107,467	5,899

*Note: 1 GJ = 278 kWh.

1.2.1 Agricultural crop residue

The total biomass in Australia is estimated at approximately 80 Mt/yr. Major sources of biomass include crop residues (27.7 Mt/yr), grasses (19.7 Mt/yr) and forest plantations (10.9 Mt/yr). Over the next 20–40 years, the total biomass potential could increase to 100–115 Mt/yr (Crawford et al., 2016). Not all biomass from agriculture is suitable as feedstocks for AD. In our study, we have considered the crop residues from wheat, rice, sugarcane, cotton, fruit, and vegetable (on-farm waste) production and also spoiled crop silage. Energy crops or grass grown specially for energy production were not considered due to unsustainable farming practices such as land clearance, food-fuel competition, eutrophication due to inorganic fertiliser application, and loss of biodiversity etc. Our estimates show that approximately 43.1 Mt TS/yr of crop residues are available for biogas production. More detailed regional analyses, including of the costs of delivered biomass, logistics and economics of harvest, transport and storage, competing markets for biomass and a full assessment of the sustainability of production are needed. The untapped biogas potential from agricultural crop residues in Australia is 24,912 GWh/yr and is the highest (79%) when compared to other feedstocks presented in Table 2.

1.2.2 Livestock manure based

With a livestock population of 25.9 million cattle (MLA, 2021), over 2.4 million pigs (Australian Pork, 2021), and 652 million poultry (ACMF, 2021) approximately, 2.9 Mt TS/year of livestock manure is produced in Australia. Manure from poultry, piggery and dairy operations can be collected at a relatively high collection and recovery rate of 70-100%. On the other hand, manure from beef cattle is difficult to collect and have a low collection rate of 40%. At a low collection rate of 40%, 2.1 Mt TS of manure can be collected per annum for AD and accounts for 4.8% of total biomass (Table 1). This amount could generate 2,504 million Nm^3/yr (984 GWh/yr). This is close to previous estimate by CEFC (2015), who have projected agricultural biogas production at 791 GWh/yr by 2020.

1.2.3 Agro-industry wastes

Agro-processing industries generally process the raw grains, fruits and vegetables to produce commercial products for consumption and/or other value products. Rice husk, sugarcane bagasse, sugarcane mill mud, sugarcane dunder and fruit and vegetable processing industry wastes are the major organic waste streams generated from agro-industries.

Sugar industry: Australia is the third largest exporter of sugar in the world, with the industry worth $2 billion per year (ARENA, 2016). A significant proportion of Australia's current renewable energy comes from burning bagasse, the lignocellulosic residue left over after extraction of sugar (Department of Industry Science Energy and Resources, 2021b). The Australian Renewable Energy Agency (ARENA) has funded a project to explore more environmentally and economically viable ways of utilising this resource via AD and production of biogas (ARENA, 2016). From the 24 sugar mills in Australia (95% in QLD and 5% in NSW), 5.7 Mt TS of bagasse could be available. If all this bagasse is used for biogas generation, we can generate 3,438 GWh/yr of energy. In addition to bagasse, sugar mill also produces other by-products such as sugarcane mill mud, molasses and dunder. Mill mud is produced after clarification and filtration of the cane juice. It is sold as soil conditioner for sugarcane fields and diversion of mill mud might incur an economic cost of $40 per tonne. Nevertheless, it is available as pure biomass and thus can be utilised as feedstock for biogas production. With a modest 50% recovery rates, 204 kt TS/yr of mill mud can generate 3,438 GWh/yr of energy. Similarly, molasses with a diversion rate of 40-50%, we can estimate 81,735-102,169 t TS/yr of energy. However, molasses will also incur an economic cost ($80-120 per tonne). Finally, dunder, a by-product of producing ethanol from the fermentation of sugarcane molasses, is applied to sugarcane and other crops as an organic soil amendment and fertiliser. With a 50% diversion rate, we can estimate 75,000 t TS/yr of dunder producing 14 GWh/yr of energy.

Rice husk is generally used as livestock bedding, mulch for gardening, pot mixture and pet litter. With 30-40% of the rice husk used either as bedding material or burned in the fields, we can estimate that approximately 50% of rice husk is available for biogas production. This amount of rice husk can generate 107.6 GWh/yr of energy. However, AD of rice husk is challenging due to high lignin content and thus limiting the bioaccessibility of holocellulose by microorganisms.

Primary processing of fruits and vegetables, which usually take place close to the farms, is called horticulture processing wastes. A significant amount of organic waste is generated during this processing. It is generally sold as animal feed (pigs, cattle) or for organic compost. With 75% collection rate, we can estimate 207 kt TS/yr of on-field horticultural waste with a biogas potential of 32 GWh/yr.

1.2.4 Food processing wastes

Food manufacturing industries in Australia represent a significant opportunity to divert organic waste from landfills. By 2019, Australia generated around of 7.6 Mt of food waste across the supply and consumption chain. Primary production (22%) and manufacturing (17%) account for the second and third largest percentage of food waste along the food value chain. The overall results of the updated national food waste baseline (2021) reported that the key generators of food waste are dairy (36%), and fruit and vegetables (24%). Baked product (3%), pasta (<1%), confectionary (<1%), beer (<1%) and other product manufacturing accounts for relatively small quantities (Department of Agriculture Water and the Environment, 2019; FIAL, 2021).

From the total food processing waste arising across the supply chain (7.6 Mt in 2019), FIAL (2021) reported that only 40,000 t were treated using AD technology. Food processing wastes represented the second lowest untapped biogas potential (445 GWh/yr) when compared to other feedstocks (Table 2).

1.2.5 Biowaste from municipal waste industry

The Clean Energy Finance Corporation (CEFC, 2015) has identified significant opportunity for implementing biogas technologies in the municipal solid waste industry, attributing this opportunity to rising landfill gate fees and the decreasing costs of biogas technology. In 2018-19, an estimated 74.1 Mt of wastes were generated in Australia with organic waste accounting 19% of the total waste (Department of Agriculture Water and the Environment, 2020). Approximately 7 Mt of organic waste were recycled, and 2.1 Mt of waste were used for energy recovery in 2018-19. The 2018-19 data comprised about 1,750 kt (82%) of energy recovery through landfill gas collection and 311 kt (15%) of recovery as fuels, the biggest portion of which was solid recovered fuels and 75 kt (4%) of AD of food-derived waste.

Food and garden organic waste, referred to as FOGO, is a major concern for most of the municipalities and is considered as the potential feedstock for AD and composting and has been documented in the National Waste Report 2020 (Department of Agriculture Water and the Environment, 2020). In 2018-19, about 5.09 Mt of food waste were generated in Australia, of which 22%, was processed through composting or AD. About 4.43 Mt (87% of the total food organics) were classified as non-hazardous. Of this, about 3.76 Mt (85%) were deposited in landfills[1], 14% was composted and 2% was processed by AD. Of the estimated 0.66 Mt of food-derived hazardous organics, three-quarters were recorded as recycled (composted), and it is likely that most of the 24% recorded as 'treated' were also composted. Similarly, the National Waste Report also found that 1.2 billion tonnes of food were lost on farms, trumping the 931 Mt wasted in retail and consumption. With the introduction of source separate collection of organic waste and appropriate logistics, we estimate 7.9 Mt TS/yr of FOGO waste generation in Australia. However, with relatively low collection of 30%, we can estimate 2.3 Mt TS/yr of FOGO waste available for biogas production. With a high methane yield from FOGO waste, we can recover 1,537 GWh/yr of energy.

1.2.6 Sewage sludge

AD from sewage sludge is an established technology that has been adopted in wastewater treatment plants for decades as a strategy to reduce the volume of sewage sludge. In 2018, the Australian water industry generated 18% (279 GWh/yr) of its electricity demand from on-site renewable electricity generation. Biogas from AD of wastewater and sewage sludge accounted for 67% (187 GWh/yr) of the

[1] This is prior to allocation of some food waste to the fate 'energy recovery' through use of landfill gas.

electricity generated, followed by hydropower (30%, 84 GWh/yr), biogas from co-digestion and waste-to-energy through AD of organic feedstock (2%, 5.5 GWh/yr), and solar photovoltaic (1%, 2.2 GWh/yr) (Strazzabosco et al., 2020). From the annual sewage sludge production of 371,000 t TS, an estimated 40 GWh/yr of energy can be generated onsite in the existing biogas plants.

Interestingly, 23% of the wastewater flowing through the 10 wastewater treatment facilities in Australia was not used for biogas generation (WEF, 2013). Thus, these biogas facilities may be too small to produce and/or use biogas profitably. Even if the physical opportunity exists to expand biogas recovery further, the economies of scale present an economic constraint for biogas in small plants. Without further economic or regulatory incentives, or a reduction in the cost of technology, it appears doubtful that the Australian water industry will make substantial use of this resource (Strazzabosco et al., 2020).

1.3 Potential environmental benefits of AD in Australia

In March 2021, agriculture accounted for 14.9% and waste accounted for 2.7% of Australia's national GHG emissions of 494 Mt CO_2-e (Department of Industry Science Energy and Resources, 2021b). The major sources of anthropogenic methane emissions in Australia include the management of livestock (48%); the management of the land through fire (9%); water supply systems (3%); waste management systems (10%); other agricultural systems (<1%); the combustion of biomass (1%) and the extraction, distribution and combustion of coal, oil and gas (29%).

Table 3 presents the GHG emissions abatement from the use of the Australian biomass based on data in Table 1 for biogas production and use of biogas for heat and electricity generation in CHP/cogeneration plants or upgraded to produce biomethane ($BioCH_4$) and biocarbon dioxide ($BioCO_2$). Production and use of biogas for energy generation can decarbonise the agriculture, energy and transport sectors, where reduction of GHG emissions is most difficult. With the use of 22.28 Mt/yr of biomass, the lowest biomass collection rate presented in Table 3, an estimated 16.4 Mt CO_2-e per year can be avoided from cogeneration of heat (@ 0.295 t CO_2/MWh) and electricity (0.929 t CO_2/MWh) in CHP/cogeneration plants. Replacing the coal-based electricity with biogas-generated electricity would avoid 63.7% of total emissions from coal-fired generation in Australia. Alternatively, use of biogas for biogas upgrading and production of biomethane for grid injection (BioRNG) or compressed for vehicle fuel (BioCNG) can abate 7.1 Mt CO_2-e per year of GHG emissions from fossil gas or petrol use.

Table 3. Greenhouse emissions abatement from production and use of biogas in electricity and heat generation in CHP / cogeneration or biogas upgrading to biomethane.

Feedstock	$BioCH_4$ replacing fossil gas or fossil fuel electricity in heat and electricity generation		$BioCH_4$ replacing fossil gas or petrol in transport (t CO_2-e/yr)
	Electricity production (kt CO_2-e/yr)	Heat production (kt CO_2-e/yr)	
Agricultural crop residues	9,815.8	3,129.9	5,639.2
Livestock manure	387.8	123.6	222.7
Agro-industry wastes	1,473.5	469.8	846.5
Food processing wastes	175.2	55.8	100.6
Biowaste	605.6	193.1	347.9
Sewage sludge	13.4	4.2	7.7
Total	12,471.4	3,976.7	7,164.8

1.4 Existing and new AD technologies

Table 4 presents a comparison between different technologies in the treatment and disposal of organic waste in Australia. AD typically occurs simultaneously in one or multiple reactors. The reactor configuration and technologies used are primarily determined by the feedstock characteristics (such as its moisture content) and the flow rate. The main differentiating parameters of the AD processes and typical AD technologies are shown in Figure 3.

Three main types of AD technologies currently exist are:

1. Wet AD process (feedstock with TS ≤ 15%): technologically mature and widely used in the world.
2. Continuous dry AD process (feedstock with TS 20-45%): technologically mature, however, it is currently used less than the wet AD process as it is more expensive than wet AD process. Suitable for substrates with a high content of crop residues, household waste and livestock manure.
3. Batch dry AD process (feedstock with TS 30-40%): technologically mature but recently emerged from research and development.

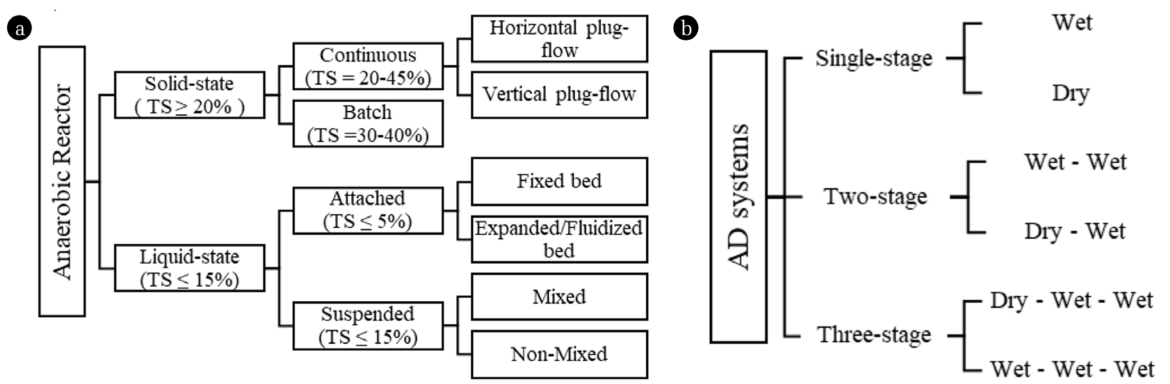


Figure 3. Classification of existing and future anaerobic digestion (a) reactor configurations and (b) systems.

1.4.1 Reactor technology

The three main types of AD reactors technologies that are commonly used in Australia are Continuously stirred tank reactor, Plug flow and Covered lagoons (Energy Farmers Australia, 2013). A brief description of each reactor technology and their applications in waste treatment along with Australian industries currently adopted these reactor technologies is presented below.

Continuously stirred tank reactor (CSTR): These are the most common reactors in AD applications. These reactors are insulated and heated with a gas tight cover to collect the biogas. Waste heat e.g. from CHP/cogeneration plant is used to heat the reactor contents thus reducing the retention time to 30-50 days under mesophilic and 20-35 days under thermophilic conditions. Commonly used for treating livestock manure, sewage sludges and co-digestion of agricultural wastes/energy crops with manure. Both farm-scale and centralised biogas plants are designed with CSTR reactor technology. Current examples of the application of CSTR technology in Australia are the ReWaste facility in Wollert, to the north of Melbourne and Richgrow's facility in Jandakot, Perth.

Plug flow reactor (PFR): Plug flow reactors have a long horizontal tubular or vertical cylindrical design with an expandable cover to capture the biogas. Feedstock is fed in one end of the reactor, which pushes reactor contents along the reactor and causes by-product to exit at the other end. Dry AD configurations utilise plug flow reactor design due to their high viscosity. The reactor is made to treat waste samples with TS solid content between 10 and 15%. Plug-flow digesters are easy to construct and operate, and they are frequently used to digest ruminant animal wastes. The efficiency is not as high as complete-mix digesters and is affected by shock loading wastes.

Uncovered anaerobic ponds (UAP): Uncovered anaerobic ponds (UAP) are a common effluent treatment technology used to simultaneously treat and store effluent and are a popular treatment option for raw piggery wastewater with high biological oxygen demand (BOD). UAPs are installed at an estimated 60% of Australian piggeries, and in recent years there has been strong uptake of biogas capture and use systems at various piggeries around Australia (APRI, 2022). UAPs are simple to build and easy operate and provide sufficient sludge storage volume. The UAP should be designed as deep as possible without reaching groundwater and should have a minimum active depth (above the inert sludge layer) of 2 m remaining at the end of the design desludging period (Hamilton et al., 2006). Deep ponds offer a smaller surface area, resulting in lower oxygen transfer, less precipitation in wet climates, and less evaporation and salt build-up in dry climates; and a more stable temperature, improving the performance of the methanogens. Well-designed, properly managed UAP can also provide good effluent treatment without odour nuisance or adverse impacts to water resources.

Covered anaerobic ponds (CAP): Covered anaerobic pond (CAP) technology is very common in Europe and the USA but the use of CAP technology in Australia has received a mixed response. CAPs are also low tech but relatively robust in nature, requiring minimal operation or monitoring. In cooler climates, pond covers may also insulate and heat ponds, via the absorption of solar radiation (Heubeck and Craggs 2010). Despite higher initial infrastructure costs when compared to UAP, CAPs offer significant advantages such as odour control, intensification of the decomposition process and biological oxygen demand (BOD) removal, an increase in feed rate and the potential for capturing methane-rich gas as a fuel source for bioenergy and the reduction in GHGs. Current examples of the application of CAP technology in Australia are Ingham's at Murarrie; Throsby's at Singleton; and A J Bush at Beaudesert.

Covered anaerobic lagoons (CAL): Covered anaerobic lagoons (CALs) are essentially plastic lined holes in the ground with a cover that traps the biogas. While a simple design, CALs are relatively inefficient. More complex variations of these designs are possible and should be considered for site-specific conditions, through multiple stages. In a one-stage system, all four stages of anaerobic biochemical reactions necessary to produce methane occur in a single reactor, whereas in two or multi-stage systems these reactions occur in multiple reactors. Multi-stage systems can be more effective at producing methane than one-stage systems for certain feedstocks, however, they are more expensive. Currently, there are over 18 CAL installation in the Australian red meat industry alone and many more treating wastewaters in the chicken industry. Unlike the CALs in the intensive livestock industry, the CALs serving the red meat industry have proven robust and reliable in terms of treatment performance and biogas production, despite significant fluctuations in raw wastewater feed volumes and composition in many facilities (MLA, 2018a).

Anaerobic flotation reactor (AFR): An anaerobic flotation reactor (AFR) ensures that the wastewater and granular sludge at the bottom of the reactor are well mixed. Most of the conversion and biogas production takes place in the reactor's middle section, with the biogas collected by a lower-level stage separator. This lifts the water through the riser tube and into the gas separator at the top of the reactor. The biogas exits the reactor at the top, while water returns via the downcomer to the reactor's base. In the second upper compartment, effluent is refined, and biogas produced here is separated in the stage separator for the top level. The reactor's effluent exits from the top. Wastewater with fats, oil and grease and/or solids such as proteins and starch, can effectively be treated in the AFR.

Up-flow anaerobic sludge blanket (UASB) systems: In up-flow anaerobic sludge blanket (UASB) reactors, the influent enters the digester at the bottom, travels through a dense layer of bacteria (the sludge blanket) and exits the reactor at the top. As the biogas is produced, it travels upwards, carrying particles towards the top of the reactor. However, as the biogas passes through the sludge blanket, these particles are trapped. These small reactors may be as tall as 15 metres. Operationally, UASB systems necessitate close monitoring of granulation and scum building in the reactors, as excessive loading might result in instabilities; hence, a high-quality fat separator is required. This reactor technology can treat high COD waste streams which frequently emanate from food, beverage and similar industries. UASB systems are currently operational at Carlton United Brewery (Brisbane, Australia), Golden Circle (Brisbane, Australia), Cadbury (Hobart, Australia), Mars (Ballarat, Australia) and Samoan Breweries (Apia, Samoa).

Internal circulating (IC) reactor technology: Internal circulating (IC) reactors enable even greater volumetric loading rates and improved process stability enabling the minimum possible footprint. These plants have low energy requirements and deliver substantial volumes of renewable biogas for plant boilers or cogeneration facilities. An IC reactor consists of three components; wastewater is fed into the reactor's first component, which contains a bed of granular sludge. The mixture of wastewater and sludge flows up the riser and into the third component, where biogas and liquid are separated, due to the production of biogas. After separation, the wastewater and sludge mixture is channelled via a downer and returned to the bottom of the first section; the higher the COD load, the more biogas will be produced, resulting in increased circulation. The second component of the IC reactor is responsible for treating the wastewater containing a lower organic load than the first component, and the treated wastewater then flows into the subsequent treatment process. IC reactors are currently operational at the Carlton United Brewery (Brisbane, Australia), Visy Paper (Sydney, Australia), Toohey's Brewery (Sydney, Australia), the Smiths Snackfood Company (Brisbane, Australia) and in Samoa and New Zealand.

Anaerobic membrane bioreactor (AnMBR): This type of reactor is also referred to as the anaerobic mixed-batch reactor. The technology of anaerobic membrane bioreactors (AnMBR) combines the biological degradation process with direct solid–liquid separation via membrane filtration. Utilising micro filtration membrane technology (with pore diameters ranging from 0.05 to 0.4 µm), AnMBR systems permit the total physical retention of bacterial flocs and almost all suspended particles within the bioreactor. Due to the nature of membranes, frequent chemical cleaning may be necessary to prevent fouling (blockage of membrane pores).

Mixed plug flow reactor (MPFR): Mixed plug flow reactors (MPFRs) have same structure as plug flow reactors with agitation as the main difference between reactors. The MPFR is suitable for wastes that have dirt, sand or grit as the agitation system help to avoid particles to settle out inside of the reactor reducing the amount of sediment and avoid problems with thick or rigid floating layer.

1.4.2 Reactor technology options for Australian industries

Dairy industry: Australian dairy effluent is typically dilute, with a low solids content of 0.08-27% solids (Tait et al., 2021). Dairy effluent could be treated in CALs if adequate footprint is available and site conditions are appropriate for their construction. UAPs are commonly used in many Australian dairy farms (Watson & Watson, 2015). Therefore, covering of effluent ponds for biogas capture is an incremental change from current practice. Anaerobic ponds can be relatively cost effective to construct. However, anaerobic ponds are intolerant of floating organic waste which form excessive scum or crust layers which can damage a cover and would be inaccessible once an effluent pond is covered, may offer minimal ability to control (e.g., temperature) and large volumes can make process corrections expensive. Therefore, CSTRs with heating could be considered but is likely to be limited hydraulically with dilute liquid organic waste such as dairy effluent.

Dairy processing wastewater: Anaerobic lagoons are the most commonly used AD systems in the world-wide treatment of liquid effluent from dairy processing (GHD, 2017). However, high-rate AD processes such as UASB and IC reactor systems have also been widely used in practice, with various system designs providing retention of biomass to minimise washout (Nadais et al., 2010). However, effluent volumes and characteristics needs to be assessed to design appropriate digester configurations. Anaerobic treatment has to date been applied in Australian dairy processing, but it appears only by a small number of larger processors. A list of example installations in Australian Dairy industry is provided by GHD (2017). Annually, 14.96 GL of liquid effluent and 0.78 GL of whey are produced in Australia, which can be translated in to a potential of 18.85 million and 15.64 million m^3 CH_4/yr, respectively (Tait et al., 2021). With the biogas energy potential of combined liquid effluent and whey, the energy demand of dairy processing can be met and can displace the need for fossil gas.

Piggery industry: An estimated 20% of the national Australian pig farms have a combination of conventional housing and deep litter housing suggesting that both piggery effluent and deep litter are potentially available for AD. Piggery effluent is a dilute mixture of manure, urine, spilt feed and wash water with significant dissolved organic matter content (22,000-96,000 mg/L total COD), predominantly comprised of volatile fatty acids (200-7,500 mg/L) which would be readily converted into biogas (Tait et al., 2021). In Australia, approximately 14% of total Australian pork production had adopted biogas systems and CALs are the main AD technology (Skerman & Tait, 2018). Some Australian pig farms also installed mixed heated digesters, specifically in-ground mixed heated CAPs and mixed tank digester systems. Unlike piggery effluent, spent piggery litter is a stackable solid organic waste type and its composition varies widely depending on bedding type and extent of soilage by the pigs (Tait et al., 2021). Currently, no anaerobic digesters in Australia are operating with spent piggery litter as feedstock. With high solid contents and good methane potential, dry AD may be an attractive option for spent piggery litter. Batch dry AD at 30-40% dry matter of spent piggery litter with and without leachate recycling along with CAL technology for treating piggery effluent and providing leaching for dry AD could be an ideal combination for handling piggery industry waste and wastewaters.

Beef industry: Cattle manure is the main organic waste from beef feedlot. This manure is typically dry scraped as a semi-solid or solid with solids content of 20-96% (Tait et al., 2021) and stockpiled to decompose and composted before land application. Currently, there are no AD plants in Australia operating with beef feedlot manure as feedstock (Tait et al., 2021). However, there has been on-going interest from Australian beef feedlots to explore AD options. Frequent and regular pen cleaning can improve and maintain good working conditions for workers and cattle and ensure sound environmental performance and manure collection. Feedlot pens should be cleaned at least every 13 weeks by using tractor drawn box scrapers, wheel loaders, excavator, slider blade or under fence pushers (Tucker et al., 2015). Ideally, pen cleaning should occur when the manure is moist (but not wet). The collected manure can be stockpiled as used as feedstock for AD. Wet AD in CSTRs with heating can be an option provided a significant quantity of water is required to adjust the solid contents of feedlot manure to less than 10%. It may be possible for the liquid fraction of digestate to be recycled for diluting the incoming feed, but ammonia levels would need to be monitored to prevent build up to inhibitory levels. Therefore, co-digestion of feedlot manure with agricultural crop residues would be an ideal option in the future. This will not only adjust the carbon to nitrogen (C/N) ratio in the AD process and improve the process stability and methane yields but can treat both high N content feedlot manure and high C content agricultural residues at the same time.

Red meat industry: Solid waste and liquid wastewaters from red meat industry are well characterised and classified according to the processing steps and waste streams (AMPC & MLA, 2010). Past research has classified effluent streams from different processing areas according to their distinct characteristics to identify tailored anaerobic treatment options. By this classification, red meat processing (RMP) effluent comprises a red stream (from slaughter floor and rendering), a green stream (from offal processing and paunch handling) and a separate high-volume dilute effluent sub-stream (from boning and cattle wash) (Jensen et al., 2014).

In Australia, anaerobic pond-based treatment has been common treatment option for liquid effluent from the RMP facility and was effective at reducing organic matter loads. However, where facilities are in urban areas, a shortage of land and risk of odour can make effluent ponds unsuitable. More recently, large Australian RMP facilities have implemented CALs to capture offensive odour and utilise biogas onsite as a boiler fuel. Hot effluent streams from RMP facilities may offer heating opportunities for AD processes, but temperatures may be initially too high for biological processes (AMPC, 2017). Progressive cooling causes coagulation and phase separation of fats (Banks & Wang, 2004) and may limit indirect heat recovery options using heat exchangers. On the other hand, the red stream with low solids concentration and thus not suitable for a CSTR process, could be treated through a high-rate anaerobic treatment systems that are tolerant of fat, oil and grease – FOG (Jensen et al., 2014). Conventional high-rate systems such as UASB have been applied to RMP effluent at laboratory and pilot scale (Banks & Wang, 2004), but have shown poor tolerance of solids, especially FOG (Jensen et al., 2014). Thus, FOG-tolerant high-rate options are required. Jensen et al. (2014) previously mentioned AnMBRs or AFRs as prospective technology options. AnMBRs are commercially available but have only been explored at laboratory and pilot-scale in Australia, and further research is required to consider their feasibility in RMP at larger scale.

Organic solid waste produced by Australian RMP include paunch contents, manure and yard waste, and screenings/float/sludge from liquid effluent treatment (AMPC, 2015). Paunch contents are typically washed into the effluent (AMPC & MLA, 2010), producing the green stream with relatively poor biodegradability compared to the red stream. AD process with a CSTR may be an option for treating screened green stream solids. However, due to low hydrolysis rate and low methane yield of paunch contents (Banks & Wang, 2004), anaerobic co-digestion of red stream, green stream solids and fat-rich sludge together in a single CSTR could improve the process performance and also methane yields through increased biodegradable organic loading, reduced long chain fatty acids (LCFA) inhibition by dilution, and potential synergistic effects on the microbial community.

Table 4. Reactor technologies and their applications in organic waste management. Source: Adapted from (MLA, 2018b)

Technology	Covered Anaerobic Lagoon (CAL)	Anaerobic Flotation Reactor (AFR)	Anaerobic Membrane Reactor (AnMBR)	Plug Flow Reactor (PFR)	Continuously Stirred Tank Reactor (CSTR)	Mixed Plug Flow Reactor
Waste Stream	Only liquid waste Total solids ≤ 3% is accepted	Liquid waste digestion <3% of total solids	Mixed liquid and solid waste Total solids from 1 to 2 %	Mixed liquid and solid waste Total solids from 11 to 13%	Mixed liquid and solid waste Total solids from 3 to 8%	Mixed liquid and solid waste Total solids >9%
Acceptance of liquid waste with fats, oils, and greases streams	YES	YES	NO	YES	YES	YES
Construction	In-ground lagoon or tank	Above-ground vessel (up to 15m)	Above-ground tank with internal or external membrane	Above-ground tank	Above-ground tank	Underground system to minimise temperature fluctuations
Process	Ability to withstand shock loads; nevertheless, in the case of heavy solids influent, there is a possibility of short-circuiting High retention times COD Removal efficiency from 60% to 90% High heat loss	COD Removal efficiency ≥ 90% No mixing No removal of nutrients	High solid retention Not removal of nutrients Quality of effluent consistency	Retention time guaranteed Affected by changes in load Affected by heavy metals, and non-volatile bio resistant organics	Outflow carry biomass causing loss Heat loss if not isolated Mixing required Solid's settlement bottom of the reactor 5% total solids limited in feed	Stable temperature Not removal of nutrients Operate up to 10% total solids in feed

Continuation Table 4. Reactor technologies and their applications in organic waste management. Source: Adapted from (MLA, 2018b)

Technology	Covered Anaerobic Lagoon (CAL)	Anaerobic Flotation Reactor (AFR)	Anaerobic Membrane Reactor (AnMBR)	Plug Flow Reactor (PFR)	Continuously Stirred Tank Reactor (CSTR)	Mixed Plug Flow Reactor
Energy	Low gas production Require energy to avoid heat loss through the cover	High gas	High energy requirement for aeration	Low energy consumption	Low gas Require energy for mixing and heating requirements	High gas Require energy for mixing and heating requirements
Operation and maintenance	Simple operation De-sludging required Removal of scum, FOG required (difficult and expensive)	Minimal plant operators' requirements	Minimal plant operators' requirements Cleaning and replacement of membranes are required depending on membranes' lifetime	Simple operation High cost for shutdown and cleaning of equipment	Skilled operators are required to optimise operating conditions Removal of settled solids is difficult	Minimal plant operators' requirements
Biosolids/waste	Difficult to remove biosolids from CAL	Extra stabilisation required	Difficult to remove	Extra stabilisation required	Extra stabilisation required	Direct irrigation can be done after liquid stream is separated, although nitrogen removal may be required
Odour	Fugitive odours related with cover leaks	Minor odour	Minor odour	Minor odour	Leakage or damage of roof prone leads to odours	High effective in odour control
Relative footprint	Large	Small	Small	Medium-Large	Small-Medium	Medium
Relative capital cost	Low	Medium	High	High	Medium - High	High

1.5 Operational factors in AD process

1.5.1 AD process

AD is a biological process that is carried out by microbial consortia in four sequential and distinct steps, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, as shown in Figure 4. These processes are carried out by syntrophic associations of bacterial consortia. The biogas production rates and composition during AD reflects the microbial processes, operational conditions and feedstock characteristics. The four main steps are discussed below.

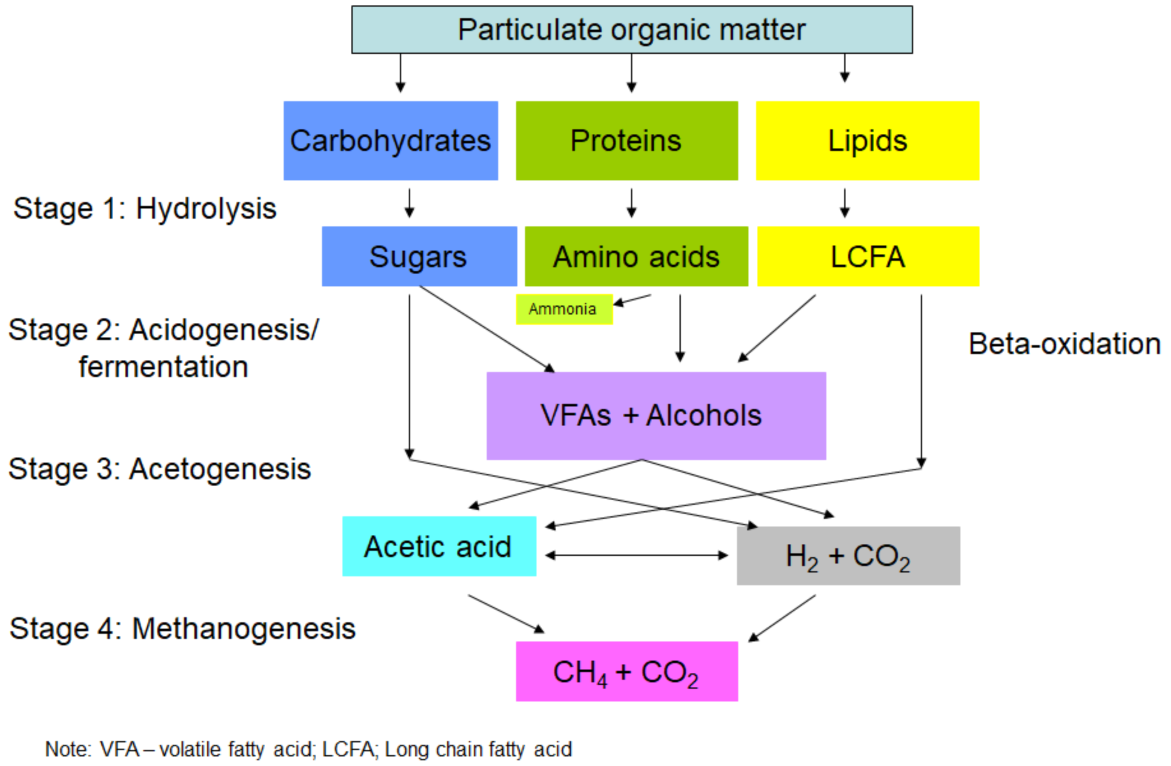


Figure 4. Biochemical process steps during the anaerobic degradation of complex organic matter

Hydrolysis: During the hydrolysis step of the AD process, macromolecules, such as carbohydrates, proteins, and lipids, are broken down to monosaccharides such as soluble sugars, amino acids and long chain fatty acids, and glycerol, respectively. This step is caried out under anaerobic conditions by extracellular enzymes excreted by hydrolytic and fermentative microbes. The bacteria involved in the hydrolysis include e.g., *Clostridium, Proteus vulgaris, Bacillus, Bacteriodes, Micrococcus, Staphylococcus*. These bacteria secrete hydrolytic enzymes cellulase, β-glucosidase and xylanase that are responsible for the degradation of polysaccharides, whilst protease degrades proteins, and lipase breaks down the lipids (Azman et al., 2015). Hydrolysis is known to be a rate-limiting step, especially for lignocellulosic substrates (Sträuber et al., 2012). This is mainly due to the recalcitrance of the lignocellulosic complex as lignin, along with cellulose and hemicellulose units, forms a rigid three-dimensional complex compound. This physical barrier protects the holocellulose (cellulose and hemi-cellulose) from the enzymatic attack. Therefore, the presence of microbes with augmented enzymatic activity is mandatory for an efficient AD, especially lignocellulosic feedstocks (Tsapekos, 2017).

Acidogenesis: In the second step of AD, simple sugars, amino acids, and long chain fatty acids (LCFA), the hydrolysed products obtained in the hydrolysis step, are further subjected to the fermentation step to produce acetic acid, volatile fatty acids (VFA), hydrogen (H_2), carbon dioxide (CO_2), and alcohols (Angelidaki et al., 2011). Facultative and obligate anaerobic bacteria (*Lactobacillus, Escherichia, Staphylococcus, Bacillus, Sarcina, Veillonella, Desulfobacter, Desulforomonas, Eubacterium limosum,* etc.) are involved in this step. Sugars and amino acids are the main substrates of this step. Acidogenic microorganisms produce high concentrations of H_2 and may cause inhibition of the production of acetate.

Acetogenesis: During acetogenesis, LCFAs are converted into acetate (by homoacetogens), H_2 and CO_2. At the same time, VFAs such as propionic acid, butyric acid, valeric acid and alcohols are also degraded into H_2 and acetic acid by acetogens. These microorganisms are slow growing and highly sensitive to environmental changes such as pH, organic loading etc. The products of acidogenesis are utilised by hydrogen producing bacteria, using CO_2 and hydrogen ions as electron acceptors (e.g. *Syntrophomonias wolfei*) through syntrophic oxidation reactions. Thus, the syntrophic relationship of acetogens with methanogens that allows the removal of H_2 during hydrogenotrophic methanogenesis (H_2 + CO_2 to CH_4), is mandatory to keep the hydrogen partial pressure low and ensure that the acetogenic reactor is energetically favourable (Treu et al., 2016).

Methanogenesis: In the methanogenesis step, acetotrophic and hydrogenotrophic methanogens (*Methanobacterium, Methanobrevibacerium, Methanoplanus, Methanospirillum, Methanosaeta, Methanosarcina*) convert acetate (by acetoclastic methanogens), H_2 and CO_2 (CO_2-reducing and H_2-oxidising methanogens) into methane (CH_4) and CO_2. Approximately 2/3 of methane is derived from acetoclastic methanogenesis and the remaining 1/3 is primarily produced from hydrogenotrophic methanogenesis (Treu et al., 2016). Alternatively, H_2 and CO_2 may be produced through syntrophic acetate oxidation (SAO) coupled with hydrogenotrophic methanogenesis (Wirth et al., 2012). Methanogens are strictly anaerobic and belong to the Archaea domain involving species belonging to orders of *Methanosarcinales, Methanobacteriales, Methanomicrobiales, Methanococcales, Methanopyrales*, and *Methanocellales* of the *Euryarchaeota* phylum.

1.5.2 Factors affecting anaerobic digestion

AD is a microbial process and thus bacterial consortia are influenced by operational parameters such as the substrate composition (e.g. biodegradability, carbon to nitrogen (C/N) ratio and water content), temperature, pH, mixing, trace elements additions, microbial culture (inoculum), organic loading rate (OLR), hydraulic retention time (HRT), volatile fatty acids (VFA), inhibitory substances, etc.

Feedstock composition: Biogas plant design and operation is designed based on the feedstock type and composition, the applied temperature and reactor configuration. The main characteristics of feedstocks include moisture content, total solids (TS), volatile solids (VS), particle size, pH, biodegradability, chemical oxygen demand (COD), biological oxygen demand (BOD), and C/N ratio. The concentration of VFAs and ammonia, both of which could cause toxicity and process failure at high concentrations, is largely dependent on feedstock characteristics and loading rates.

Methane yield varies significantly among different substrates based on their chemical composition. Table 5 shows the theoretical COD and the potential biogas yield from different types of substrates. The productivity differs due to varied biochemical structure and rate of its biodegradability. Feedstocks such as food waste, meat processing waste and the organic fraction of municipal solid waste (OF-MSW) are characterised with high moisture content and high biodegradability leading to high methane yields compared to other feedstocks such as lignocellulosic feedstocks. Agricultural crop residues, which are composed of lignocellulosic material, are characterised of poor degradability but high organic material. Hence, pretreatment of crop residues can improve their biodegradability and thereby improve their kinetics and methane yields.

Table 5. Theoretical methane yield of typical compounds (Source: Kougias and Angelidaki (2018))

Compounds	Chemical composition	COD/VS (g/g)	CH_4 yield[(a)] (mL CH_4/g VS)	CH_4 yield[(a)] (mL CH_4/g COD)	CH_4 content[(b)] (%)
Carbohydrate	$(C_6H_{10}O_5)_n$	1.19	417	350	50
Protein[(b)]	$C_5H_7NO_2$	1.42	497	350	50
Lipids	$C_{57}H_{104}O_6$	2.9	1,015	350	70
Ethanol	C_2H_6O	2.09	732	350	75
Acetate	$C_2H_4O_2$	1.07	375	350	50
Propionate	$C_3H_6O_2$	1.51	529	350	58
Iso-butyrate/Butyrate	$C_4H_8O_2$	1.82	637	350	63
Iso-valerate/Valerate	$C_5H_{10}O_2$	2.04	714	350	65

Notes: a) Methane yields are calculated at standard temperature and pressure conditions, i.e. 0°C and 1 atm. It is assumed that all the organic matter is converted to methane and carbon dioxide. b) CH_4 content by volume.

The reactor type is largely determined by the solids content (dry matter content) of the feed/influent to be treated. For wastewaters with less than 0.5 g/L total suspended solids (TSS), reactors with flocculent sludge can be used. For higher TSS content in the influent substrates (0.5 to 2–3 g TSS/L), immobilised granular sludge type reactors such as UASB or EGSB can be used. Finally, CSTRs are most commonly employed for slurries, such as manures, with TSS in the range of 30 to 70–80 g/L. For higher dry matter content substrates (>100 g/L), special types of rector configurations have been developed considering mixing and transportation of the solid influents.

The initial design of a biogas plant configuration is dependent on the selection of fermentation processes. Dry fermentation is characterised by AD of feedstock with high solids content ranging from 15% to 35% (or even higher for batch garage type reactors using solid waste). Wet fermentation is carried out when solids content is up to 10%, and thus the liquid content is comparatively higher (Stolze et al., 2015). Methane yield varies significantly among different substrates based on their chemical composition (Table 6).

pH: pH plays a pivotal role in the operation of biogas plants as the pH changes at different stages of the AD process (Figure 4). pH and temperature are interdependent. The optimum pH for stable process and to enhance biogas yield is between 6.5 and 7.5. In general, changes in the pH are correlated with other operational parameters. An accumulation of organic acids (acidification) will typically lower the pH, while an increased ammonia concentrations or CO_2 removal will lead to an increase in pH values. Some organic wastes, such as cattle manure, have high buffer capacity, and thus, are able to maintain a balanced system pH. A pH drop will occur only in cases that the concentration of VFA is remarkably high, exceeding a threshold level, and frequently the process is already severely influenced. Therefore, the VFA accumulation can be seen as a result of an already inhibited process and is not considered as the actual reason. pH changes when total VFA concentration exceeds 4 g/L and glucose is inhibited for fermentation (Siegert & Banks, 2005). The concentration of VFA and acetic acid should be monitored regularly and should be < 200 mg/L for maintaining optimum level of pH (Gashaw, 2016). The pH within the digester can be maintained within the range of 6.5- 7.5 by maintaining adequate buffering capacity and/or operating the reactors at optimal organic loading rate. A decrease in the pH in the reactor can be controlled by the addition of lime or recycling of digestate.

Table 6. Biogas production from selected substrates (Source: Kasinath et al. (2021))

Substrate	% DM	Biogas yield	Methane content [%][(a)]	Methane yield [m^3 CH_4/kg VS]
Pig manure	8–17	3.6–4.8 (m^3/kg DM)	70–80	0.25–0.35
Cow manure	8–16	0.2–0.3 (m^3/kg DM)	55–75	0.20–0.25
Chicken manure	25	0.35–0.8 (m^3/kg DM)	60–80	0.30–0.35
Sewage sludge	20	0.35–0.50 (m^3/kg DM)	65–70	0.30–0.40
Straw, grass	~80	0.35–0.40 (m^3/kg DM)/ 0.53–0.60 (Nm^3/kg VS)	54	0.20–0.25
Maize	20–48	0.25–0.40 (m^3/kg DM)/ 0.56–0.65 (Nm^3/kg VS)	52	0.25–0.45
Rye	33–46	0.67–0.68 (m^3/kg DM)/ 0.56–0.78 (Nm^3/kg VS)	53	–
Triticale	27–41	0.68–0.77 (m^3/kg DM)/ 0.59–0.62 (Nm^3/kg VS)	54	–
Sugar beet	19–22	0.39–0.76 (m^3/kg DM)	53	0.23–0.38
Rice straw hull (husks)	86	0.014–0.018 (m^3/kg DM)	–	0.20–0.25
Bagasse	33	0.165 (m^3/kg organic DM)	–	–
Wheat	88.9	0.65–0.7 (Nm^3/kg VS)	54	–

Notes: a) CH_4 content by volume.

Temperature: Temperature is an important factor for determining the efficiency of the AD process. Overall, AD processes can be operated under three temperature ranges: a) Thermophilic (50-60°C), b) Mesophilic (30-40°C) and c) Psychrophilic (below 25°C). However, commercial biogas plants are generally operated under mesophilic (35-37°C) and thermophilic (52-55°C) conditions as anaerobes are most active in the mesophilic and thermophilic ranges. Temperature has a profound influence on the microbial growth rates and biodegradation. Temperature fluctuations can cause process imbalances associated with the accumulation of VFAs and concomitant decreases in biogas production (Angelidaki et al., 2005). AD at higher temperature aids in increased biogas production but results in lower methane and increased CO_2 content in biogas leading to a lower heating value of the biogas.

Table 7 summarises the corresponding advantages and disadvantages at three different incubation temperatures for AD.

Table 7. Advantages and disadvantages of AD under mesophilic and thermophilic conditions

<table>
<tr><th>Technology</th><th>Operating temperature</th><th>Advantages</th><th>Disadvantages</th><th>Reference</th></tr>
<tr><td rowspan="2">Wet AD (feedstock with TS ≤ 15%)</td><td>Mesophilic (30-40°C)</td><td>• Used in landfills
• High internal rate of return
• Pre-treatment method to improve the efficiency of biogas process
• Low level of sludge generation
• Stable operation</td><td>• Less diffusion of the technology
• Large periods cultivations</td><td>(Moya et al., 2017)</td></tr>
<tr><td>Thermophilic (50-60°C)</td><td>• Production of hydrogen and methane, increased gas production
• High organic loading rate due to faster reaction rates
• Low operational and maintenance costs
• Resistance to foaming
• Improves the overall energy balance and lowers the initial investment costs due to smaller reactor size</td><td>• Less stable
• Instability problems
• Higher residual VFAs concentrations
• The process requires more energy to maintain the high thermal needs, which can achieve with good insulation and efficient heat exchangers</td><td>(Suhartini et al., 2014) (Ghasimi et al., 2015).</td></tr>
<tr><td rowspan="2">Dry AD (feedstock with TS ≥ 15%)</td><td>Mesophilic (30-40°C)</td><td>• Less accumulation of VFAs
• Lower specific growth rate of microorganisms (Fermentation reaction last between 30-35 days)
• Highest organic matter removal rate</td><td>• Lower reductions of cellulose and hemicelluloses
• A larger operating time to obtain methane and organic matter degradation (40 days)</td><td>(Angelidaki & Ellegaard, 2003)</td></tr>
<tr><td>Thermophilic (50-60°C)</td><td>• Greater reductions of cellulose and hemicelluloses
• Faster reaction rates that lead to shorter operating (lasting 15-21 days)
• Higher coefficient of methane production
• Inhibited due to ammonia with organic loading rate
• Improvement of the rheological properties of the digested sludge
• Produce lower amount and high-quality digestate with a high pathogen inactivation efficiency
• Improves the overall energy balance and lowers the initial investment costs due to smaller reactor size</td><td>• Accumulation of VFAs
• Prone to process instability due to high ammonia loads
• Higher specific growth rate of microorganisms
• The process requires more energy to maintain the high thermal needs, which can be achieved with good insulation and efficient heat exchangers</td><td>(Angelidaki & Ellegaard, 2003) (Rulkens, 2008), (Bouallagui et al., 2004) (Ghasimi et al., 2015), (Angelidaki & Ahring, 1994)</td></tr>
</table>

Carbon/nitrogen ratio: Carbon is necessary to provide a suitable substrate for digestion, whilst nitrogen at a certain concentration is also necessary for the protein formation for microorganisms. Thus, the C/N ratio plays an important role to determine the suitability of organic matter (OM) for AD. High C/N ratio indicates a low nitrogen content for microbial growth and as a result methanogens uptake the nitrogen for protein production thereby leading to carbon wastage which ultimately leads low biogas yield (Aworanti et al., 2017). In contrast, low C/N ratio can lead to accumulation of ammonia, nitrogen which may cause inhibition in the anaerobic digestion process (Aworanti et al., 2017). The optimum range of C/N for the proper functioning of biodigesters was found to be 20-35:1 (Kwietniewska & Tys, 2014). Higher temperatures require higher C/N ratios to lessen the possibility of ammonia inhibition (B. Wang et al., 2014). The optimal C/N ratio ensures better methane yields. Increasing C/N ratios can decrease methane concentrations in biogas (Hills, 1979).

The C/N ratio has also been a subject of attention as co-digestion of multiple substrates has become increasingly utilised. For example, poultry manures have been known to have a relatively low C/N ratio due to a high ammonia content, possibly due to urea; as such, carbon-rich substrates such as straw may be co-digested to prevent the possibility of ammonia inhibition (Callaghan et al., 2002; Wang et al., 2012). Temperature also plays an important role in an optimal C/N ratio. For instance, mesophilic and thermophilic AD co-digestion of dairy manure, chicken manure, and rice straw showed that an optimal methane potential and reduced ammonia inhibition were observed at C/N ratios of 25:1 for mesophilic conditions and 35:1 for thermophilic conditions (X. Wang et al., 2014).

Organic loading rate (OLR): The loading rate is referred to as the amount of organic material fed to a reactor per day in continuous digesters. The OLR is directly proportional to the amount of volatile solids fed to the reactor, which also influences the biogas yield. Overloading of a reactor may lead to process imbalances as quick hydrolysis and acidification of feed may cause a build-up of VFAs, which has the potential to inhibit the slow-growing methanogens, thus disrupting the stable AD process (Rincón et al., 2007). In wet AD processes, the OLR should be between 0.5-4 kg VS/m^3/day. For CSTRs, the OLR can be between 1-6 kg VS/m^3/day in high-rate anaerobic reactors. On the other hand, in high solids batch processes, the OLR can be only half of a single-stage wet AD process and thereby reduce the footprint (Verma, 2002). Rapid shocks in the loading rate can cause a shift in microbial populations, with methane yields returning to normal levels after developing a tolerance to higher loading rates. The improved reactor process performance and resistance to overloading after an initial instance of overloading is due to an increased diversification of methanogenic microorganisms (Chen et al., 2013).

Hydraulic retention time (HRT): HRT refers to the mean length of time that liquids remain in a reactor. HRT is influenced by the reactor technology, operational temperature and feedstock type and characteristics. HRT is related to the organic loading rate. A shorter HRT corresponds to a higher loading rate. As such, shorter HRTs are known to be associated with VFA build-up, which could lead to process failure due to VFA inhibition (Kim et al., 2013). Nevertheless, shorter HRTs allows for an increased process efficiency and decreased capital costs. However, longer HRTs are necessary for the optimal digestion of lignocellulosic feedstock (Shi et al., 2017). Generally, a mesophilic AD process is designed with a HRT of 15–30 days and a thermophilic AD process is operated at 14–21 days of HRT (Mao et al., 2015). However, after cost-benefit analyses of municipal wastes, the highest benefit is found for digesters operating on a low loading rate and high HRT (Meegoda et al., 2018). A too-short retention time might result in the bacteria being washed out of the digester at a lower rate than they are being multiplied thus leaving the digester at a standstill state and longer retention time would increase the volume of the reactor.

Table 8. Recommended hydraulic retention times (days) for commonly used reactor types and operational temperatures

Reactor type	Solids content (%)	Hydraulic retention time (d)	Temperature
Covered anaerobic lagoons	N/A	30-40	Ambient to psychrophilic
Plug flow	11-14	10-25	Mesophilic or thermophilic
Continuous stirred tank reactor	5-10	10-25	Mesophilic or thermophilic
Upflow anaerobic sludge blanket	<1	2-4	Mesophilic or thermophilic
Anaerobic fixed bed	<1	A few days	Mesophilic or thermophilic

Trace elements (TE): TEs are important co-factors of enzymes that take part in the methanogenesis and metabolic processes (see review (Choong et al., 2016)). Table 9 presents the important TEs and their roles in the AD process. TEs can be inhibitory, stimulatory or even toxic in the digestates depending on their concentration (Jagadabhi et al., 2019; Lallement et al., 2021). The role of co-factors in enzymes is to degrade larger organics to simple smaller soluble molecules (Bożym et al., 2015). The most important TEs involved in AD process are cobalt (Co), nickel (Ni), molybdenum (Mo), iron (Fe), zinc (Zn) and selenium (Se). In general, these TEs are supplied with feedstock and their deficiency during the AD process might lead to poor performance and methane yields (Jagadabhi et al., 2019; Lebuhn et al., 2008). The negative influence of TEs is determined by concentration in the substrate and pH of digestates (Jagadabhi et al., 2019). In general, mono-digestion of energy crops or food wastes were shown to produce high VFAs due to lack of sufficient amounts of TEs. Addition of TEs was shown to alleviate the inhibition. However, the concentration of TEs cannot exceed the threshold standards (Bożym et al., 2015). Toxic effects of trace metals is mostly attributed by replacing naturally occurring elements with enzyme prosthetic groups or due to disruption of enzyme function and restructure by bindings of trace metals with thiols and other groups on protein molecules (Chen et al., 2008).

Table 9. Important TEs and their function in AD process (Adapted after Schattauer et al. (2011))

Element	General function (microorganisms)
Chromium	Glucose metabolism
Cobalt	Metallic enzyme activator. Can inhibit metabolism
Copper	Metallic enzyme activator. Can inhibit metabolism. Reduce other metals toxicity
Iron	Redox property. Electron acceptor
Manganese	Activate enzymes of bacteria. Stabilises methane producing bacteria. Redox reaction, cofactor of various enzymes
Molybdenum	Inhibitor of sulphate reducing bacteria, cofactor of various enzymes
Nickel	Synthesis of coenzymes, cofactor of urease
Selenium	Hydrogenase in methane producing bacteria, cofactor and components of many proteins and metabolic compounds
Zinc	Metallic enzyme activator. Stimulates cell growth. Can exacerbate toxic effects of other metals and inhibit metabolism. Hydrogenase in methane producing bacteria

Table 10 presents the optimal concentration of TEs required for AD.

Table 10. Recommended concentration of TEs in AD process

Trace elements	(Takashima et al., 1990)	(Bischofsberger et al., 2005)	(Seyfried et al., 1990)	(Oechsner et al., 2010)	
	Concentration (mg/L)			Optimum value mg/kg TS	Desired range mg/kg TS
Chromium	--	0.005-50		--	
Cobalt	>0.00059-0.12	0.06	0.003-0.06	1.8	0.4-10
Copper				40	
Iron	>0.28-50.4		1-10	2,400	750-5,000
Manganese	360-4,800	0.005-50		300	100-5,000
Molybdenum	>0.00096-0.048	0.05	0.005-0.05	4	0.05-16
Nickel	0.0059-5	0.006	0.005-0.5	16	4-30
Selenium	0.079-0.79	0.008	0.008	0.5	0.05-4
Tungsten	0.018-18.3	--	0.1-0.4	0.6	0.1-30
Zinc	--	--	--	200	30-400

1.5.3 Optimisation strategies to enhance biogas production

Table 11 presents the challenges and approaches for improving the operational efficiency of biogas plants. Process stability and operational efficiency that can be achieved through optimal biomass pretreatment and biogas processes by improving substrate biodegradability, balancing nutrition, and optimising microbial physiology (Koniuszewska et al., 2020). On the other hand, biogas processing for heat and power generation and/or upgrading to biomethane for grid injection or vehicle fuel use, and digestate processing to enrich nutrient content for fertiliser production can generate revenue and improve the economic viability of biogas plants. Operational parameters such as OLR, HRT and temperature, are key factors that determine the operational efficiency of biogas production and the process stability of AD (Panigrahi & Dubey, 2019). Selection of an appropriate reactor technology and operating that reactor at optimal process conditions can improve the microbial growth and activity resulting in improved process stability and biogas yield (Cheng et al., 2018).

Table 11. Approaches and challenges to optimise the stages of the biogas production and use (Wu et al., 2021)

Domains	Approaches	Challenges to overcome
Feedstock processing	Chemical pretreatment (acid, alkali, oxidative) Physical pretreatment (mechanical, thermal, ultrasound) Biological pretreatment (fungal, enzymatic, bacterial, composting, ensiling) Combined pretreatment (steam explosion, thermochemical	High investment and energy demand. Possible formation of inhibitory by-products. Relatively low operational efficiency. Possible generation of toxic inhibitory compounds.
Biogas production	Anaerobic co-digestion	Improper mixing ratio resulting in process instability. Seasonal availability of different waste in different regions. Extra capital cost such as transportation.
	Effluent recirculation	Potential risk of ammonia inhibition.
	Manipulation of OLR, temperature, HRT and mixing	Risk of process instability. Adequate management and precise control.
	Bioaugmentation	Might not be effective under all operational conditions.
	NP additives (ZVI NPs, metallic and metal oxide NPs, and carbon-based NPs) Trace element (Co, Fe, Cu, Mn, Mo, Ni, Zn) supplementation	High investment. Strictly control the concentrations of additives Risk of process instability. Environmental and health-related complications.
Biogas processing	Physical technology (water scrubbing, pressure swing adsorption, absorption with amine solutions and organic solvents, membrane separation) Chemical technology (chemical hydrogenation/Sabatier reaction) Biological technology (photosynthetic reaction chemoautotrophic reaction)	High investment and energy demand. High risk of biological contamination. Need for large amount of reductant.
Digestate processing	Nutrient composition of the digestate Technologies for solids-liquid separation Storage and transport of digestate	Market for sale of digestate. Need investment and energy demand. Legislation on application of digestion. Regulation on use of digestate.

1.5.3.1 Biomass mono- and co-digestion

As mentioned in earlier section 1.5.1, bacterial consortia performing AD are easily influenced by operational parameters such as the substrate characteristics (e.g., biodegradability, C/N ratio, water content), temperature, pH, mixing ratios, additives and other factors (Mao et al., 2017). Thus, understanding feedstock types and characteristics are important prior to designing AD processes. In general, biomass with a high nutritional value will yield higher biogas yields if the AD process is operated at the optimum C/N value of 25:1. The feedstock solids content, moisture content and pH should be appropriate. The amount of possible toxic substances e.g., VFAs and ammonia should be limited.

In Table 12, the biogas production and methane yield from selected substrates are presented. Based on this data, pig manure and sewage sludge are the most profitable substrates for AD. Pig manure yields a high amount of methane; however, the ammonium content should be monitored due to its possible inhibition of biogas production. Thus, many studies have already focused on protein-, lipid-, and cellulose-rich substrates to evaluate their combined potential for biogas production and methane yields.

Co-digestion is the AD of two or more substrates together in the same reactor and is generally used to improve the process stability and methane yields. In the case of the co-digestion process, energy-rich organic materials such as lipids or proteins used are co-digested along with other co-substrates that are rich in macro- and micro-nutrients to supplement the AD process and to meet the species-specific nutrient requirements of microorganisms involved in degradation. Table 12 presents a suitable co-digestion process that can significantly improve the biogas yields compared with mono-digestion. However, the choice of the co-substrates should be dependent on their chemical composition, methane potential and their costs and/or availability. Thus, in certain cases, to increase methane production, locally available co-substrates can be pretreated prior to AD. It should be noted that each substrate shows different methane yields, which may vary because of the treatment used, the different mix ratios used and the characteristics of substrates.

Table 12. Methane yield from co-substrates (Source: Kasinath et al. (2021))

Co-substrates	Mixture ratio	Methane yield
Pig manure: corn stover	75:25 (VS basis)	0.21 (Nm^3/kg VS added), specific methane yield 0.22 (m^3/kg VS added)
Pig manure: wheat straw	75:25 (VS basis)	0.24 (Nm^3/kg VS added), specific methane yield – 0.26 (m^3/kg VS added)
Pig manure: potato waste	80:20 (VS basis)	0.30-0.33(Nm^3/kg VS added), specific methane yield – 0.32–0.35 (m^3/kg VS added)
OFMSW: vegetable oil	83:17 (DM basis)	0.70 ± 0.01 (Nm^3/kg VS added)
OFMSW: animal fat	83:17 (DM basis)	0.51 ± 0.02 (Nm^3/kg VS added)
OFMSW: cellulose	83:17 (DM basis)	0.25 ± 0.01 (Nm^3/kg VS added)
OFMSW: protein	83:17 (DM basis)	0.29 ± 0.01 (Nm^3/kg VS added)
Buffalo manure: maize silage	70:30 (VS basis)	0.36 ± 0.04 (Nm^3/kg VS added)
Cow manure: straw	70:30 (VS basis)	0.21 ± 0.02 (Nm^3/kg VS added), specific methane yield – 0.26 (m^3/kg VS added)
Cow manure: barley straw	80:20 (volume basis)	0.16 (Nm^3/kg VS added), specific methane yield – 0.17 (m^3/kg VS added)
Cow manure: fruit and vegetable waste	50:50 (DM basis)	0.45 (Nm^3/kg VS added), specific methane yield – 0.48 (m^3/kg VS added)
Cow manure and distillery wastewater	81:19 (wet mass basis)	specific methane yield – 0.12 (m^3/kg VS)
Cow manure: forage beet silage	80:20 (DM basis)	0.40 (Nm^3/kg VS added), specific methane yield – 0.42 (m^3/kg VS added)
Organic kitchen waste: cow manure	75:25 (VS basis)	0.15 (Nm^3/kg VS added)
Algal sludge: wastepaper	50:50 (VS basis)	1.17 ± 0.07 (Nm^3/kg VS added)
Food waste: cow manure	67:33 (VS basis)	0.39 (Nm^3/kg VS added)

Co-substrates	Mixture ratio	Methane yield
Dairy manure: potato waste	75:25 (VS basis)	0.23 (Nm^3/kg VS added)
Dairy manure: used oil	75:25 (VS basis)	0.36 (Nm^3/kg VS added)
Dairy manure: cheese whey	75:25 (VS basis)	0.25 (Nm^3/kg VS added)
Dairy manure: switchgrass	75:25 (VS basis)	0.21 (Nm^3/kg VS added)
Microalgae and wheat straw	80:20	0.29 ± 0.01 (m^3/kg VS) – pretreated
Microalgae and wheat straw	50:50	0.30 ± 0.01 (m^3/kg VS) – pretreated
Microalgae and wheat straw	0.89	0.31 ± 0.01 (m^3/kg VS) – pretreated
Fish waste and sisal pulp	50:50	0.31 (m^3/kg VS)
Fish waste and sisal pulp	33:67	0.62 (m^3/kg VS)
Fish waste and sisal pulp	25:75	0.48 (m^3/kg VS)
Fish waste and sisal pulp	0.89	0.44 (m^3/kg VS)
Sewage sludge (SS) and (fats, oils and grease – FOG)	40:60	specific methane yield – 0.49 (m^3/kg VS)
Waste-activated sludge (WAS) and FOG	34.5:65.5	specific methane yield – 0.75 (m^3/kg VS)
SS and grease trap waste	77:23	specific methane yield – 0.63 (m^3/kg VS)
Sewage sludge and food waste	60:40	specific methane yield – 0.18 (m^3/kg VS)

1.5.3.2 Biomass pretreatment

In general, hydrolysis, the first step of AD process, is considered as the rate-limiting process for many lignocellulosic feedstocks. Lignocellulosic feedstocks are mainly composed of cellulose, hemicellulose, and lignin. To make the cellulose and hemicellulose accessible to microbial degradation, pretreatment of lignocellulosic feedstock is essential. Thus, different pretreatment methods that can shorten the duration of the hydrolysis stage and at the same time increase the bioavailability of soluble substances for methanogenic bacteria have been tested and implemented. Biomass pretreatment is adapted according to the feedstock structure to help solubilise and hydrolyse complex organic matter (Zhen et al., 2017); however, this step can also be used to extract more biogas from the same amount of feedstock.

Different pretreatment technologies such as mechanical, thermal, chemical, and biological and/or their combination can be used (Carlsson et al., 2012; Cho et al., 2013; Deepanraj et al., 2017; González-Fernández et al., 2008; Li et al., 2012; Zhen et al., 2017). In general, all the pretreatment methods mentioned above can improve the feedstock accessibility for microorganisms by increasing the surface area, biomass porosity, decrystallisation and solubilisation (Carlsson et al., 2012). Biomass pretreatment efficiency can be assessed as an increase in the methane yield or biogas production. However, indirectly, the efficiency of pretreatment can also be evaluated through the increased solubilisation of cellulose, hemicellulose, and lignin. However, proper evaluation of the substrate pretreatment technology in AD through increased methane yields needs to be assessed against the costs and energy requirements of pre-treatments to justify its implementation. Table 13 presents the advantages and disadvantages of biomass pretreatment prior to AD.

Table 13. Advantages and disadvantages of biomass pretreatment prior to AD (Adapted from (Cesaro & Belgiorno, 2014; Montgomery & Bochmann, 2014; Seidl & Goulart, 2016))

Pretreatment type	Advantages	Disadvantages
Physical	Reduces process severity, water consumption and co-product formation when combined with thermochemical treatments	Increases power consumption
	Possibility to ensure anaerobic process stabilisation	Possible formation of compounds that are difficult to degrade, with an overall reduction in methane yields
	High efficiency in improving organic matter solubilisation	High energy consumption for thermal pretreatment
	Low capital costs	
Chemical	High efficiency in improving organic matter solubilisation and methane production from the anaerobic process	High capital cost
	Methane production up to 100% higher than that of the control	Possible formation of less biodegradable by-products. Limited application for wet digestion systems (TS < 10%)
	Strong oxidising power ensuring a short reaction time	High operating costs if large amounts of waste must be treated
	High solubilisation improvement	Possible formation of toxic compounds
	No addition of chemicals to the substrate in the ozonation method	Hazardous, toxic and corrosive chemicals require neutralisation, detoxification and chemical recovery steps, as well as anti-corrosive materials
Biological	No chemical addition	Long reaction time
	Low capital and operating cost requirements	Increase in methane production
	No restriction to specific AD technologies	Difficult to apply very complex substrates
	The pretreatment is selective, requires no chemical addition, uses low energy and has low severity	Enzymatic hydrolysis has a long incubation time, low production rate and high sensitivity to inhibition
		Loss of cell activity, requires highly controlled conditions

Pretreatment of sewage sludge from Wastewater Treatment Plants (WWTPs)

Dewatering and AD are the common methods for sewage sludge treatment. However, the complex microstructure of sewage sludge makes dewatering and hydrolysis ineffective. This is mainly due to the presence of extracellular polymeric substances (EPS), such as polysaccharides, proteins and DNA, which entrap water and have high viscosities (Y. Li et al., 2016).

Pretreatment of sewage sludge has shown to reduce its high resistance to both dewatering and biodegradation by rupturing the flock structure and bacterial cell walls and thereby releasing intercellular matter into the aqueous phase (Khanal et al., 2007). The increase in nutrients accessible to microbes enhances the digestion rates, reduces the retention time, and increases methane yields (Zhen et al., 2017). The effectiveness of the pretreatment is assessed through increased methane productivity and solubilisation of organic components. As biomass solubilisation and methane productivity are not always directly linked with methane production, it is suggested that the AD performance is evaluated as the improved methane yield, i.e., the volumetric methane production under standard conditions (m^3 CH_4/day) per unit of material fed, such as total solids (TS), volatile solids (VS), chemical oxygen demand (COD) or wet weight.

To date, thermal, thermal-alkaline, alkaline and electrochemical pre-treatments were reported as the most effective methods for solubilising sewage sludge, and thereby increasing methane yields significantly (F. Xu et al., 2018). However, other pretreatments such as ultrasonication, microwave and high-pressure homogenisation have also been tested and reported to improve methane yields.

In the early 1960s, the first commercially used thermal pretreatments such as "Porteous" and "Zimpro" were implemented for sludge pretreatment. Both these processes were typically operated between 200 and 250°C (Camacho et al., 2008). However, both these pretreatments generated odours and produced high strength reject water and caused extensive corrosion. Thus, these pretreatments were terminated in the early 1970s or modified to lower temperatures and subsequently used to enhance the dewaterability of sewage sludge (Camacho et al., 2008). During the 1980s, various combinations of thermal and chemical based (acid- and alkaline) pretreatment technologies were tested (e.g., Synox and Protox) but none of these pretreatment technologies were successful commercially due to high costs (Neyens & Baeyens, 2003). In the 1996 CambiTHP™ process, a combination of thermal hydrolysis and high pressure was introduced and showed to increase biogas production and digester loading (D. Ferraro, 2019). In this 3-stage Cambi process, sewage sludges (primary and secondary) at 16–18% solids are homogenised and preheated to 100°C in a pulper tank. Then, the sludge is fed to the second stage hydrolysis reactor operated at 180°C for 20–30 min and at pressure of 6 bars. The hydrolysed and sterilised sludge is then fed to the Flash tank, where a sudden pressure drops cause further substantial cell destruction and the release of dissolved organic matter. This solubilised sludge is then cooled to the desired AD temperature by heat exchangers, water is added and it is then pumped to the AD reactor (D. Ferraro, 2019). Another thermal hydrolysis process coupled with AD, BIOTHELYS®, was introduced by Veolia in 2006. In BIOTHELYS®, the dewatered sludge is first subjected to thermal hydrolysis (30 min) in batch phase with steam injected under a pressure of 6–8 bars and a temperature of approximately 165°C. A separate continuous process, called Exelys™, is operated at adjustable feed-rates. Both Veolia processes are advertised for thermal pretreatment of a wide range of industrial and municipal sludges, including those containing fats, oils and grease (FOG) (Carrère et al., 2010).

However, sewage sludge pretreatment by the CambiTHP™, BIOTHELYS® or Exelys™ processes had some technical issues, especially the requirement of qualified staff to operate the plant and the treatment of rejected water, as well as the presence of ammonia in the recycled stream and the cost efficiency of the process. Thus, the low-temperature (<100°C) thermal pretreatment of sewage sludge has been extensively studied to make it practically applicable for industrial AD, especially for smaller municipal WWTPs (Kasinath et al., 2019a, 2019b; Solé-Bundó et al., 2017). Application of low temperature thermal hydrolysis pretreatment (up to 55°C) prior to AD, under pending patent numbers P.430820 and P.430821, showed to obtain a final methane yield that reached 75% (Kasinath et al., 2019a, 2019b). However, the economic feasibility of each implemented process needs to be comprehensively evaluated along with the net energy gain including sewage sludge management prior to and after AD, as well as the final disposal.

Pretreatment of agricultural waste, food and municipal solid waste

The composition of agricultural and food waste, as well as the organic (biodegradable) fraction of municipal solid waste, differs significantly. For food waste, the use of a single pretreatment technology (mechanical, ultrasound, microwave, chemical, thermal and biological) was found to be ineffective. However, a combination of biological-physiochemical treatment was shown to enhance biogas production by 208% (Peng et al., 2014).

Pretreatment of agricultural waste is mainly dependent on the type of organic wastes, such as cattle, cows, pigs or poultry manure. Based on its availability, lignocellulosic biomass such as energy crops and crop residues are a highly prospective feedstock for biogas production. However, lignocellulosic biomass is mainly composed of cellulose, hemicelluloses and lignin and thus is resistant to microbial degradation and oxidation (Nizami et al., 2009). Thus, pretreatment of lignocellulosic biomass is often applied, generally combining elevated temperatures and chemical treatment, however thermal and other mechanical pretreatment methods are also considered. The pretreatment efficiency of the lignocellulosic biomass is dependent on the lignin content of the pretreated biomass (Fernandes et al., 2009).

Livestock manures also consists of lignocellulose fibres. Hence, pretreatment of manures is similar to that for energy crops/crop residues. However, the applied pretreatment conditions for livestock manure need to be milder than that of energy crops/crop residues otherwise formation of inhibitory compounds furfurals, 5-HMF and phenolics were noticed especially under high-temperature thermal pretreatment conditions. Sugar degradation by-products e.g., furfural formation, which may enhance the biogas production at a low concentration (appx. 1.4 g/L) were shown to be inhibiting methanogenic activity at higher concentrations (>2 g/L) (Ghasimi et al., 2015). Similarly, thermo-acid pretreatment, especially of lignocellulose/cellulose-rich biomass, might also generate furans and phenolic compounds, which may inhibit the microbial activity (Taherzadeh & Karimi, 2008; Vavouraki et al., 2013).

Table 14 presents the best possible substrate pretreatments to maximise the amount of the produced methane from various feedstocks.

Table 14. Substrate pretreatments to maximise the amount of methane produced

Feedstock	Pretreatment	Results	Reference
Dairy Cow manure	Thermochemical	Thermal-alkali pretreatment improved the methane potential compared to the test with a raw substrate. The methane potential was enhanced by 24% after pretreatment with 10% NaOH at 100°C for 5 min. The maximum production rate was improved under all studied conditions	(Passos et al., 2017)
Treated chicken manure and maize silage	Mechanical and co-fermentation	In the batch reactors, approximately 27% more methane was produced from treated chicken manure (T-CM) than from chicken manure. Co-digestion of T-CM with maize silage further increased the methane production, presumably due to the improved C/N	(Böjti et al., 2017)
Sugar beet pulp	Enzymatic hydrolysates and thermal pressure	The highest cumulative biogas productivity, i.e. 898.7 mL/g VS, was obtained from enzymatic hydrolysates of ground and thermal-pressure pretreated sugar beet pellets. This value was slightly higher compared to the biogas yield from enzymatic hydrolysates of thermal-pressure pretreated but not ground SBP (890.5 mL/g VS)	(Ziemiński & Kowalska-Wentel, 2017)
Sunflower stalks, corn stover	Chemical	Pretreatment with 4% H_2O_2 under a thermophilic condition enhanced the anaerobic biodegradability of sunflower stalks along with an increase in methane	(Monlau et al., 2012; Passos et al., 2017; Paudel et al., 2017)
Bamboo	Steam explosion	A 67% increase in the biodegradation rate	(Paudel et al., 2017)
Harvest residue and dairy cow manure (DCM)	Thermal pretreatment and anaerobic co-digestion	The highest biogas and methane yields (491.37 cm^3/g VS and 306.96 cm^3/g VS, respectively) were obtained after anaerobic co-digestion with DCM and thermally pretreated corn stover at 175°C for 30 min; these values were 24 and 23% higher than the biogas and methane yields (372.42 and 234.62 cm^3/g VS, respectively) of monodigested DCM. A 27% increase in methane production in comparison to the untreated variant.	(Kovačić et al., 2018)
Horse manure	Mechanical	Methane generation increased with the pretreatment time, and the increase in methane exceeded 64%	(Mönch-Tegeder et al., 2014)
Waste-activated sludge (WAS)	Ultrasonic	Methane yield increased by 22% at 160°C, while harsher pretreatment conditions led to a lower methane yield	(Wang et al., 1999)
Corn stover	Steam explosion	Methane yield increased by 22% at 160°C, while harsher pretreatment conditions led to a lower methane yield	(Lizasoain et al., 2017)

Among the substrates studied, the highest methane yield was observed with sewage sludge. In the livestock manure category, highest methane yields were observed with chicken manure when co-digested with thermally pretreated meadow silage grass. This was evident from the fact that the addition of thermal pretreated meadow silage grass to pig or mink manure resulted in a higher methane yield when compared to the same substrate without a co-substrate. In addition, thermal pretreatment and co-digestion with fruit/vegetable waste also resulted in higher methane yields when using cow manure as a substrate. This indicates that the addition of the fibre-rich co-substrate (meadow silage grass, fruit/vegetable waste) to manure facilitates in adjusting the C/N ratio and reducing toxicity due to ammonia. In the case of lignocellulosic biomass (meadow grass silage, sugar beet and straw), mechanical pretreatment seems to improve the methane yields through increased surface area and biomass porosity, and improves the accessibility of the biomass components to microorganisms. On the other hand, the addition of corn straw or no co-substrate resulted in the lowest methane yields. In the case of corn straw, soybean straw and sunflower stalk substrates with a manure co-substrate, thermal pretreatment slightly increased the methane yields. A similar pattern was also observed for the microalgal biomass. Thermochemically pretreated microalgal biomass co-digested with wheat straw resulted in a higher methane yield than from microalgal biomass without pretreatment or with no co-substrate addition.

As the biogas production process is very complicated and there are many possible features influencing the methane yield, the only way to gain full control over it is to use data exploration and machine learning techniques which are ideally suited to capturing complex and nonlinear data to enable the accurate prediction of biogas production as discussed elsewhere (De Clercq et al., 2019; Kasinath et al., 2021; Wang et al., 2021). High-quality datasets would allow a full optimisation of the biogas production process by identifying the most significant features or their combinations.

1.5.3.3 Feedstock type and its composition

The majority of full-scale biogas plants have been exposed to different feedstocks with varying chemical composition leading to process imbalances as mentioned in section 1.5.2. The concept of co-digestion is used worldwide to enhance biogas production. In Denmark, co-digestion led to the construction of 20 centralised and 60 farm-scale biogas plants. These biogas plants typically treat 70–80% manure slurry together with 20–30% industrial organic waste of various types (Angelidaki et al., 2005; Nielsen & Angelidaki, 2008a). On the other hand, the concept of on-farm co-digestion AD systems was introduced in Germany, with more than 4,000 biogas plants, to improve plant's economy. However, co-digestion of different substrates from various sources is extremely complex and improper feed composition may result in either successful process optimisation or failure (De Francisci et al., 2015; Gu et al., 2020).

The unavoidable variation in biomass composition may have a significant impact on AD process stability. Several studies have shown that the amounts of cellulose, hemicellulose, and lignin in lignocellulosic feedstock vary across different genotypes, maturity, and harvest times (Sawatdeenarunat et al., 2015). Similarly, seasonal variation in biochemical characteristics such as moisture content and VS for food waste, wastewaters from processing industries and organic fraction of municipal solid waste were reported (Zhang et al., 2007). Furthermore, pretreatments that are generally applied for some substrates also contribute to changes in feedstock characteristics. For instance, food waste and meat processing wastes generally contain high levels of lipids and are reported to generate large amounts of LCFAs during the AD process, especially under thermophilic conditions. Subsequently, the adsorption of LCFAs onto biomass can result in various operational problems such as flotation and clogging of gas and effluent lines. More importantly, high concentrations of LCFAs produced by lipids can cause acute toxic inhibition to the AD process. For this reason, removal of some lipids prior to AD is widely practised as an effective method of minimising the inhibitory effects of LCFAs and to improve the operational performance of biogas plants (Zhang et al., 2017).

The effect of pretreatment methods on the biochemical characteristics of feedstock is widely reported in the literature. Chemical pretreatments have shown to generate biomass with extreme pH values, which are not favourable for the subsequent AD process (Xiao et al., 2001). Similarly, melanoidins can be produced by reactions between amino acids and carbohydrates in organic waste at high temperatures (Panigrahi & Dubey, 2019). Phenolic compounds and furan derivatives can also be formed during the hydrothermal pre-treatment of lignocellulosic biomass at a high temperature (Lee & Park, 2020). All these refractory by-products inhibit the activity of methanogenic archaea and result in reduced methane yields. Therefore, monitoring of specific biochemical characteristics of feedstock after pretreatment is also strongly recommended.

1.5.3.4 Organic loading rate (OLR)

As defined earlier in Section 1.5.2, OLR is the amount of VS in the substrate added to a reactor per m^3 of active reactor per unit of time, normally expressed as kg COD/m^3/d or kg VS/m^3/d. The OLR is the most important design parameter in the operation of biogas plants. In general, biogas plants operated at a higher OLR will have a higher processing capacity and greater biogas production resulting in higher economic benefits (L. Li et al., 2015). Thus, most of the biogas plants are expected to operate close to the maximum organic load with a goal to increase overall efficiency. This is also the main concern as most of the commercial CSTR plants are operated at an OLR of less than 4 kg VS/m^3/d. This OLR is generally below the maximum value (Kleyböcker et al., 2014). Long-term monitoring of two full-scale biogas plants fed with energy crops showed that one of these biogas plants could be optimised by increasing the OLR to produce more biogas and electricity (Bauer et al., 2009). Similarly, the OLR of almost 80% of the biogas plants fed with organic waste and energy crops was found to be 2 kg VS/m^3/d, with the highest being 3.2 kg VS/m^3/d, leaving considerable room for optimisation (Sonnleitner, 2012). In contrast, most CSTRs studied in laboratories are usually operated at a relatively higher OLR of 5–10 kg VS/m^3/d.

The significant difference in operational OLR between lab-scale and full-scale CSTRs is as follows. Firstly, use of suboptimal OLR is often considered as advisable safety precaution. Interestingly, operating a biogas plant at maximum OLR and simultaneously maintaining its stability are two conflicting objectives (Nguyen et al., 2015). Increasing the operational OLR often results in inevitable disturbance and increased risk of process instability, especially for easily degradable organic materials such as food waste and vegetable waste (Sonnleitner, 2012). At high OLR, these organic materials can be degraded easily into VFAs. Considering the slow growth rates of methanogens with respect to acidogenic and acetogenic bacteria, a higher OLR will further aggravate the uncoupling of acetogenic bacteria and methanogens. This leads to the accumulation of massive amounts of VFAs, H_2, and CO_2, commonly known as "over-acidification." Therefore, most of the commercial CSTR plants operate with a relatively low OLR to reduce the risk of process imbalance. Also, CSTRs at the laboratory level involve additional measures such as recirculation of digestate, the addition of trace elements and acid-base control, which enhance biogas production and allow such reactors to achieve a relatively high operational OLR.

Investigations of sludge recirculation have led to the development of AnMBRs for treating high-strength organic waste (Cheng et al., 2018). In AnMBRs, the membrane will effectively prevent the washout of slow growing methanogens, therefore maintaining a higher sludge retention time (SRT). In the long term, AnMBRs are a promising reactor technology that could be used to optimise existing AD plants and meet the requirements of subsequent effluent quality and future capacity expansion.

1.5.3.5 Feeding frequency

Frequency of feeding within the day has shown to affect the process stability and methane yields (Bombardiere et al., 2007). Small amounts and frequent feeding, for several hours per day, is usually recommended as it can ease the effects of sudden organic loading shock and help to maintain stable process (Lv et al., 2014). For instance, the overall level of VFAs and pH remained more constant and moderate in reactors that were fed more frequently than in reactors fed less frequently (Lv et al., 2014). Similar findings were also reported during AD of food waste and waste-activated sludge in CSTR with a feeding frequency of once every 15 min and facilitated to operate at high OLR of 11.2 kg VS/m^3/d (HRT = 7.5 d) and 30.2 kg VS/m^3/d (HRT = 3 d) under mesophilic and thermophilic conditions, respectively (Li et al., 2017).

Foaming problems in a full-scale biogas plant have been resolved by adjusting the feeding frequency to one dosage every 20 min (Moeller et al., 2012). However, frequent feeding relies on automatic feeding procedures to feed the right amount of feed, which has a high energy cost. Farm-scale biogas plants located in rural areas may find it difficult to achieve this goal due to a lack of budget or skilled operators. For this reason, infrequent feeding with a long feeding interval of several days or even weeks has attracted increasing attention (Manser et al., 2015; Zealand et al., 2017). The optimisation and applicability of such feeding strategies depend on the OLR and, most importantly, the dosage of each feeding. Biochemical methane potential (BMP) testing is recommended to determine the maximum single dosage that exceeds the critical value for organic overload.

1.5.3.6 Temperature management and control

Temperature is the most important process parameter that affects the microbial growth, degradation kinetics and process stability during AD. As discussed in Section 1.5.1, the AD process can be classified as psychrophilic, mesophilic and thermophilic. The choice of an operating temperature is dependent on several factors such as the characteristics of the feedstock, energy demand, financial support and sanitisation requirements. Thus, the main concern during the design, construction and operation of any AD system should be the temperature management and control. Nowadays, with recent improvements in AD design and construction practices, techniques focusing on temperature management and control have become relatively mature and well-developed.

AD plants operated under psychrophilic conditions without active heating may lack economic returns due to slow microbial growth and low biogas yield. Heating and insulation are straightforward methods to achieve the optimal mesophilic (30–37°C) or thermophilic (50–55°C) temperature at the industrial level (Yao et al., 2020). It should be emphasised here that these two common AD process temperature ranges are more economically viable than any other temperature ranges. For instance, changing the operating temperature from a mild 47°C to a more favouring thermophilic range of 55°C improved the biogas production from 0.45 to 0.62 m^3/kg VS in a medium sized commercial biogas plant (Cavinato et al., 2010). Although the total operation cost for the biogas plant in the above study was increased to 719,885 €/yr, the gross energy capacity reached 8,789 MWh/yr with economic benefits of 1,933,473 €/yr (Cavinato et al., 2010).

Any operating temperatures outside the preferred mesophilic or thermophilic range disturbs the metabolic activity of the microbial community and affects the thermodynamics and kinetics of their biological processes. Moreover, if the rate of temperature change exceeds 1°C per day, process instability may be noticed, especially in biogas plants operating under thermophilic conditions. The thermophilic process is more highly sensitive to changes in temperature than mesophilic temperature. A small change of a few degrees can have a strong detrimental effect on the overall performance of thermophilic biogas plant. This is due to the reduction in microbial diversity at thermophilic temperatures and the optimal temperature range for thermophilic operation is relatively narrow (Kovalovszki et al., 2020). However, thermophilic AD is still the most popular process temperature for full-scale biogas plants due to the advantages of reduced HRT and a higher rate of methane generation. For instance, thermophilic AD is preferred in most full-scale and farm-scale Danish biogas plants performing co-digestion of manure and organic waste (Cavinato et al., 2010).

Unexpected temperature changes due to mechanical malfunctions may lead to subsequent process instabilities. For instance, a sudden rise in process temperature from 35°C to 38°C increased microbial cell lysis and the release of mucilage and storage substances such as extracellular polymer substances (EPS) (Moeller et al., 2012). These excreted EPS substances were shown to increase the viscosity of the reactor contents and thereby contribute to foam formation and in turn a decrease in biogas production. Unforeseen malfunctions that cannot be controlled, for example a power outage, can trigger a decrease in temperature and thereby affecting the methanogenic activity and VFA conversion rate (Wu et al., 2021). Accumulation of VFAs in turn inhibits the metabolic activity and growth of methanogens. Upon restoring the temperature, rapid hydrolysis of the substrate may lead to accumulation of a high concentration of VFAs and thereby, increasing the potential risk of process instability (Sun et al., 2019).

Seasonal variations in ambient temperature, incoming feed temperature from high temperature processing activities and the application of high temperature pre-treatment methods can also contribute to changes in the operational temperature. AD processes performed during warm summer days with a relatively high ambient temperature, may not match the temperature required by the biogas plants operating under mesophilic conditions. In general, the substrate originating from a high temperature process, pretreatment or stored in a buffer tank usually has a high temperature. If the feeding procedure continues without countermeasures such as heating exchange, a significant fluctuation in operating temperature can occur.

To avoid the mentioned long-term process failure caused by temperature fluctuation the use of remote alarm systems should be considered as primary requirement in all biogas plants (Wu et al., 2021). Thermocouples can be installed to monitor temperatures in digesters followed by remote alarm system allowing the system to be monitored and controlled (Iswanto et al., 2021). Furthermore, insulation, heating elements, heat exchanges, steam injections and water baths, can be used to control the temperature of the biogas plant according to each plant requirement (Dedgaonkar et al., 2018).

1.5.3.7 Hydraulic retention time

As mentioned in Section 1.5.2, HRT is the mean time that the substrates remain in the reactor. Shorter HRTs are used for AD process conducted under thermophilic conditions or with a high concentration of active inoculum. On the other hand, longer HRTs are required for AD process operated at lower temperatures and with lower levels of microbial activity. The common recommended HRTs for thermophilic and mesophilic conditions are approximately 14–21 and 15–30 days, respectively. However, relatively long HRT are used for full-scale biogas plants. For instance, many full-scale agricultural biogas plants in Germany usually have HRT longer than 50 days (Drosg, 2013). Although long HRTs can mitigate process instability, the initial capital cost for biogas plants is significantly higher due to the large investment required to build large reactors. On the contrary, operating at a shorter HRT can reduce the reactor volume and maximise treatment capacity, although the risk of hydraulic overload is increased (Ferrer et al., 2010). Operating biogas plants at relatively short HRT may lead to accumulation of VFAs as the time for the multiplication of anaerobic microorganisms is insufficient and may lead to "wash out" of methanogens along with the effluent removal (Ketheesan & Stuckey, 2015). Thus, operating at a lower HRT and a higher OLR may lead to high losses and lower methane yields.

Currently, most of the biogas plants use high strength organic waste e.g., food waste, agricultural waste, and manure. These feedstocks contain high solids content and dilution is necessary to avoid potential mixing problems and maintain a solids content suitable for wet AD systems, which represent the majority of existing biogas production facilities (Zamanzadeh et al., 2016). Dilution of high solids feedstock is generally carried out with fresh water, low solids feedstock, digestate, or process water obtained from the digestate after solid–liquid separation. However, the presence of a high volume of liquid in feedstock can lower its retention time. Thus, online measurement instruments or flow and level meters to measure the amount of liquid feedstock or digestate in storage tank is essential to quantify the liquid volume.

1.5.3.8 Mixing strategy exploration

The main purpose of mixing is to ensure homogeneity and good contact between the substrate and microorganisms in anaerobic reactors. In addition, mixing also facilitates the uniform distribution of temperature within the reactor and the transfer of gas from the liquid phase. In general, adequate mixing has been shown to improve the performance of biogas plants by preventing sedimentation/stratification, formation of floating layers of solids, localised overloading, dead zones, and foam formation (Kaparaju et al., 2008). Mixing strategies generally include mixing methods and modes. The commonly applied mixing methods include mechanical, hydraulic, pneumatic and gas mixing. The optimal mixing method varies depending on the reactor configuration, solids contents in the reactor and feasibility of the biogas plant (Kaparaju et al., 2008). Pneumatic mixing has shown to exacerbate foaming incidents due to the development of favourable conditions as the rising gas bubbles attach themselves to foaming agents and thereby accelerate the physical process consequently leading to potential risk of process instability (Chapman & Krugel, 2011). For full-scale biogas plants, insufficient mixing can promote the formation of a dead zone. Mechanical failures of mixers and sudden stops are shown to be the reason for process instability. The failure of a mixing and pumping device located in an influent pit has shown to stratify feed made of highly biodegradable and acidic cheese whey and corn silage leading to shock loading of VFAs and process instability (Labatut & Gooch, 2012).

Mixing should also be optimised to increase energy efficiency and process stability. Continuous and vigorous mixing has been reported to consume 29–54% of full-scale biogas plant energy consumption (Kowalczyk et al., 2013). Further, the distribution and structure of microbial communities in the reactors is influenced by mixing intensities and duration (Kaparaju et al., 2008). For instance, a higher proportion of *Bacteroides*, which can convert acetates and other simpler substrates to H_2 to facilitate hydrogenotrophic methanogenesis, was noticed in semi-continuously mixed reactors in comparison with that of continuously mixed reactor (Zhang et al., 2019). Continuous and vigorous mixing has also been shown to damage long filaments of *Methanosaeta concilii*, an archaeum responsible for methane formation. Finally, intensive mixing may also disrupt the spatial juxtaposition of syntrophic bacteria and their methanogenic partners leading to higher levels of acetate and propionate in reactors with vigorous mixing compared to gentle or minimal mixing (Kaparaju et al., 2008; Stroot et al., 2001). However, a change in mixing mode from vigorous to gentle has shown to consume propionate immediately as the syntrophic relationship among microbial organisms was restored. Consequently, minimal (10-20 min) intermittent mixing (once in every 60 min) appears to be the optimal strategy for reducing energy consumption and maintaining process stability.

The ideal mixing strategy varies and is mainly dependent on the feedstock characteristics, the mixing method, and reactor type (Yao et al., 2020). Optimisation of the ideal mixing strategy for a specific biogas plant remains a challenge in the design of energy-efficient AD systems. Use of computational fluid dynamics (CFD) can allow optimisation of the mixing duration and energy consumption for achieving a more energy-efficient AD process with a higher biogas yield and net energy output. CFD simulation results for a full-scale biogas plant showed that mixing at 3–5 min on and 25–30 min off was sufficient, while mixing for long periods was ineffective in preventing dead zones formation. In addition, the use of hydro-mixers rather than slowly rotating stirrers was recommended for highly biodegradable material with high solids contents (Nsair et al., 2019). The overall specific yield in the above study was increased by 22% and energy consumption by the stirrers was decreased by 14%. Therefore, CFD-based techniques should be employed to optimise the design and operation of mixing strategies once the basic information regarding reactor design, mixing methods, the rheological properties of the digestate, and the characteristics of the substrate were obtained.

1.5.4 General operational status and performance of commercial biogas plants

For full-scale commercial biogas production, stable and consistent quantities of desired biogas quality should be delivered. Further, the AD process must be designed to operate with low input requirements and reduced internal energy consumption. For instance, reactor operational parameters such as OLR and HRT are designed based on the characteristics of the substrate which will then influence the initial capital investment and subsequent revenue. However, operational and maintenance costs are largely dependent on operational parameters such as reactor heating, adjustment to attain a proper feeding ratio of substrate, reactor mixing, pumping rate, and feeding frequency.

Some of the process instability parameters at industrial biogas plants worldwide are presented in Appendix A. Overall, the malfunction of some of the common equipment such as pumps and mixing devices are reported to cause process instability because of inadequate or faulty operating procedures such as overloading, changes in feeding composition, fluctuation in temperature and sub-optimal HRT. In general, AD process instability occurs when the balance between the production and consumption of intermediate products such as VFAs is upset (Li et al., 2014). The sensitivity of different members of the microbial community to changes in operational parameters can disrupt the balance leading to unstable AD processes or complete process failure, with severe financial loses. For instance, poor AD performance and system failure in a biogas plant in New York State resulted in the plant producing less than 60% of its electrical energy potential (Labatut et al., 2014).

Operating a biogas plant at its optimal process conditions should be the priority however most full-scale biogas plants are often operated under suboptimal conditions. For example, some plants operate at a lower OLR or longer HRT to avoid process instability. If a 500 kW electricity equivalent biogas plant is operated under suboptimal conditions, this can cause a 10% reduction in biogas yield, resulting in an 11% loss of annual revenue from electricity sales (Wiese & Haeck, 2006). Similarly, sub-optimal operation of a biogas plant in Denmark digesting manure and organic waste, resulted in up to 30% of the biogas potential remained in the digestate (Nielsen & Angelidaki, 2008a).

Thus, there remains significant potential for improving the overall performance of biogas plants through process optimisation. The focus of the industry is to optimise the AD process with the goal of improving the efficiency of existing biogas plants. Therefore, the biogas industry in Australia should focus on both process stability and process optimisation as both these activities are closely related to the configuration of operational parameters.

1.5.4.1 AD process monitoring

The main objective of process monitoring is to stabilise the AD process and maximise methane production. The most important parameters for process monitoring and control can be classified as those characterising the AD process, and early indicators of process imbalance.

Appendix B summarised the parameters which can potentially be used for characterising AD process at full-scale biogas plants, and guidelines for each process parameter for a CSTR under mesophilic conditions.

1.6 Biogas utilisation

Raw biogas may contain trace amounts of numerous gases such as hydrogen sulphide, water vapour, ammonia, oxygen, and siloxane depending on the types of feedstock and the digestion process (Table 15). For example, trace levels of oxygen and siloxane are frequently detected in landfill gas but are not expected from biogas generated from well controlled AD. On other hand, biogas from wastewater sludge treatment tends to have an elevated H_2S concentration at round 1,000 ppm or even higher. These trace level impurities significantly add to the complexity of biomethane utilisation. When accounting for these trace gases, the composition of raw biogas differs substantially from that of fossil gas (Table 15), causing regulatory and financial uncertainties. Although they occur at a very low concentration, the removal of some of impurities such as siloxane can be expensive and technologically challenging.

Table 15. Typical composition of biogas from AD, landfill gas, and fossil gas (Awe et al., 2017; ERA WA, 2007)

Parameters	Unit	Biogas from AD	Landfill gas	Dampier to Bunbury natural gas pipeline - Australia
Lower heating value	MJ/Nm³	23	16	37
Maximum Higher heating value	MJ/Nm³	-	-	42
Density	kg/Nm³	1.1	1.3	-
Relative density	-	0.9	1.1	-
Wobbe index, upper	MJ/Nm³	27	18	51
Wobbe index, lower	MJ/Nm³	-	-	46.5
Methane (CH_4)	vol%	60-70	35-65	-
Heavy hydrocarbons Water	vol%	0	0	-
vapour (H_2O) Hydrogen	vol%	1-5	1-5	-
(H_2)	vol%	0	0	-
Carbon dioxide (CO_2)	vol%	30-40	15-40	4(*)
Nitrogen, range (N_2)	vol%	0-0.5	15	
Oxygen (O_2)	vol%	0	1	0.2(*)
Max inert gases	vol%	-	-	7
Max total sulphur – Unodourised gas	mg/m³	-	-	10
Max total sulphur – Odourised gas	mg/m³	-	-	20
Hydrogen sulphide (H_2S)	ppm	0-4,000	0-100	1.3(**)
Ammonia (NH_3)	ppm	100	5	-
Total chlorine as Cl^-	mg/m³	0-5	20-200	-
Maximum radioactive components	Bq/m³	-	-	600

(*) mol%

(**) mg/m³

In theory, biogas can be upgraded and utilised for a range of applications including heating, heat and electricity generation (cogeneration), and as raw ingredients for the chemical industry to produce methanol and nitrogen fertilisers. In practice, biogas upgrading to biomethane has only been implemented in a few countries for transport fuel and gas pipeline network injection. A notable example is Sweden, where more than half of the produced biogas is used as a transport fuel, supporting 44,000 light vehicles, 750 buses, and 2,200 trucks (CNG Europe, 2017). Germany is currently the world largest biogas producer. Thus, although a small portion of biogas is purified and used as transport fuel, it is enough to power about 96,000 light vehicles, 1,700 buses, and 200 trucks (CNG Europe, 2017). An emerging biomethane market as transport fuel is also evident in several countries such as Denmark, France, Switzerland, and South Korea (Figure 5).

Australia is significantly behind European countries in terms of high value biogas utilisation. Figure 5 shows that about 50% of the produced biogas is unutilised and flared to avoid fugitive methane emissions.

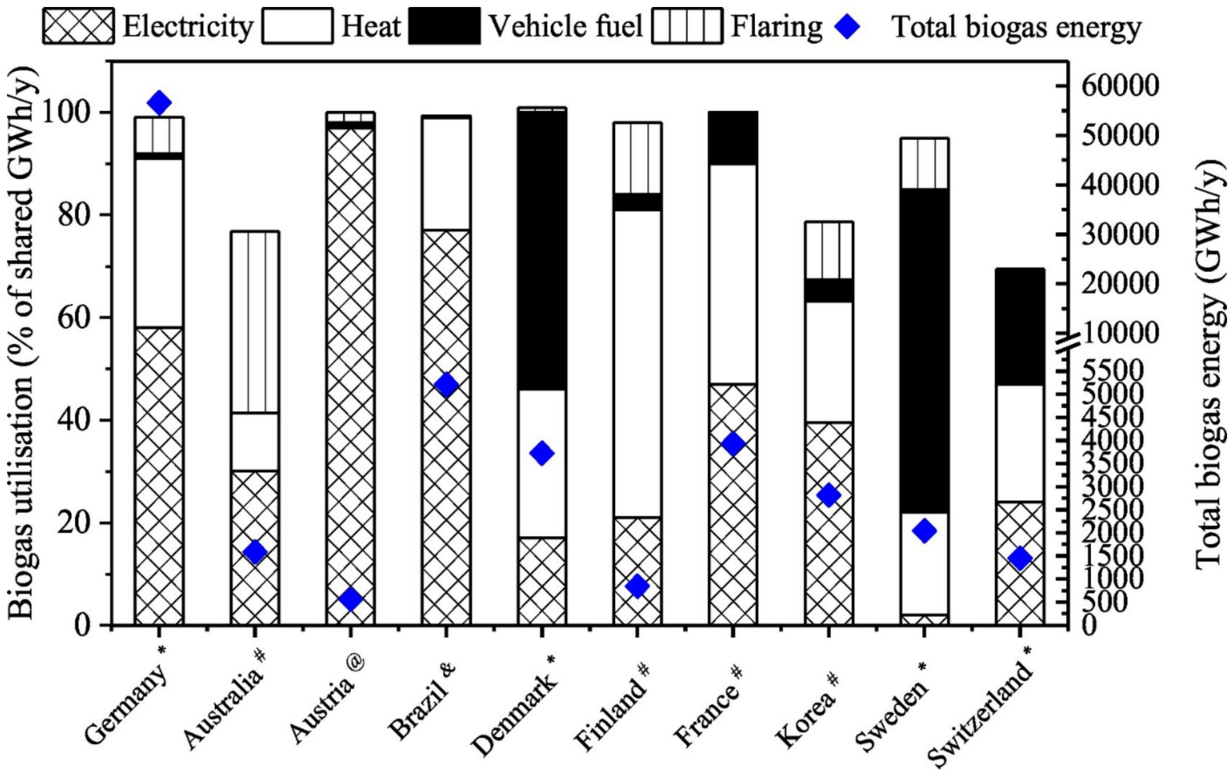


Figure 5. Major biogas usage (i.e. % of shared GWh/yr) in selected countries and total energy from biogas. The symbol *, #, &, @ indicated data source from 2018, 2017, 2016, and 2013, respectively (Source: Nguyen et al. (2021)).

Biomethane injection into the current gas pipeline network presents the most significant opportunity to scale up the biogas market. Liquefied biomethane (Bio-LNG) and compressed biomethane (Bio-CNG), are also possible alternatives as they allow for cost-effective transport of biomethane for off-site consumption. Bio-LNG and Bio-CNG can also be gasified at a hub for grid injection. Thus, the process of liquefying or compressing biomethane is often called 'virtual grid injection'. Most European countries and California have established standards for regulating the quality of biomethane for grid injection as can be seen in Table 16. Table 16 also shows the current quality requirement of fossil gas in Australian gas grid specified by the Australian Energy Market Operator (AEMO). The AEMO standards are for fossil gas quality in the network rather than biomethane injection. Therefore, the AEMO standards are silent on the limit of most biogas impurities (Table 16).

Due to limited grid injection experience, even in Germany and other European countries, the current standards for grid injection are expected to be conservative. California has one of the least conservative grid injection standards reflecting strong regulatory support to renewable biomethane. However, siloxane content in biomethane is not regulated in Europe whereas California has set a very stringent limit of 0.1 ppm. This is because there is no or very little landfill gas in Europe as a result of limited landfilling applications and successful organic waste diversion from landfill. By contrast, California has landfill gas potential similar to that of Australia. As discussed above, siloxane contamination occurs frequently in landfill gas but not in biogas from engineering anaerobic digestion. Given the similarity between Australia and California, a limit on siloxane is expected in the future biomethane standards in Australia.

Table 16. Examples of grid injection standards around the world (Source: (Australian Energy Market Operator, 2017; Muñoz et al., 2015))

Parameters	Unit	Germany	Sweden	France	California	Australia
Wobbe index	MJ/Nm^3	46.1-56.5	44.7-46.4	48.2-56.5	47.6-51.6	46.0-52.0
Methane content		n/a	97	86	n/a	n/a
CO_2	vol%	6	3	2.5	3	n/a
H_2	vol%	5	0.5	6	n/a	n/a
O_2	vol%	3	1	0.01	0.2	0.2
H_2S	mg/m^3	5	15.2	5	88	5.7
Total sulphur	mg/m^3	30	23	30	265	50
Mercaptans	mg/m^3	15	n/a	6	106	5
NH_3	ppm	20	20	3	10	n/a
Siloxanes	ppm	n/a	n/a	n/a	0.1	n/a
Halogenated compounds	mg/m^3	1	1	1	n/a	n/a

1.6.1 Biogas upgrading technology

Biogas upgrading is the process of separating methane from the carbon dioxide and other gases (Nguyen et al., 2021). The purified biogas (with 85-100% methane content) is called 'biomethane' or 'renewable natural gas'. Biogas upgrading increases the calorific energy value of the gas. For example, the calorific value (i.e. Wobbe index) of biogas with 70% methane content is 21.5 MJ/Nm^3 whereas that of biomethane is 35.8 MJ/Nm^3. Biogas upgrading removes the impurity gases (CO_2, H_2S) to protect the downstream utilisation.

Biogas upgrading technology can be applied to AD, wastewater treatment facilities, and landfill sites (Nguyen et al., 2021). The biomethane market has gained significant momentum in recent years. The number of new biogas upgrading plants is increasing worldwide (Table 7). Germany, United Kingdom, and Sweden have the largest markets for biomethane in the world. As of 2019, Germany has 203 biogas-upgrading plants are in operation, providing 389 GWh of biomethane (i.e. equivalent to 20.5% of the whole amount of fossil gas) as a vehicle fuel. In 2018, Germany also achieved 255 biomethane filling stations. In UK, the number of biogas upgrading plants more than doubled from the period of 2014 to 2016 along with an 800% surge in demand for biomethane since 2017. The UK is expected to use biomethane as a major source of their future gas supply. In Sweden, 90% of produced biogas is upgraded to biomethane for transportation.

Biogas upgrading technologies are already available at commercial scale. They include scrubbing (i.e. water, organic solvent, and chemical scrubbing), pressure swing adsorption, membrane separation, and cryogenic technology. Amongst these technologies, as of 2019, water scrubbing was the most widely applied technology due to low capital and operation cost (Table 18). However, the number of new water scrubbing plants has been on a lower growth rate than membrane separation (Figure 6). Membrane separation has emerged as the dominant technology for biogas upgrading with new installations doubling in number from 2015 to 2019. Key benefit of membrane separation includes a modular and compact design with less moving parts and less methane losses (below 2%). The compact design also allows membrane technology to fit different scales of operation. The first Australian biogas upgrading plant also uses membrane separation technology. Conversely, chemical scrubbing, pressure swing adsorption, organic chemical scrubbing and cryogenic technologies have high CapEx and OpEx, thus fewer new installations.

Table 17. Number of known biogas upgrading plants in selected countries around the world (Source: (*Nguyen et al., 2021*)).

Country	2014	2016		2019	
	Number of plants	Number of plants	Plants capacity (Nm^3/h Raw gas)	Number of plants	Plants capacity (Nm^3/h Raw gas)
Australia	0	0	n/a	0	n/a
France	8	30	7,935	47	10,755
Denmark	12	32	18,650	34	16,850
United Kingdom	37	85	83,200	96	69,266
Italy	5	7	n/a	8	0
Finland	9	12	3,221	17	3,231
Switzerland	24	31	7,962	45	12,430
Netherlands	21	26	17,910	53	29,385
Germany	178	194	220,311	203	230,434
Austria	14	15	5,790	13	5,630
Sweden	59	63	40,880	69	41,815
South Korea	n/a	n/a	5,953	10	5,953
Japan	n/a	6	2,400	6	2,400
USA	n/a	n/a	n/a	50	90,000

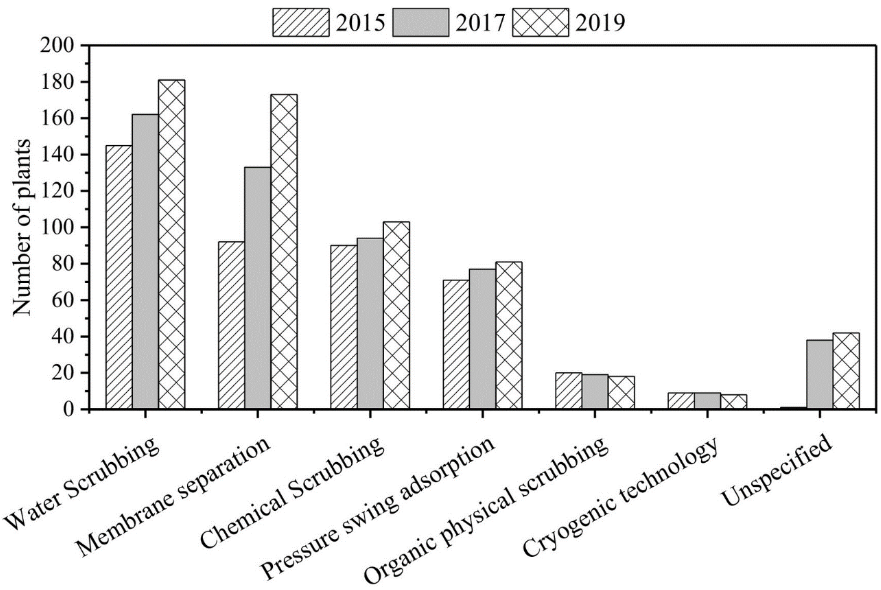


Figure 6. Distribution of biogas upgrading technologies amongst full-scale plants up to 2019 (Source: (Nguyen et al., 2021)).

Table 18. Energy consumption, methane loss, CapEx and OpEx of biogas upgrade technologies

Technologies	Biomethane quality (CH_4 %)	Energy consumption (kWh/Nm^3)	Methane loss (vol %)	Cost for 1,000 Nm^3/h plant*	
				CapEx (million $AUD	OpEx ($AUD/year)
Water scrubbing	95–98	0.2–0.5	0.5–5	1.5	23,000
Organic physical scrubbing	93–98	0.1–0.33	1–4	1.5	58,000
Chemical scrubbing	<98	0.05–0.18	0.5	3	88,000
Pressure swing adsorption	<98	0.16–0.43	1.5–2.5	2.5	84,000
Membrane separation	90–99	0.18–0.35	0.5–2	4	35,000
Cryogenic	99	0.18–0.25	0.1	n/a	n/a

* Exchange rate is 1.50 $AUD = 1 Euro

1.6.2 Grid injection

After upgrading biogas, the biomethane can be injected into the gas via a grid connection unit or a gas transportation container. In addition to gas quality, other considerations for safe and reliable grid injection include pressure and volume capacity. The pressure in a gas network is 4-12 bar and the transportation container is 200-300 bar. The gas transmission pipeline pressure is 4-60 bar, depending on the types of line. To ensure grid stability, methane injection must be controlled by the network owner through a grid connection or remote automated flow (RAF) unit. Basic components of a RAF unit are illustrated in Figure 7.

Biomethane injection into the gas pipeline network is an emerging practice in Europe and to a lesser extent California. As of 2015, there were 340 biomethane plants with grid injection (about 75% of all biomethane plants at the time) in Europe (Scarlat et al., 2018). However, the annual contribution of renewable biomethane to the grid was 1.5 million m^3, which is insignificant compared to the total biomethane production of 1.2 billion m^3 in the same year (Scarlat et al., 2018). There were also 697 filling stations in Europe to support their biomethane fleets (Scarlat et al., 2018). In Europe, biomethane injection to the grid is expected to significantly increase over the next few years due to fossil gas shortages and a decrease in the cost of biogas upgrade and injection technology. In 2018, the US EPA estimated that the infrastructure cost of biomethane injection is about $1.5 million per injection point. With mass production and standardisation of biomethane injection equipment such as the RAF unit in Figure 7, the cost of biomethane injection is expected to fall rapidly.

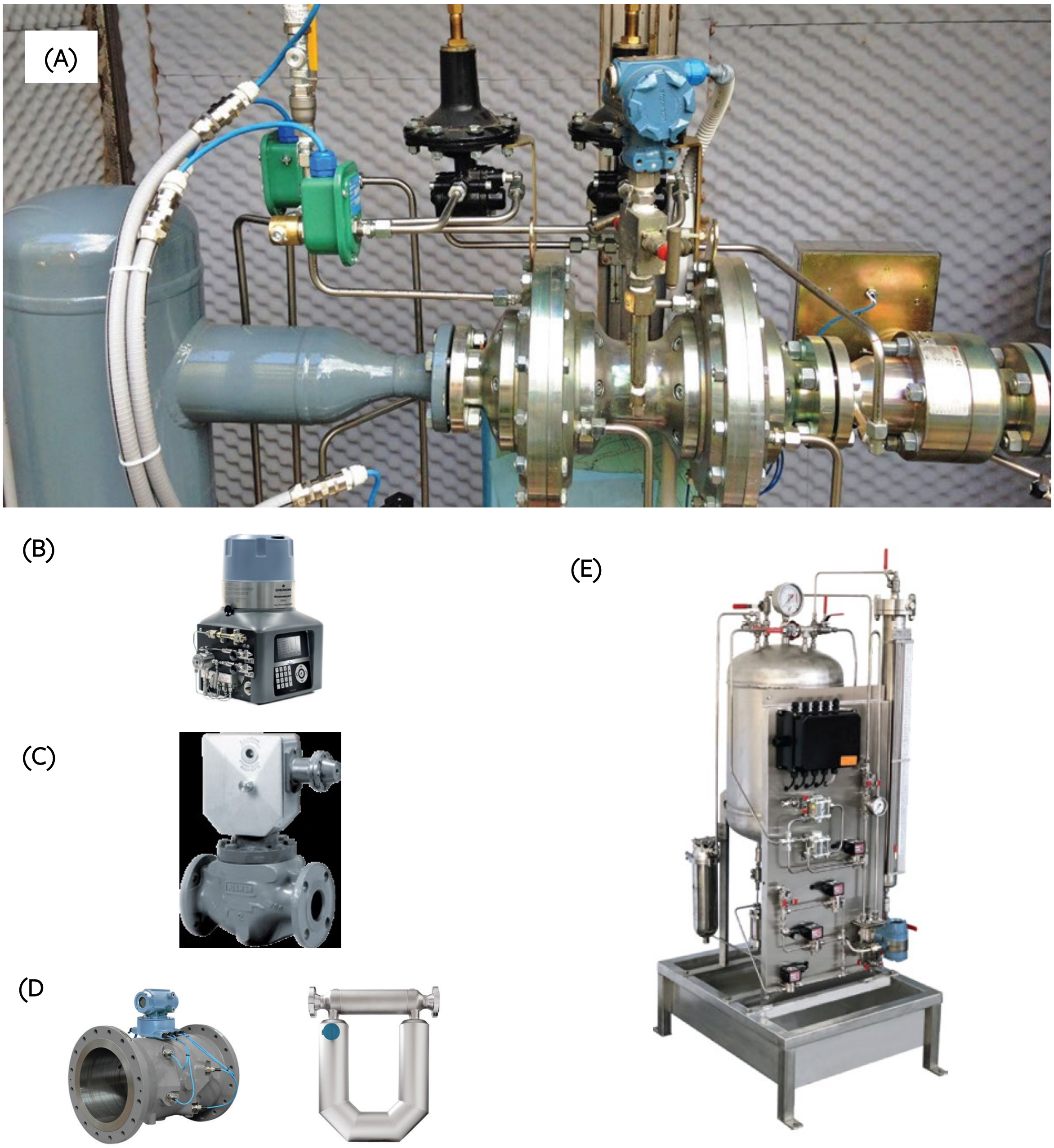


Figure 7. (A) Example of a RAF unit commercially available from Emerson and key components: (B) In-line gas chromatograph for gas analysis, (C) Pressure regulator, (D) Remote automated valve, and (E) Odourant injection unit.

1.6.3 Power to synthetic methane

Producing synthetic methane from surplus renewable electricity is an emerging technology for large scale energy storage (Hidalgo & Martín-Marroquín, 2020; Yilmaz et al., 2022). Power-to-Gas (P2G) is the concept of producing hydrogen for a subsequent reaction with CO_2 to produce methane. In the P2G process, hydrogen is produced by electrolysis using surplus electricity that is otherwise wasted. The reaction between H_2 and CO_2 can be achieved using a catalytic system or microbes, known as chemical and biological methanation, respectively.

As of 2022, there have been about 10 P2G demonstration projects using either chemical or biological methanation (Hidalgo & Martín-Marroquín, 2020). The current technology readiness level (TRL) of these P2G projects is above TRL6. Audi e-gas is the largest project (6 MW equivalent in energy storage capacity). Commissioned in 2013 at Werlte in the Emsland region of Germany, the Audi e-gas project is based on the catalytic methanation of pure hydrogen and carbon dioxide in a single isothermal fixed-bed reactor (Ghaib & Ben-Fares, 2018). According to Audi, the plant produces about 1,000 tonnes of renewable synthetic methane per year (Ghaib & Ben-Fares, 2018). Another noteworthy example is the Jupiter 1000 project (www.jupiter1000.eu/english). Jupiter 1000 claims to be the first industrial project that integrates green hydrogen and carbon capture for producing 25 m^3/h of synthetic methane (equivalent to 1 MW energy storage capacity). The Jupiter 1000 project is expected to end by 2023.

1.7 Digestate and biosolids management

1.7.1 Digestate composition

Digestate from the AD process is a nutrient-rich product used as compost and organic fertiliser. The composition of digestate depends on the composition of substrates, inoculum, operating conditions of biogas plant (pH, temperature, organic loading rate (OLR), hydraulic retention time (HRT) and reactor configurations (without or with post digester)). In addition, pretreatment of the substrate can also affect the AD process and in turn the composition of the digestates (Mata-Alvarez et al., 2014; Monlau, Sambusiti, Ficara, et al., 2015; Tampio et al., 2016). In general, digestate shows a high variation of undigested organic matter with VS/TS ratio ranging from 39 to 85% (Teglia et al., 2011). For instance, operating biogas plant at high OLR and short HRT of pre-treated biomass resulted in undigested organic matter of up to 35% in the digestates (Tampio et al., 2016). Digestate composition of different AD processes from the literature are presented in Appendix C.

The digestate resulting from the AD of agricultural waste may be rich in ammonium and other nutrients that are important for plant growth and therefore could be used as organic fertiliser (Adekunle & Okolie, 2015). Further, substrate type and composition, nutrient concentration and form (mainly N, P and K) in the digestate and nutrient requirements of the crop determine whether the digestate/liquid can be used as fertiliser.

Co-digestion with other suitable feedstocks can improve the digestate nutrient composition by diluting toxic compounds and at the same time improve the economics of the biogas plants by operating at higher organic loads, better buffering conditions favouring microbial synergy and growth, and improving biogas production (El-Mashad & Zhang, 2010). Anaerobic co-digestion with molasses was shown to improve nutrient balance and methane yields of cattle slurry, chicken manure, and activated sludge (De Vrieze et al., 2015). Similarly, green grass and yard waste were shown to be ideal feedstocks for fertiliser and soil amendment due to their high N, P and K content (Mostafazadeh-Fard et al., 2019).

Digestate originating from the co-digestion of manure and industrial organic waste can also be applied as fertilisers for crop production (K. Li et al., 2015). However, care should be taken about the concentration of ammonia in the digestate. Several studies have shown that the concentration of ammonia in the digestate depends on the type of substrate (especially manure) and the process conditions. For instance, anaerobic batch digestion of different manures at OLR 8 kg VS/m^3 showed the highest ammonia concentration in the digestate for chicken manure (1.07 g N/L) followed by pig manure (0.56 g N/L), dairy manure (0.45 g N/L) and rabbit manure (0.35 g N/L) (K. Li et al., 2015).

Digestates produced by the AD of clean feedstocks such as yard and agricultural waste do not pose any health risk associated with pathogenic bacteria that are noticed in the untreated digested residue of animal waste. Digestate from mesophilic anaerobic digestion of Sudan grass contained lower concentrations of N, P and K nutrients and heavy metals than those prescribed by the European Union (Voća et al., 2005). Mostafazadeh-Fard et al. (2019) demonstrated the feasibility of liquid organic fertiliser production through hydrolysis and acidification without production of biogas in a leachbed reactor. Results showed that the use of higher organic loads produced much higher concentrations of TN–TP–K nutrients in the leachate. The TN, TP, and K concentrations in the leachate were as high as 10,800, 2,315 and 7,400 mg/L, respectively, and N–P–K percentages of 1.08–0.23–0.74.

1.7.2 Technologies for solid-liquid separation of digestate

Digestate separation provides a storable solid digestate and liquid fraction that can be pumped through pipes across the fields, produces a nutrient-rich market product that can be exported, and reduces the volume of liquid for transportation (Lukehurst et al., 2010).

In recent years, local and regional transportation of raw digestate over more than 5–10 km has shown to exceed the costs of its fertiliser value (Kratzeisen et al., 2010) and consumes large amounts of fossil fuel (Rehl & Müller, 2011). Therefore, solid-liquid separation of raw digestate has been recommended to reduce the cost of digestate transportation for use (Delzeit & Kellner, 2013).

Solid-liquid separation of digestate is generally carried out by using either sieves, double circle bow sieve, sieve belt press, sieve drum press, press screw/auger separator, sieve centrifuge or decanter centrifuge (see e.g. (Burton & Turner, 2003). The most common solid–liquid separation technology used in full-scale biogas plants are screw presses, screening drum presses (vibrating screen) and centrifuges (Al Seadi et al., 2013). Use of precipitating agents such as aluminium sulphate (Al_2SO_4), ferric chloride ($FeCl_3$), ferric sulphate ($Fe_2(SO_4)_3$) and lime ($Ca(OH)_2$), flocculants or organic polymers (acrylamide) and functionalised chitosan have been shown to improve and/or facilitate solid-liquid separation (David et al., 2016; Drosg et al., 2015; Meixner et al., 2015).

Figure 8 shows the various types of separators used to process digestate as a function of their separation efficiency.

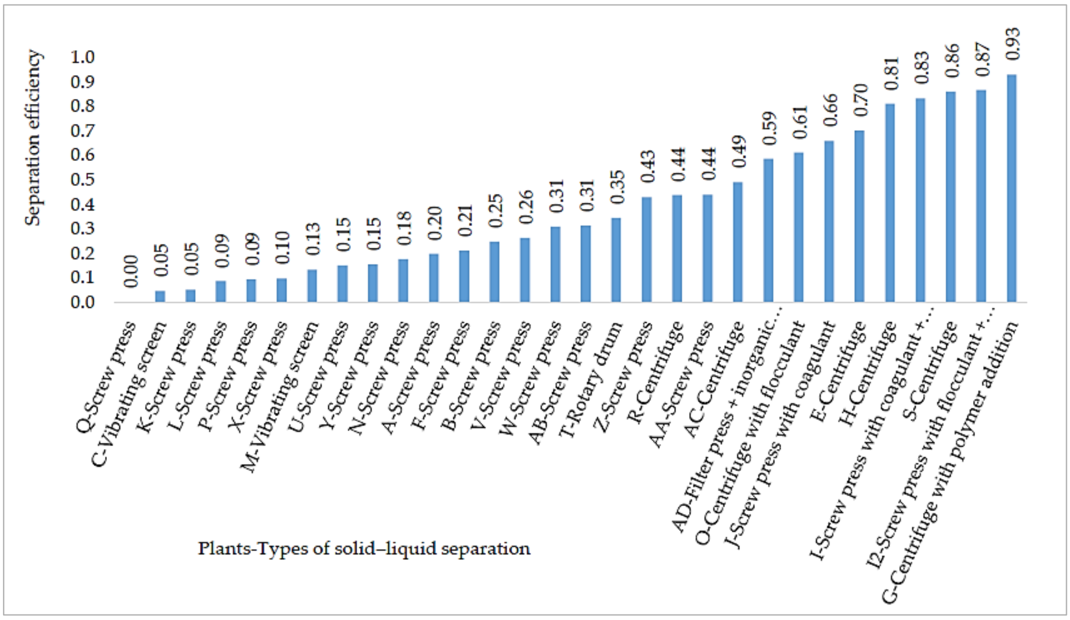


Figure 8. Separation efficiencies of various separators (Akhiar et al., 2021)

Screw press

Screw presses and other screen-based separators like belt presses and mesh screens, have a lower efficiency of solid separation, contrary to decanter centrifuge separation. A screw press is a large mechanical screen that is rotated using a rotatory screw at the centre. During the rotation the solid matter in the digestate is pressed against the screen while allowing the liquid and smaller particles (<1 mm) to pass through the screen. The liquid flows into the outer cylinder and is transferred into an outlet pipe. The solid fraction retained on the screen is pushed to the end of the separator and pressed against a scraper, where it exits. The separation efficiency can be varied by adjusting the mesh size and rotating speed.

Belt press

In a belt press filter, the digestate that is trapped between two belts in series is passed over and under several rollers at different diameters. Due to the increased application of pressure, the liquid is squeezed out and collected separately, while the solids travel across the complete length of the belts and are collected in a free drainage zone. Some advantages of the belt press are low staff requirements, low maintenance, immediate start up and shutdown and less noise during operation. The energy consumption for a belt press may reach up to 80 kWh/t of solid sludge.

Decanter centrifuge

Centrifuge separation works on the principle of generating a centrifugal force that collects the solid at the bottom and liquid in the centre. However, the most commonly used centrifuges in farms/small scale biogas plants are horizontal decanter centrifuges. The high-speed centrifugal motion allows the solids to collect in an inner wall containing dry matter and outer layer of liquid containing lower dry matter. The separation performance depends on the rotating speed, viscosity of the digestate and density of the particles. Generally, centrifuges separate most of the phosphorous content from the digestate in the solid fraction.

Table 19. Concentration of solids in solid and liquid fraction for all separators

Digestate fraction		Screw press	Belt press	Centrifuge
Liquid digestate	DM (%)	5.6	5.4	4.5
	Weight (tonnes)	106,000	88,000	93,000
Solid digestate	DM (%)	26	16.7	21
	Weight (tonnes)	18,700	36,000	31,000
Energy consumption		0.4–0.5 kWh/m³	1.5–2 kWh/m³	3–5 kWh/m³
Separation efficiency		0.936	0.938	0.948

From various studies, decanting centrifuges has been more efficient in the removal of total phosphorous and total solids content compared to screen-based separators. These results corroborate the separation efficiencies mentioned in Table 19. Møller et al. (2000) explained that nitrogen separation efficiency was higher in decanter centrifuges due to the centrifuge's capacity to separate even finer solids. The solid fraction usually consists of small trace quantities of organic nitrogen, while the liquid faction has inorganic dissolved ammoniacal nitrogen (NH_3-N).

Table 20. Distribution of the principal constituents after solid-liquid separation (adapted from Drosg et al. (2015))

Parameter	General range		Screw press		Centrifuge	
Mass	Liquid (%)	Solid (%)	Liquid (%)	Solid (%)	Liquid (%)	Solid (%)
Total Solids (TS)	14–52	48–86	52	48	14	86
Volatile solids (VS)	35–45	55–65	–	–	–	–
Ash	50–60	40–50	–	–	–	–
Total nitrogen (TN)	65–83	17–35	83	17	75	25
Ammonia–nitrogen (NH_4^+–N)	70–93	7–30	82	9.2	92.5	7.5
Phosphorus (P)	22–45	55–78	–	–	22	78
Potassium (K)	70–93	7–30	90	10	93	7
Carbon I	30–40	60–70	–	–	–	–

1.7.3 Solid fraction of digestate

The solid fraction of digestate is generally used as a nutrient source directly for crop cultivation and soil conditioner (Rehl & Müller, 2011) or after composting, as organic fertiliser (Ganesh et al., 2013). In many biogas plants, the solid fraction of digestate is dried either using a belt dryer, drum dryer, feed-and-turn dryer, fluidised bed dryer or solar drying system and even palletised to be sold as bio-fertilisers (Drosg et al., 2015) or solid fuel (Kratzeisen et al., 2010). Owing to the high organic fraction as well as high nutrient contents, new technologies have been proposed for solid digestate valorisation (Monlau, Sambusiti, Ficara, et al., 2015), such as production of biofuel in domestic furnaces (Pedrazzi et al., 2015), production of biochar (Monlau, Sambusiti, Antoniou, et al., 2015; Stefaniuk & Oleszczuk, 2015), post treatments (thermal, alkaline and enzymatic) for methane recovery (Kaparaju et al., 2002; Sambusiti et al., 2015) or bioethanol production. A study conducted by Cathcart et al. (2021) stated that production of digestate pellets was less expensive than briquettes for combustion to produce energy.

1.7.4 Liquid fraction of digestate

The chemical composition of the liquid fraction of digestate after solid–liquid separation is presented in Appendix D. In general, the liquid fraction accounts for 90–95% of the total mass of digestate (Zeng et al., 2016). TS and VS concentrations along with the VS/TS ratio are lower in the liquid fraction than raw digestate (Gioelli et al., 2011). In addition, the liquid fraction has a low residual methane potential (Gioelli et al., 2011) but high concentrations of COD concentrations (Ganesh et al., 2014; Ganesh et al., 2013; Xia & Murphy, 2016) of total nitrogen (TN) and ammonia nitrogen (NH_4-N) as well as nutrient (Xia & Murphy, 2016). The pH ranges from 7.5 to 9.4 and depends on the feedstock characteristics and biogas plant operation conditions. The TS and VS of the liquid fraction of digestate can range from 1.1 to 8% and from 0.5 to 4.8%, respectively. On the other hand, there is high variation in COD (0.3–17.6 g O_2/L), organic carbon (7.4–20.6 g C/L), NH_4^+-N concentration (0.37–5.1 g N/L) and C/N ratio (1.6–11.9). Similarly, a high variation in TN concentration ranging from 0.1 to 8.0 g N/L along with potassium (K) (0.1–5 g K/L) was also noted. On the other hand, total phosphorus (TP) and phosphate (PO_4^{3-}) concentrations range from 0.03 to 1.2 g P/L and from 0.01 to 0.3 g/L, respectively. However, little or no information is available on the full characterisation of the liquid fraction of digestate that is generated from co-digestion plants. Most published data was focused on nitrogen and phosphorus concentrations and their removal, recovery and/or reuse.

1.7.4.1 Technologies for nutrients recovery from liquid fraction of digestate

Nutrients recovery and reuse from the liquid fraction of digestate have been intensively studied and reported in the literature. Technologies and processes for nutrient removal/recovery and reuse are presented below.

Ammonia stripping

Ammonia stripping is considered as one of the most effective environmental technologies for nutrient recovery from liquid digestates (Sheets et al., 2015). During the ammonia stripping, NH_3 in liquid form is converted to NH_3 gas by injecting air or steam that contains no or little NH_3 into the liquid digestate (Sheets et al., 2015). The factors that affect the ammonia stripping process include pH, temperature, air/liquid ratio and pressure (Guštin & Marinšek-Logar, 2011; Sheets et al., 2015). Alkaline pH levels of 9–10.5 have been found to have the most effect on ammonia stripping followed by air flow rate and temperature (Guštin & Marinšek-Logar, 2011). Previously, continuous ammonia stripping from the liquid fraction of centrifuged pig slurry digestate showed up to 93% and 88% removal of ammonia and total nitrogen, respectively (Guštin & Marinšek-Logar, 2011). In a similar study, AD coupled with ex-situ ammonia stripping by using biogas as the stripping medium was shown to remove 48% of NH_4^+-N at ≥70°C and pH of 10 (Serna-Maza et al., 2015). Finally, ammonia stripping using $Ca(OH)_2$ at 12 g/L and pH >7 resulted in 90% of NH_4^+-N and 97% of soluble P removal in liquid fraction of digestate originating from pig manure (X. Li et al., 2016).

Vacuum evaporation

Vacuum evaporation is a physical process in which liquid digestate is boiled at a temperature lower than the typical boiling temperature at atmospheric conditions under negative pressure. Vacuum evaporation of the liquid fraction of digestate obtained after screw press of digestate originating from swine manure, corn silage and other biomasses showed that 1.7%, 1.9% and 1.5% of TS, VS and TKN, respectively, could be recovered in a two stage vacuum evaporation with acidification (Escudero et al., 2015). The above two-stage system removed 94% of mass containing 2.5% mass of TKN (Escudero et al., 2015). pH adjustment to 5 was necessary to prevent vaporisation of ammonia (Escudero et al., 2015). In a similar study, vacuum evaporation of the liquid fraction of digestate originating from pig manure at pH 6 was shown to recover 114% and 225% in NH_4^+-N and soluble phosphorus concentrations, respectively (X. Li et al., 2016).

Struvite recovery

Precipitation of magnesium, ammonium and phosphate ions to struvite ($MgNH_4PO_4{\cdot}6H_2O$) is seen as a promising method to recover magnesium, ammonium and phosphate in liquid fraction of digestate. Struvite formation is a simple, efficient and environmental sustainable technology (Escudero et al., 2015; Tao et al., 2016). Struvite precipitation depends on the source of PO_4^{3-}, Mg^{2+}, solids content, pH and $Mg{:}NH_4{:}PO_4$ molar ratio. However, high Ca^{2+} concentration, ionic strength, suspended solids, alkalinity and complex chemical composition can reduce the struvite precipitation efficiency (Tao et al., 2016). Previously, ammonia stripping followed by absorption of ammonia in H_2SO_4 acid to recover ammonium sulphate $(NH_4)_2SO_4$ was successfully demonstrated with no TS, VS, P and K (Tampio et al., 2016). In the above study, ammonia stripping (with H_2SO_4 acid scrubbing) combined with reverse osmosis recovered $(NH_4)_2SO_4$ and removed TS, VS, total nitrogen, NH_4-N, P and K from the liquid fraction of digestate (Tampio et al., 2016). Further, struvite precipitation can also be used for ammonium removal. For instance, 95% of the initial NH_4^+ concentration (2.5 g/L) was recovered with the addition of $Na_3PO_4{\cdot}12H_2O$ and $MgCl_2{\cdot}6H_2O$ at a molar ratio of 1:1:1 for $Mg{:}NH_4{:}PO_4$ without pH adjustment (Escudero et al., 2015).

Table 21. Economics of struvite production

Description	Cost (converted to A$/t)	Reference
Cost of producing 1 tonne of struvite	187	(Booker et al., 1999)
Suggested market value for struvite	1,175	(Booker et al., 1999)
Conservative estimate of struvite as “boutique” fertiliser	358	(Münch et al., 2001)
Suggested market value of struvite	265–442	(Münch & Barr, 2001)

Vacuum thermal stripping with acid absorption

Vacuum thermal stripping with acid absorption is a recent innovative technology that can recover ammonia at a higher flow rate in the recirculation line of a mesophilic anaerobic digester compared to thermal stripping with higher temperature (Ukwuani & Tao, 2016). Ammonia is stripped out and absorbed into an H_2SO_4 acid solution to form $(NH_4)_2SO_4$ crystals. In the above study, more than 95% of ammonia was stripped out of the liquid digestate at an optimum boiling point of 65°C and pressure of 25.1 kPa (Ukwuani & Tao, 2016).

Combined evaporation and reverse osmosis

The combination of evaporation and reverse osmosis for nutrients recovery was demonstrated to recover 99.7, 99.1, 100 and 100% of total nitrogen, NH_4^+-N, P and K, respectively (Tampio et al., 2016). In the same study, combination of ammonia stripping before evaporation and reverse osmosis was shown to recover 100% of total nitrogen, NH_4^+-N, P and K (Tampio et al., 2016).

1.7.5 Biosolids production and management in Australia

Biosolids are a product of the sewage sludge which normally contain up to 3% solids (ANZBP, 2022a) once it has undergone further treatment to reduce disease causing pathogens and volatile organic matter significantly. The stabilised biosolids product normally contains between 15% and 90% solids and is suitable for beneficial use. Biosolids are carefully treated and monitored, and they must be used in accordance with regulatory requirements.

During sewage treatment, microorganisms digest the sewage, completely breaking down the original organic solids that have been discharged into the sewerage system. The water content of the solids is then reduced, usually by passing through mechanical processes. The resultant product is biosolids. Biosolids comprise dead microorganisms, a small portion of active microorganisms, and inert solids such as sand that may enter the sewage system. The final quality of the biosolids produced depends on the quality of the sewage entering the treatment plant and the treatment process. Strict state and national guidelines in Australia and New Zealand specify the allowed uses of specific biosolids. Australian and New Zealand water industries use some of the most advanced wastewater treatment and biosolids production technology and quality assurance programs in the world to ensure the safe and sustainable management of biosolids.

Figure 9 and Figure 10 present the amount of biosolids generated and their end-use in Australia between 2010 and 2021. According to the Australian and New Zealand Biosolids Partnership (ANZBP), the total amount of biosolids produced was about 349,000 t TS/yr (ANZBP, 2022a). Biosolids production has decreased by 6% between 2019 and 2021. The weighted average solids content of dewatered biosolids in the 2021 was around 25%. Therefore, the total biosolids production in 2021 was equivalent to 1.4 Mt in dewatered form (also called wet tonnes).

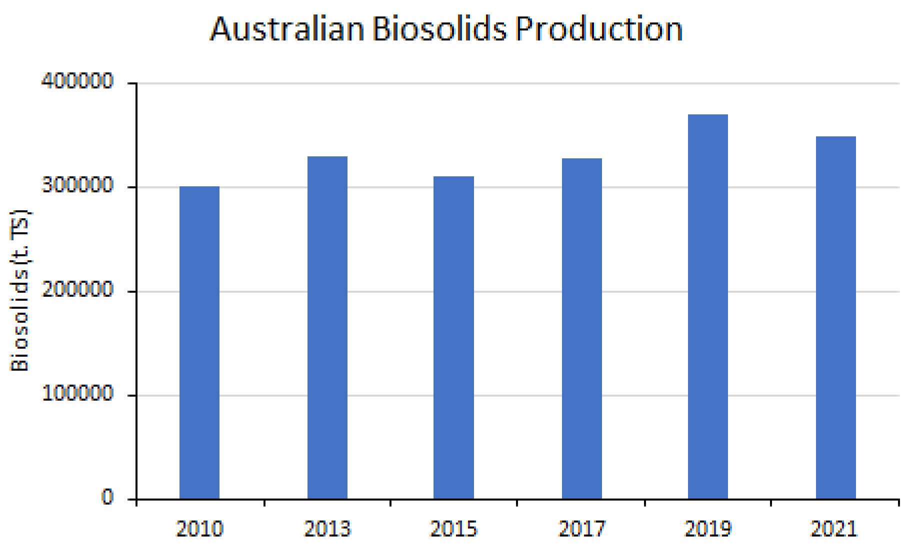


Figure 9. Biosolids total production in Australia from 2010 to 2021. Source: (ANZBP, 2022b)

In 2021, about 83% of biosolids were beneficially used, down from 91% in 2019 and 94% in 2017 (Figure 10). This change is due to the increase stockpiling of biosolids, particularly in Victoria (13% stockpiled in 2021 compared with 5% in 2019).

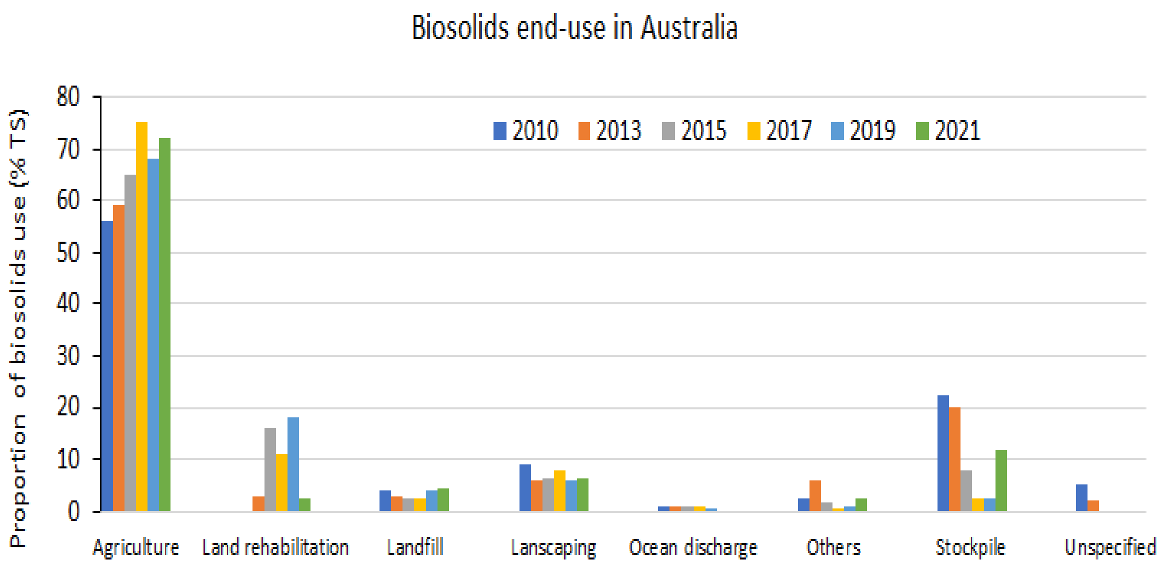


Figure 10. Biosolids end-use (dry mass basis), Australia from 2010 to 2021. Source: (ANZBP, 2022b)

1.7.6 Composition and properties of biosolids

Biosolids products are rich in nutrients that can have beneficial effects on soil fertility and plant growth (Table 22). The major plant nutrients in biosolids are nitrogen (N), phosphorus (P), sulphur (S) and potassium (K). While some of the N in biosolids is present in inorganic forms such as ammonium (NH_4^+) and nitrate (NO_3^-), much of the N in biosolids is in organic forms, so that plant uptake generally requires mineralisation of the organic N (McLaughlin et al., 2008). The nutrients in biosolids are therefore slow-release with 15–25% of the N and P becoming available in the first year and the remainder over subsequent years. Biosolids also contribute to soil properties such as structure, moisture retention, moisture content and cation exchange capacity.

Table 22. Selected chemical properties of the biosolids used in the National Biosolids Research Program in Australia (T: total; after (McLaughlin et al., 2008). SA: South Australia, VIC: Victoria, NSW: New South Wales, QLD: Queensland, WA: Western Australia)

Biosolids source and name	EC	pH	TC	TN	KCL NH_4-N	KCL NH_3-N	CEC	T Cu	T Zn
	(dS/m)	$CaCl_2$	%	%	mg/kg	mg/kg	cmol(+)/kg	mg/kg	mg/kg
Bolivar agitated air dried (SA)	6.29	7.4	6.3	0.77	28	1,690	35	315	435
Bolivar dried lagoon (SA)	7.04	7.4	8.6	0.98	49	1,370	28	340	500
Goulburn Valley Water (VIC)	3.79	7.1	6.5	0.83	89	1,420	24	65	180
North East Water (VIC)	6.47	5.0	11.6	2.03	480	4,010	49	100	300
Vic Gippsland Water (VIC)	6.78	5.6	20.4	2.85	3,280	3,910	61	70	180
Vic East Gippsland Water (VIC)	4.10	4.6	10.6	1.25	82	2,580	21	150	290

Biosolids source and name	EC (dS/m)	pH CaCl₂	TC %	TN %	KCL NH_4-N mg/kg	KCL NH_3-N mg/kg	CEC cmol(+) /kg	T Cu mg/kg	T Zn mg/kg
Malabar STP -LSB 2002 (NSW)	4.06	7.6	20.2	1.55	1,480	104	32	420	650
Bondi STP dewatered cake 2003 (NSW)	5.92	6.2	28.7	2.50	3,560	357	37	880	870
Noosa (QLD)	2.86	6.8	27.2	4.79	480	22	84	355	495
Luggage Point (QLD)	7.61	6.6	32.8	5.72	4,660	3	68	830	1,705
Woodman Point WWTP 2005 (WA)	4.39	6.9	32.2	5.17	4,520	4	68	1,500	900
Beenyup WWTP 2005 (WA)	4.34	6.8	34.7	5.54	4,480	3	60	1,170	615

EC: electrical conductivity; TC: total carbon; TN: total nitrogen; KCL; potassium chloride; NH_3-N: ammoniacal nitrogen; CEC: cation exchange capacity; T Cu: total copper; T Zn: total zinc.

1.7.7 Management of biosolids in Australia

Management of biosolids in Australia is regulated by State-based Environmental Protection Authorities (EPA) (or equivalent bodies) using the guidelines that apply in that State or Territory or adopting those used in other States or national guidelines (see ANZBP (2022a). The primary objective of regulation is to maximise the sustainable use of biosolids while ensuring a high level of protection for both the environment and public health. The Environment Protection Acts set out the rules and regulations concerning the use and disposal of biosolids (Darvodelsky & Morris, 2003). Environmental Protection Acts typically have the purpose of being "a legislative framework for the protection of the environment having regard to the principles of environment protection" (EPA Act 1970). This is consistent with the principles of the waste management hierarchy; Waste avoidance, reduction, reuse, recycling and recovery (energy) are preventive strategies and are highly preferred, while waste treatment, containment and disposal to landfill are the least preferred options. The waste hierarchy has been adopted to guide policy and development of waste management strategies. Each state in Australia also has state-specific guidelines for the use of biosolids, which sets out best management practices. The guidelines are not legal documents on their own, but have legal significance, especially when called up in the relevant legislation. The guidelines are developed such that compliance with them would normally lead to compliance with other relevant regulations and there can be a statement in the guidelines to this effect. The biosolids guidelines deal exclusively with the application of biosolids to land. Other uses of biosolids (e.g., energy through incineration, discharge to sea) are covered by general legislation, which is specific to the respective area; for example, for incineration would be the air pollution act (Darvodelsky & Morris, 2003).

1.7.8 Guidelines for biosolids management and use in Australia

Table 23 presents the timeline for the development of biosolids management and use regulations in Australia. In Australia, New South Wales (NSW) was the first state to develop guidelines for biosolids use in 1997 (Table 23). The remaining states followed NSW and used NSW regulations as a template to produce their own state-specific guidelines with some minor changes. Current Australian National Biosolids Guidelines, published in 2007, is also based on the NSW guidelines (McLaughlin et al., 2007).

Table 23. Timeline leading to the development of biosolids guidelines. Source (Darvodelsky & Morris, 2003)

Year	Guideline
1986	EU Sludge Directive
1987	NSW Agriculture
1993	US EPA 40CRF503 rule
1996	SA EPA
1997	NSW EPA
1999	Tasmanian EPA
2000	Use and Disposal of Biosolids Products. NSW EPA
2001	Qld EPA Operational policy
2001	Safe Sludge Matrix (UK Water and British Retail Consortium)
2002	WA EPA
2003	New Zealand WWA supported by Ministry for the Environment
2004	Guidelines for Environmental Management. Biosolids Land Application Environment Protection Authority Victoria, Publication 943, Melbourne, VIC EPA
2004	National Water Quality Management Strategy (National guideline)
2004	The NT Health Department employs the November 2004 National Guidelines for Sewerage Systems Biosolids Management
2010	SA EPA Guidelines for the safe handling and reuse of biosolids in South Australia
2010	WA EPA (draft)
2011	ACT Waste Management Strategy: Towards a sustainable Canberra 2011-2025
2012	Western Australian Guidelines for Biosolids Management, DEC WA (2012)
2020	Tasmanian Biosolids Reuse Guidelines, EPA Tasmania, June 2020
2020	QLD End of Waste Code for Biosolids under the Waste Reduction and Recycling Act 2011. The Code has been amended for use as of January 2020

The guidelines are based on practices used in the European Union (EU) especially from the United Kingdom (UK), and in Australia they ensure the protection of the environment, public health and agricultural production. These guidelines were designed to provide a framework for biosolids management that can promote responsible management of biosolids, protect public health and the environment, promote consistent practices and acceptance of biosolids use by society.

1.7.9 Biosolids processing technologies

Technologies for processing biosolids include stabilisation, pathogen reduction and reduction of the water content. Figure 11 presents a comparison of various treatment technologies which can achieve the objectives and Table 23 provides an overview of technologies currently used for biosolids treatment in Australia.

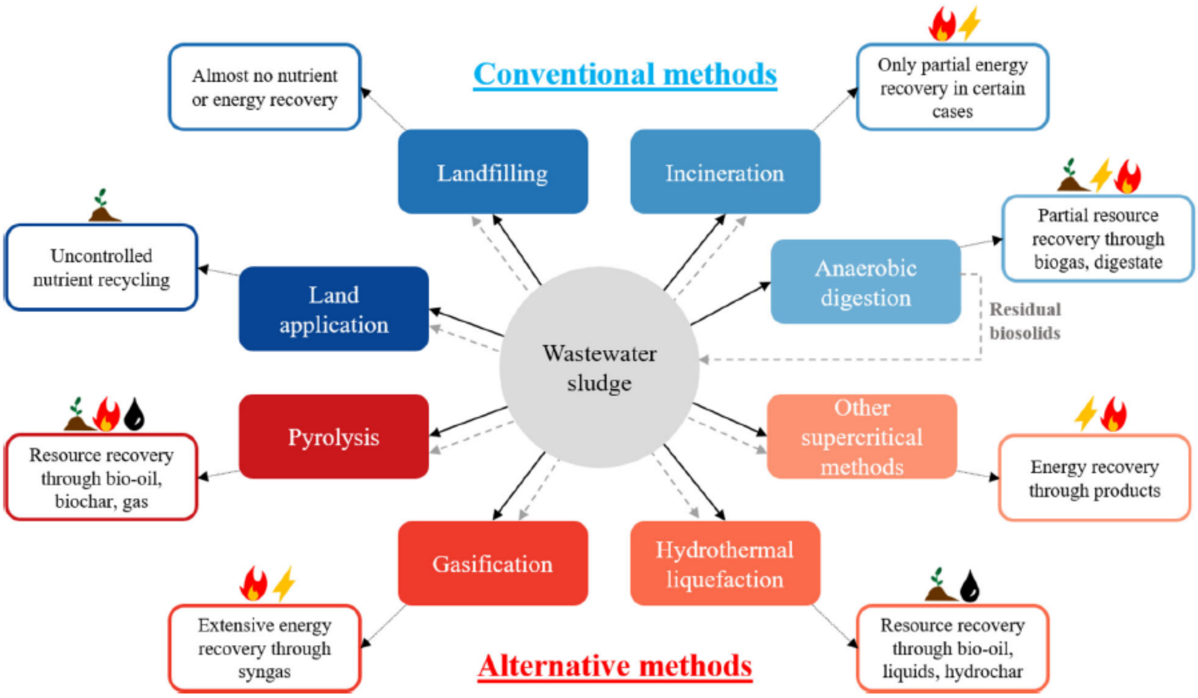


Figure 11. Conventional and alternative thermochemical conversion methods for wastewater sludge along with their extent of energy and nutrient recovery.

The intermediate steps such as drying and downstream processing steps for the products are not shown in this representative figure. The dotted lines in grey represent the residual biosolids produced from the AD which can then proceed to any of the other methods. Symbols: seedling, nutrient recycling; flame, energy (heat); lightning, electricity; droplet, bio-oil. Source (Bora et al., 2020)

Table 24. Biosolids treatment technology overview in Australia. Adapted after (Van Oorschot et al., 2000)

Process	Stabilisation	Pathogen reduction	Reduction of water content
Alkaline Stabilisation			
Custom Processes	●●	●●	●
N-VIROTM Soil	●●●	●●●	●
RDP Envessel pasteurisation	●●●	●●●	●
Anaerobic digestion	●●	●●	●
Autothermal thermophilic aerobic digestion ATAD	●●●	●●●	●
Aerobic digestion	●●	●	●
Incineration	●●●	●●●	●●●
Composting	●●●	●●●	●
Sludge lagoon	●●	●●	●●
Wet air oxidation/Vertech process	●●●	●●●	●
Thermal drying	●●●	●●●	●●●
Oil from sludge technology OFS	●●●	●●●	●●●
Active Sludge Pasteurisation ASP	●●●	●●●	●●●
Filter presses	●●	●●	●●
Drying pans	●●	●●	●●●
Drying beds	●●	●●	●●●

●●●: Good; ●●: Medium; ●: Poor

1.7.9.1 Alkaline stabilisation

Alkaline stabilisation is generally carried out by mixing lime (quick lime, CaO or hydrated lime, $Ca(OH)_2$) with dewatered biosolids. The alkaline pH and temperature due to the addition of lime will kill the microorganisms in the sludge. Two proprietary processes capable of achieving a high level of stabilisation and pathogen reduction in biosolids include (a) RDP Envessel pasteurisation and (b) N-VIRO™ Soil process.

RDP Envessel pasteurisation: In this technology, biosolids cake is heated prior to addition of quicklime in proprietary equipment, which mixes and heats the blended material. The temperature of the material will rise to 70°C due to heating and quicklime addition. Thereafter, the biosolids cake is transferred into an enclosed, heated and insulated vessel, where its temperature is maintained at 70°C for approximately 30 minutes.

N-VIROTM soil process: In the N-VIROTM soil process, dewatered biosolids are mixed with quicklime and cement kiln dust to raise the pH to greater than 12 and temperatures to around 50°C. From the mixer the blended materials are discharged to a stockpile before being windrowed. Complete pasteurisation is not achieved until after stockpiling and windrowing.

Conventional lime treatment: To stabilise dewatered biosolids, the cake is mixed with hydrated lime or quicklime in a pug mill and discharged to bins for storage. The process conditions will need to be selected to suit the biosolids characteristics. Often reported problems with alkaline stabilisation are release of odours and poor mixing of lime with the dewatered biosolids. Special attention to the mixing device and enclosure of the lime-dosing unit with odour scrubbing is therefore recommended. Indicative capital and operating costs for the three lime stabilisation options, based on annual sludge quantities (dry solids) to be treated, are provided in Figure 11.

1.7.9.2 Composting

Composting is decomposition of organic material by aerobic microorganisms to produce a stable end product suitable as a soil conditioner. Both raw and anaerobically digested sludge can be composted. Raw primary sludge has a great potential for odour. Composting processes can maintain a moisture content between 40% and 60%, achieve a temperature between 55°C and 60°C, pH between 6.5 and 9.5 and C/N ratio of 26-31:1 (WPCF, 1985). The final matured compost will have a biosolids content between 5% and 30% (dry weight), typically around 10%. For correct pasteurisation, the temperature of the piles must maintain a temperature of 55°C for at least three days, based on Australian Standard AS4454-2012.

Table 25. Impurity, pathogen, heavy metal and organic contaminant limits for compost products for unrestricted use according to (AS 4454, 2012)

Product Characteristic	Unit	Maximum limits for compost quality based on AS 4454
Impurities		
Glass, metal and rigid plastic	%TS[1]	< 0.5
Plastic – light, flexible or film	%TS	< 0.05
Stones and lumps of clay	%TS	< 5
Pathogens[2]		
Faecal coliforms	[3]MPN/g	< 1,000
Salmonella spp.		absent in 50 g dry weight equivalent

Product Characteristic	Unit	Maximum limits for compost quality based on AS 4454
Heavy Metals[2]		
Arsenic	mg / kg TS	20
Boron*	mg / kg TS	100
Cadmium	mg / kg TS	3
Chromium (Total)	mg / kg TS	100
Copper	mg / kg TS	100 (150)**
Lead	mg / kg TS	150
Mercury	mg / kg TS	1
Nickel	mg / kg TS	60
Selenium	mg / kg TS	5
Zinc	mg / kg TS	200 (300)**
Organic Contaminants[2]		
DDT/DDE/DDD[3]	mg / kg TS	0.5
Aldrin	mg / kg TS	0.02
Dieldrin	mg / kg TS	0.02
Chlordane	mg / kg TS	0.02
Heptachlor	mg / kg TS	0.02
Lindane	mg / kg TS	0.02
BHC[3]	mg / kg TS	0.02
[4]PCBs***	mg / kg TS	Not detected
HCB[5]	mg / kg TS	0.02

[1] TS: Total solids or dry matter; [2]Pathogen, heavy metal and organic contaminant limits are largely aligned with NSW Biosolids Guideline values for Grade A product; [3]MPN: Most Probable Number; * Testing for boron is generally only necessary for products that are based on seaweed, seagrass or unseparated solid waste that have a component of cardboard packaging; ** A product that contains levels of copper between 100 mg/kg and 150 mg/kg and/or zinc between 200 mg/kg and 300 mg/kg whilst not exceeding the limit values for all other contaminants, shall provide a warning label in accordance with labelling requirements.*** The detection limit for PCBs shall be 0.2 mg/kg TS. [3]DDT/DDE/DDD: Dichlorodiphenyltrichloroethane/ Dichlorodiphenyldichloroethylene/ Dichlorodiphenyldichloroethane. BHC[3]: Benzene hexachloride. [4]PCBs: Polychlorinated biphenyls. [5]Hexachlorobenzene.

Composting can be carried out using windrow composting, aerated static piles and in-vessel composting methods. The relative advantages and disadvantages of the three principal composting methods are summarised in Table 26.

Windrow composting: Biosolids are spread on the open ground and piled into long rows (windrows). The piles are turned mechanically and mixed at regular intervals for about 18 weeks until composting is complete.

Aerated static pile: Biosolids and bulking agents are mixed and piled over a network of pipes on a hard stand area. Air is blown through the pile and exhausted through a compost filter for odour control. Sometime the piles are covered with a layer of matured compost to further prevent odour release. This composting process takes about 8–10 weeks to mature.

Table 26. Comparison of different composting technologies used in Australia. Source: (Van Oorschot et al., 2000)

Compost	Advantages	Disadvantages
Windrow	Low capital cost Low operation and maintenance cost	Large area required Possible odour problems Difficult to achieve required temperatures Potential for poor mixing Long composting period
Aerated Static Pile	Enhanced odour control Good temperature maintenance Shorter composting period	Capital cost of aeration system Moderate operating and maintenance costs
In-vessel	Small area required High degree of process control Very good temperature and odour control	High capita, operating and maintenance cost Applicable to large scale operation only

In-vessel composting system: In this process, composting takes place inside an enclosed container. Composting process parameters are closely monitored and controlled. It also facilitates the treatment and management of odours. In-vessel composting processes take relatively short composting times and a more consistent product quality in relation to pathogen reduction is achieved. The produced compost has unrestricted use depending on process conditions, i.e. temperature and composting period.

According to the Australian Organics Recycling Industry (AORI), there were 305 composting facilities in Australia processing 7.5 Mt of organic material per year in 2018-19 (Department of Agriculture Water and the Environment, 2020). Garden organics make up the largest portion of organic materials recycled nationally comprising 41.6%, followed by biosolids (18.8%), timber (13.7%) and food organics (7.2%). In 2018-19, NSW recycled 2.75 Mt (36.7% of total) followed by VIC with 1.49 Mt (19.8%), SA with 1.26 Mt (16.8%) and QLD with 1.12 Mt (14.9%) of organic material (Department of Agriculture Water and the Environment, 2020).

Direct economic benefits from the Australian composting industry include providing 4,845 direct jobs with a collective industry turnover of over $2 billion (AEAS, 2020), indirectly providing 4,070 jobs and $579 million as goods and services. The GHG emissions avoided from organic recycling through composting was estimated to be 3.8 Mt of CO_2-e in 2018-19 (AEAS, 2020).This is equivalent to the annual GHG emissions from 876,663 cars in Australia or 5.7 million trees would be needed to absorb the same amount of CO_2-e.

1.7.9.3 Vermiculture

Vermiculture is a biological process where organic material is fed to a variety of worm species with the aim of converting the organic material into increased worm biomass and vermicast. The excreta from the worms, called vermicast, is used as a plant growth medium and soil conditioner. In addition, the worm biomass is sold as bait and animal feed, and for domestic and small composting systems. The largest vermiculture facility operating on wastewater sludge is at Redland near Brisbane, Queensland. It has a sludge treatment capacity of 400 m^3/week and is operated by Vermitech. The produced soil conditioner is used for broad acre farming, turf farming, horticulture, viticulture, and seedling propagation.

Vermicast is mainly targeted for use at high value horticulture, viticulture, and seedling propagation. Vermiculture produces a high value-added product suitable for a wide range of markets. There is still a lack of widespread experience as the first large scale plant was commissioned at Redland Shire in January 1998. The capital cost for the Redland plant was around $3.2 M with operating costs between $35 and $55 per m^3 of wet sludge, 18% dry solids, treated.

Table 27. Typical biological and chemical composition of vermicast in Australia. Source: (Australian Vermiculture, 2022)

Biological composition (mg/kg Fresh Matter)	concentration
Total microorganisms	204.1 mg/kg
Total bacteria	41.0 mg/kg
Total fungi	160.1 mg/kg
Protozoa	2.8 mg/kg
Mycorrhizal fungi	4.181 mg/kg
Pseudomonas	6.641 mg/kg
Actinomycetes	2.272 mg/kg
Nutrient composition (wet weight, %)	
Nitrogen	4.0%
Phosphorus	3.0%
Potassium	1.4%
Calcium	3.0%
Magnesium	1.0%
Iron	0.979%
Copper	0.354%
Boron	0.284%
Sodium	0.177%
Cadmium (P)	10.3 ppm

Note: ppm: Parts per million

1.7.9.4 Incineration

Incineration is the complete thermal destruction of materials to their inert constituents in the presence of oxygen. For sewage sludge (3% TS), the process yields a weight reduction of well over 90% of the input sludge and thermal breakdown of pathogens and toxic organic compounds (Khiari et al., 2004). The solids product from the incineration of sewage sludge is an inert and sterile ash which can be used as a soil conditioner, and in road surfacing, concrete aggregate etc.

The purpose of the incineration of sewage sludge is to:

- dry the sludge cake
- destroy the volatile content by burning (at 760°C to 980°C)
- produce a sterile residue or ash and
- produce a flue gas to zero visible emissions

There are two main types of incinerators, namely the multiple hearth and fluidised bed, with the latter technology superior to that of the former. Both technologies have been commonly used as an energy recovery and waste minimisation method in highly populated municipalities, particularly in Japan, USA, Belgium, Demark, France, and Germany (Werther & Ogada, 1999). Fluidised bed incinerators offer better control of combustion conditions and hence more complete and reliable combustion (Werther & Ogada, 1999).

Incineration is generally considered a means of waste minimisation rather than energy generation since external energy supply is essential to dry and combust dewatered biosolids. Energy balances in biosolids incineration is dependent on the biosolids composition and its heating value. The lower heating value of dried, digested biosolids is in the range 13.1–17.0 MJ/kg (Fytili & Zabaniotou, 2008), similar to brown coal, but the heating value in biosolids is much lower (Stasta et al., 2006). Thus, incineration is a costly alternative due to the external energy requirements mainly associated with dewatering. Further, incineration must comply with air pollution regulations. Particulate and gaseous emissions can be hazardous and require further treatment. Nevertheless, new technologies such as co-incineration with municipal solid waste have allowed the maintenance of gaseous emissions within regulatory levels but increased the costs of incineration.

Co-combustion of biosolids in existing power and heating plants and cement kilns represents an advantage for a low investment cost, no additional off-gas cleaning and rapid implementation (Zabaniotou & Theofilou, 2008). Approximately 5% of dewatered biosolids can be cofired together with coal without significantly decreasing the temperature of the process (Kääntee et al., 2004). Co-combustion of biosolids in coal-fired power plants has been applied in Germany for more than 10 years and has shown a positive energy balance using existing infrastructures (Cartmell et al., 2006; Stasta et al., 2006). However, due to the large amounts of heavy metals, the ash originated from the co-combustion of coal and biosolids is potentially more toxic than the ash from coal alone (Barbosa et al., 2009).

Nevertheless, biosolids incineration is perceived poorly by the community, and, consequently, other methods of management are preferred. Ash from biosolid incineration requires special consideration for disposal, but it may be used as a raw material for the construction industry. Incineration in Australia is limited. Problems associated with incineration of biosolids include quality inconsistency, the need for biosolid handling systems, and reduced boiler capacity because of the high moisture content. Since 1978, incineration has been carried out at Canberra's Lower Molongolo Wastewater Treatment plant at an estimated operating cost of $120 per tonne (includes dewatering, incineration and transport of ash).

1.7.9.5 Hydrothermal technologies

Hydrothermal technologies are broadly defined as chemical and physical treatment operated at high-temperature (200–600°C) and high-pressure (5–40 MPa) using liquid or supercritical water (Peterson et al., 2015). These technologies can operate efficiently at low solid concentrations of 5–30% (Mulchandani & Westerhoff, 2016). Thermochemical reformation of biomass has energetic advantages over other thermal technologies such as pyrolysis and gasification as when water is heated at high pressures a phase change to steam is avoided. This avoids large enthalpic energy penalties. Biological chemicals undergo a range of reactions, including dehydration and decarboxylation reactions, which are influenced by the temperature, pressure, concentration, and presence of homogeneous or heterogeneous catalysts. Several biomass hydrothermal conversion processes are in development or demonstration. Liquefaction processes are generally lower temperature (200–400°C) reactions which produce liquid products, often called "bio-oil" or "bio-crude". Gasification processes generally take place at higher temperatures (400–700°C) and can produce methane or hydrogen gases in high yields.

Hydrothermal liquefaction (HTL): Hydrothermal liquefaction (HTL) can chemically convert high moisture biomass such as biosolids into an energy-dense biocrude in hot compressed water (Peterson et al., 2008), and simultaneously avoids a costly energy input for drying prior to traditional conversions (Minowa et al., 1995). HTL technology is considered superior to thermal drying processes. Several studies have shown that the yields and compound compositions of biocrudes obtained from sewage sludge (SS) HTL at 350 and 400°C for 30 min, and the risk assessment of heavy metals (Cd, Cu, Zn and Pb) in solids (Zhai et al., 2014), and the total concentration and chemical speciation of heavy metals in solids after HTL (Yuan et al., 2011).

Temperature and liquefaction solvent have profound influences on the redistribution of heavy metals during SS liquefaction. A comprehensive study on the effects of increasing temperatures (260-350°C) showed that 340°C was the optimal temperature for maximising bio-oil yield (D. Xu et al., 2018). In addition, a rise in temperature was shown to improve the bio-oil quality and the gas yields with concomitant decreases in solid yields and water-soluble substances. The potential of the HTL to treat very dilute streams of digested sludge, primary and secondary sludge was also reported in the literature (Marrone, 2016). Techno-economic feasibility of replacing current sludge treatment and stabilisation methods (specifically ADs) with hydrothermal liquefaction showed promising results as long as the bio-oil could be upgraded and sold profitably (Snowden-Swan et al., 2016).

Australia's first integrated demonstration plant using HTL was opened by Muradel in Whyalla, SA. In 2018, Southern Oil Refining partnered with Melbourne Water and constructed a demonstration-scale HTL plant in Gladstone, QLD that treats a targeted capacity up to 1 million tons biosolids per year. The renewable biocrude is then upgraded to renewable diesel and potentially renewable jet fuel by means of existing Southern Oil's refining facilities (Sustainability Matters, 2022).

Supercritical water oxidation (SCWO): Supercritical water oxidation (SCWO) oxidises organic materials, in a liquid or cake form, completely into CO_2 and water at supercritical temperatures and pressures. The degree of oxidation depends on the temperature and pressure selected. Above the critical point of water (374°C, 221 bars) nonpolar organic compounds and oxygen are generally highly soluble and miscible in water, while nonpolar inorganic compounds such as metal salt precipitate out (Hodes et al., 2004; Marrone et al., 2004). Products from SCWO are CO_2, H_2O, and N_2 without the formation of SO_x or NO_x gases.

The SCWO process have been developed that have reduced the capital and operating costs of processing municipal biosolids below that of incineration (Svanström et al., 2004). It is reported that at 10% dry solids, biosolids can be oxidised with virtually complete recovery of their energy value as hot water or high-pressure steam. Liquid CO_2 of high purity can be recovered from the gaseous effluent and excess oxygen recovered for recycling. The net effect of removing gases is to reduce the stack to a harmless vent with a minimal flow rate of clean gas. The solid residue in the SCWO process has the potential for P extraction (Svanström et al., 2007). Successful commercialisation of the SCWO process will depend mostly on the approach to controlling scale build up and corrosion (Marrone et al., 2004).

1.7.9.6 Pyrolysis

Pyrolysis is the thermal decomposition of organic material at extremely high temperature (200-500°C) in the absence of oxygen to produce a mixture of gaseous and oils (organic liquids and tar), and a solid inert residue mainly carbon or char. The process involves a complex series of chemical reactions to decompose organic materials. The synthesised oil, char and gas can be used as alternative fuels and temperature has been shown to be an important factor in determining the yields of the various products (Caballero et al., 1997). Generally, temperature ranges between 275°C and 500°C have been used to produce oil from sewage sludge with optimal oil production at 400°C (Kim & Parker, 2008). Pyrolysis is of interest due to the recovery of oil with low emissions of NO_x and SO_x. It also avoids the formation of toxic organic compounds such as dioxins, with lower operating costs compared to incineration (Werther & Ogada, 1999). The effect of pyrolysis temperature on the chemical properties of biochars is presented in Table 28.

Economic analysis of drying and pyrolysis of primary, waste activated and digested biosolids was conducted and compared with the price of crude oil (Brown, 2007). The results showed that the temperature of pyrolysis and the volatile solids content in biosolids were the major factors affecting oil and char yield. The char produced during the low- and medium-temperature pyrolysis may be used as fuel to dry biosolids to reduce external energy input (Brown, 2007). Further, chemically stable char can also be applied to soil as a source of organic C to increase long-term soil C and to improve soil productivity (Lehmann, 2007). Besides oil and char, syngas (CO and H_2) can also be produced by using microwave-induced pyrolysis of biosolids (Domínguez et al., 2008; Domínguez et al., 2006). The first commercial biosolids pyrolysis plant was built in Western Australia (Bridle & Skrypski-Mantele, 2004). However, this plant has now been discontinued, as the resultant product was found to be unsuitable for diesel engines and the economics of the system were poor (GVRD, 2005; US EPA, 2020).

Recently, the possibility of using pyrolysis of biosolids prior to landfilling is being explored. This would reduce the potential release of pollutants from the resulting char in landfill, compared to the biosolids or an incinerated residue (Hwang et al., 2007). Thus, pyrolysis is a promising method of treating biosolids before landfilling to not only reduce the leaching of pollutants but also to reduce the amount of space required for landfilling.

Table 28. Effect of pyrolysis temperature on the physic-chemical characteristics of biochar's derived from biosolids

Temperatures	Main Findings	Reference
350, 400, 500, 700°C	Higher pyrolysis temperature leads to less char but to less plant-available heavy metals (as measured by DTPA). Strong contrast in pH depending on temperature	(Hossain et al., 2011)
300, 400, 500°C	Impregnation of sludge catalyses pyrolysis. Higher yield at lower temperature	(Agrafioti et al., 2013)
500, 600, 700, 800, 900°C	Biochars outperform commercial activated carbon for heavy metal sorption. This is related to aromatisation and development of pore structure at higher temperatures	(Chen et al., 2014)
300, 450, 600, 750°C	Most P in biosolids available for plants after transformation to biochar	(Roberts et al., 2017)
400, 600°C	Total amount of heavy metals increased with temperature, but metals were less extractable	(Méndez et al., 2013)
300, 400, 500, 600, 700, 800°C	pH similar to original biosolids. Surface area quadrupled at higher temperatures	(Antunes et al., 2017)

1.7.9.7 Oil from sludge (OFS) technology

Oils from sludge (OFS) or ENERSLUDGE™ technology is a patented process that converts the organic content of sludge to oil with properties similar to diesel fuel (Bridle et al., 2000). OFS process operates at relatively low temperatures (350°C to 500°C) and at atmospheric pressure (Van Oorschot et al., 2000). Both raw primary sludge and thickened excess activated sludge are used as feedstock. The OFS technology is a part of a four-mode treatment train (Bridle et al., 2000). Mode 1 (chemical stabilisation) is comprised of sludge blending, dewatering, chemical stabilisation and odour control. In Mode 2 (LPG-Fried dryer), sludge blending, dewatering, drying, gas cleaning and odour control. Mode 3 (Autogenous sludge dryer) is comprised of Mode 2 plus a hot gas generator, which combusts sludge pellets and grit and screenings to provide the energy for sludge drying. Mode 4 (sludge conversion) is comprised of mechanically dewatering (25–35% TS) and drying of the sludge to about 95% TS to be used as feed for OFS. The process produces oil, char, non-condensable gas (NCG) and reaction water (RW). Char is burnt in a hot gas generator (HGG), similar to a fluidised bed incinerator, which produces most if not all the energy for sludge drying and reactor heating.

A large burner heats up gas (from the sludge) and air to a temperature of about 450°C which passes through a heat exchanger to heat the drying drum. Dewatered sludge is usually mixed with under and oversized pellets prior to introducing it into the drying drum. Odorous gasses generated are returned to the combustion chamber and oxidised. Dust is extracted from the air and used again. After leaving the drum, the dry granules are separated into grades, cooled and bagged, ready for use. The granule from the thermal drying process is classified as a Class 1A product (van Oorschot et al. 2000). The oil is suitable for combustion in engines, while the char from the reactor has similar properties to activated carbon used for the adsorption of heavy metals. The principal product with all heat drying processes is sludge granules or pellets with moisture content between 5 and 40% (w/w). This pelletised product is not unlike traditional artificial fertiliser in size and appearance and is used as a valuable commercial soil conditioner. Its nutrient value is dependent on the input sludge quality. This thermal drying technology is part of the Subiaco WWTP in Perth (Western Australia).

1.7.9.8 Active sludge pasteurisation (ASP) process

ASP process negates the need for stabilisation of biosolids whilst pasteurising and enriching it with the nutrients N and P. In the ASP process, dewatered sludge (stabilised or non-stabilised primary, secondary, tertiary sludge) of at least 15%–20% dry solids is processed (Van Oorschot et al., 2000). The process consists primarily of an alkaline reactor, acid reactor and drier. Anhydrous ammonia (NH_3) is added to the sludge, which raises the temperature and pH of the sludge to about 60°C and 12 respectively. This step provides pasteurisation of the sludge through high pH, high temperature and ammonia toxicity. In addition, the NH_3 reacts with the organic matter in the sludge, fixating part of the added NH_3. In the second stage of the process, phosphoric acid (H_3PO_4) is added to neutralise the mixture to a pH of 7.0 while raising the temperature to about 70°C. The heat produced is utilised by a heat exchanger for the overall process. The non-chemically bound NH_3 is evaporated and reused. Dry warm air is blown over a thin layer of final product to evaporate the moisture and dry the sludge. The dried sludge is separated from the moist air in a cyclone separator to produce the final pelletised or granular product. It has a moisture content of about 15% (w/w) and is not unlike artificial fertiliser in size and appearance.

Table 29. The different methods of organic waste disposal and treatment technologies in Australia (Adapted after Ngo et al. (2021)).

Technology	Energy production (kWh_{el}/t)	GHG emissions/tonne of waste (kg CO_2-e)	Advantages	Disadvantages	References
Landfilling	0.00078	+350	Disposal of a large amount of waste at a time	Environmental pollution via landfill gas production Groundwater contamination and negative impacts on human health Emission of large quantities of greenhouse gas into the atmosphere after closure	Dastjerdi et al. (2019) US EPA (2020) Lu et al. (2020) EAR (2018) Sustainability Victoria (2019)
Incineration	0.000047	+1,396.5	Reduction of waste mass and volume by up to 75% and 90% Heat and electricity production	Suitability of waste for incineration remains challenging	EIA (2019) Kristanto and Koven (2019) Dastjerdi et al. (2019) Lu et al. (2020)
Compositing	Nil	+171.5	Simple to operate; Stabilise organic waste; Produces valuable compost with high value	Potential for large quantities of methane to be produced and emitted if poorly conducted Hygiene concerns in densely populated areas	Lu et al. (2020) Kristanto and Koven (2019)
Anaerobic digestion	222.3	-143	Natural biodegradation of organic matter	Constant monitoring Strict requirements involved which may incur high costs	Phong (2012) Gebrezgabher et al. (2010)

1.8 Scale of Technology

The increasing scale of agribusiness operations makes AD and biogas production increasingly attractive and economically feasible. A credible economic feasibility of CAL and biogas cogeneration from wastewaters from agriculture has been published by ReNu Energy (ReNu Energy, 2017). In the above study, economics of scale was studied by comparing four different meat processing plant sizes viz., small, low-medium, high-medium, and large plant (Table 29). For the above wastewater generation, the capital costs increased from $1.62 million reaching to $7.54 million for 90 ML plant size. The increase in scale to 22 ML CAL decreased the cost of production to $110,455/ML and with a further increase in CAL size to 90 ML (83,722/ML)

Table 30. Comparison capital cost of CAL by meat processing plant size. Source: (ReNu Energy, 2017)

Item	Small Plant	Low-Medium Plant	High-Medium Plant	Large plant
Wastewater flow (kL/d)	500	1,500	4,300	7,000
Size of CAL (ML)	7.5	22	60	90
Capital cost ($ million)	1.62	2.43	4.81	7.53
Cost of production biogas ($/ML)	216,667	110,455	80,267	83,722
Cost of energy generation ($/GWh)	1,355	633	590	430

Figure 12 presents the scale of production and capital costs for the four different CAL capacities. The results showed that the capital cost of the CAL was dependent on the size of the CAL, which is dependent on the total amount of wastewater generated.

Although the Meat and Livestock Australia Limited capital cost estimates are targeted to abattoir applications, the figures are broadly applicable to all CALs and biogas cogeneration application in Australia (ReNu Energy, 2017). However, the above study doesn't discuss the operation costs, especially the costs associated with the sludge removal. Moreover, the effluent quality and CAL efficiency is not mentioned in the report.

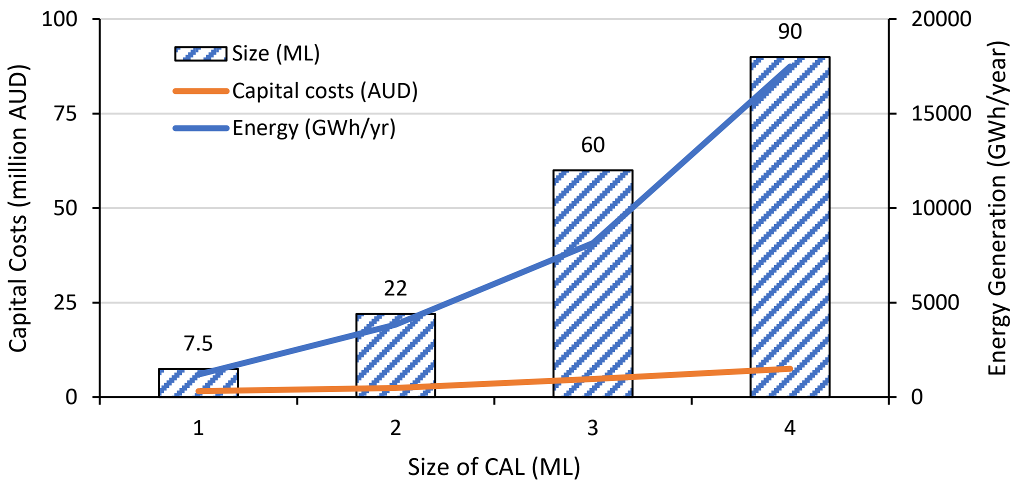


Figure 12. Capital costs and scale of biogas generation from covered anaerobic lagoons in Australia. Source ReNu Energy (2017)

A techno-economic analyses of on-farm biogas production and use options for a pig farm in Victoria showed that economic feasibility was moderate for 535-sow farrow-to-finish piggery farm (Tait & McCabe, 2020). The estimated capital investment in the above case study was $615K with a simple payback period of 6.3 years and NPV of $621K over a 20-year period. On the other hand, it was most economical for larger piggeries with 1,000+ sows due to economies of scale and higher farm energy costs. This is obvious as small to medium farms would produce low to moderate levels of biogas and would generate less effluent for biogas production in covered anaerobic ponds (Tait & McCabe, 2020). These piggeries could consider import of other organic wastes for co-digestion and/or use of straw as bedding material for biogas production in existing covered anaerobic ponds. On the other hand, the economics for a large piggery with 57,000 standard pig units with sale of raw biogas to an external party was a $2.4M capital investment with a payback period of 4.5 years. The corresponding values in the above scenario when the raw biogas is sold to a third party that purchases and converts the biogas and sells biomethane and bio-CO_2 is $3.3M in capital investment and 4.5 year of payback period. However, these larger piggeries should produce a minimum of >250 m^3/h of biogas and a third-party commercial gas manufacturer-supplier should agree to purchase the gas. The involvement of a third-party gas utility would complicate purchase arrangements but would also significantly de-risk the project for the pig farms.

Recently a feasibility study on co-digestion of 20,000 t/yr of sugarcane bagasse and 30,000 t/yr of mill mud with 5,000 t/yr of locally available chicken manure in a full-scale biogas plant using heated CSTR reactor was carried out (Kaparaju et al., 2022). Approximately 9.35 million Nm^3 of biogas per year could be produced. Economics and scales of production was evaluated on the use of biogas. Three different scenarios were evaluated for the economic viability of the project. The produced biogas will be used for electricity and heat generation in a CHP/cogeneration plant (Scenario 1), upgraded to compressed biomethane (BioCNG) (Scenario 2) or upgraded to biomethane for grid injection (BioRNG) (Scenario 3). In Scenarios 2 and 3, a part of the biogas will be used for CHP/cogeneration to meet the plant energy demands, with the remaining biogas updated to biomethane. The carbon dioxide from the biogas upgrading process will be recovered and liquefied for sale (BioCO_2).

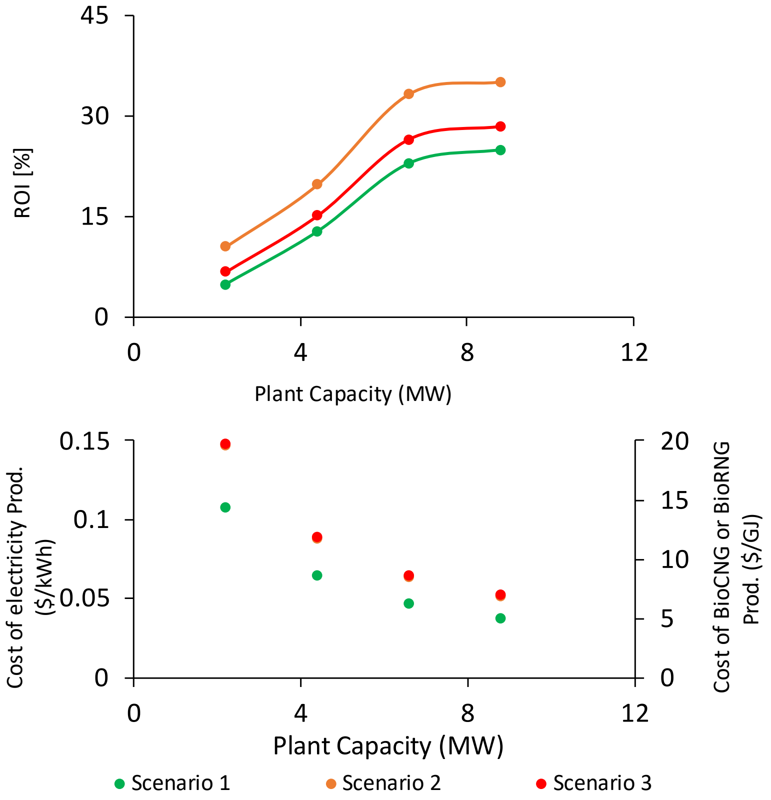


Figure 13. The influence of plant capacity on return on investment (ROI, %) (above) and cost of electricity ($/MW), BioCNG ($/GJ) and BioRNG ($/GJ) (below) for Scenario 1 (CHP/cogen), Scenario 2 (CHP/cogen + BioCNG) and Scenario 3 (CHP/cogen + BioRNG).

Note that in the lower figure, Scenarios 2 and 3 have the same values, so the red dot represents both scenarios.

Total investment required for the project varied and dependent on the biogas usage. The total investment required was $24–25 million for Scenarios 2 or 3 and $20.4 million for Scenario 1. The general breakdown of the individual categories of CapEx into sub-components depended on the equipment of the biogas plant's process line with some significant and recurring categories of expenditure. Total CapEx increased from $13 million in Scenario 1, when biogas was used for 100% heat and electricity generation in CHP/cogeneration, to $15–16 million, when the biogas is upgraded and compressed to BioCNG (Scenario 2) or to BioRNG (Scenario 3). Investment in both CHP/cogeneration and biogas upgrading equipment in Scenarios 2 and 3 would incur an additional CapEx of $3–4 million. Of the total CapEx, the biogas plant alone accounted for 77% in Scenario 1, 66% in Scenario 3 and 63% in Scenario 2.

Scale of production had a more profound influence on the return on investment (ROI) and production costs of electricity, BioCNG and BioRNG than any of the parameters studied (Figure 13). When increasing the plant design capacity from 2.2 to 8.8 MW, the cost of electricity production dropped sharply when the plant size was increased from 2.2 to 4.4 MW and then dropped more steadily as the plant size was increased from 4.4 to 8.8 MW. At the same time, the ROI increased significantly when the plant size was increased from 2.2 to 6.6 MW and remained unchanged thereafter. Both these results suggest that a large-scale centralised CSTR biogas plants with an average plant size of about 6.6 MW and digesting 450 t/d of feedstock would be economically viable in Australia with a ROI of 27–33%.

The cost of production of electricity (in $/kWh) or biomethane (in $/GJ) is presented in Figure 13. The cost of production of electricity decreased from $0.11/kWh at 2.2 MW plant size to $0.04/kWh when the plant size reached 8.8 MW. Similarly, the estimated cost of biogas upgrading and feeding biomethane into the gas pipeline network decreased from $19.71/GJ at 735 m^3/h of raw biogas upgrading capacity to $6.9/GJ when the upgrading capacity is 2,940 m^3/h raw biogas. For BioCNG production, the cost of production decreased with an increase in upgrading capacity from $19.56/GJ (750 m^3/h raw biogas) to $6.84/GJ (3,000 m^3/h raw biogas).

1.8.1 Feasibility of AD with economic support and other policies

The influence of various factors such as funding received, feedstocks used, digestate uses, power purchase agreement and other government incentives eligibility for three different full-scale biogas plants with different reactor technology and feedstocks in Australia was performed (Ngo et al., 2021) and is presented in Table 31. Given the status of biogas industry in Australia, the authors in the above study did not take into account the capacity factor and operation and maintenance costs. The study showed that the Goulburn Bioenergy plant with CAL technology is the most economically viable project among the three studied projects. This is mainly due to the financial support that the Goulburn Bioenergy plant received under the Emission Reduction Fund. Approximately 33% of the total $6.39 million capital cost was funded by ARENA (Table 31). On the other hand, the Jandakot Bioenergy Plant in Perth using CSTR reactor technology for digesting food waste received only 16% of its $8-10 million capital cost from the Clean Technology Investment Program and WA State Government. Finally, ReWaste plant at Yarra Valley Water, VIC treats source separated food waste using CSTR technology and was commissioned with an investment cost of $27 million. Interestingly, this plant did not receive any financial support from the federal or state government. Other factors that affected the economics of the biogas plants were the proximity to the feedstocks. Goulburn Bioenergy plant is situated next to the Southern Meats abattoir and receives the feedstock directly from them and thereby eliminates the costs associated with the purchase and transport of feedstock. On the other hand, both the Jandakot Bioenergy and ReWaste plant have to obtain feedstock from different suppliers and also secure the feedstocks supply. Finally, Goulburn Bioenergy plant had made a 20-year power purchase agreement with Southern Meats abattoir for supplying electricity. On the other hand, there are no power purchase agreement for the other two project. Therefore, lack of a power purchase agreement may increase the risk for the project. Thus, for AD plants to achieve financial viability, polices and schemes that can support the investment e.g. Emission Reduction Fund or ACCUs, green certificates etc should be in place.

Table 31. Comparison between capital investments, feedstock cost, disposal cost and government incentives for 3 different biogas projects in Australia. (Adapted after Ngo et al. (2021)).

Project name	Funding (AUD)	Feedstock	Fate of digestate	Government incentives eligibility	Power purchase agreement (PPA)	Reference
Jankadot Bioenergy plant	$8-10 million capital cost out of which: ○ $A 2.2 million loan from CEFC ○ $A 1.6 million grant from Clean Technology Investment program and Western Australia State Government	Commercial and industrial biowaste from various sources	Blended with existing products to improve agricultural values; sold as bio-fertiliser	NIL	NIL	Carlu, Truong and Kundevski (2019)
ReWaste plant at Yarra Valley Water	$27 million capital cost with no financial support	Commercial and industrial biowaste from various sources	Can be sold for agricultural use	Emission Reduction Fund	NIL	Carlu, Truong and Kundevski (2019)
Goulburn Bioenergy Project	$6.39 million capital cost out of which $2.1 million funded by ARENA	On-site feedstock supply, industrial wastewater from proximal abattoir	NIL	Australian Carbon Credit Units (ACCUs)	20 years PPA with Southern Meats abattoir	ARENA (2020)

2 Market status and potential

According to the IEA, modern bioenergy is the 'overlooked giant of the renewable energy field'. The same can certainly be said for Australia, where the biogas potential in Australia is estimated to be 371 PJ (103 TWh) or almost 10% of the total energy consumption of the country (Victoria Government, 2022). Although relatively small in the current energy mix, biogas is expected to play a major role in the future zero emission economy in 2050. According to Infrastructure Victoria, the most realistic and cost-effective scenario for the state to achieve zero emission by 2050 is to rely on the balanced adoption of renewable electricity, green hydrogen, and biogas at around 65%, 20%, and 10% respectively of the energy mix (Victoria Infrastracture, 2021). This scenario also has the most balanced risk profile as it maximises the use of existing fossil gas infrastructure during the transition to net zero (Victoria Infrastracture, 2021). A similar contribution from biogas in the future energy mix has also been proposed in the USA (ENA, 2020). Within the EU, about one quarter of renewable gas is expected from anaerobic digestion by 2050 with the remaining gas supply to come from gasification of biomass and green hydrogen (Navigant, 2019).

Despite the anticipated role of biomethane in the future zero emission economy, the global biogas industry is still in its infancy. Australia is even further behind. At the time of this report, there are no known biogas upgrading plants in Australia. The produced biogas is used exclusively for basic heating and electricity generation, representing a very small fraction of the potential of bioenergy via the AD pathway in Australia. As of 2019, electricity generation from AD was 4.74 PJ or 1.3 MW in generation capacity. This is equivalent to 1.3% of the estimated available potential. The produced biogas is used mostly for industrial heating and electricity generation.

Biomethane has been produced and used for human benefits for hundreds or even thousands of years. However, until recently, the potential of biomethane has been suppressed by fossil gas and petroleum oil, which were cheaper (since the cost of carbon emission was excluded). Biomethane has also, along with bioenergy overall, been relegated to the edge of the "renewables" dialogue, mainly as a result of focused attention on other forms of renewable energies (solar and wind) as well as the cost and complexity of biogas projects. Although technologies to purify biogas into biomethane are already available at commercial scale, it is still difficult to achieve economies of scale due to the highly variable composition of impurities and lack of long term regulatory and financial institutional support. Given the recent global commitment to phase out fossil fuels, there has been a much stronger focus on the role of biomethane in the future energy mix. Biomethane can maximise the use of existing infrastructure for fossil gas in the transition toward net zero emission, especial for hard to abate sectors and applications that are difficult to decarbonise by electrification.

This section will examine the current status of the Australian biogas industry to analyse existing market drivers, opportunities and barriers for advancing AD in Australia. Strategies and areas for further development are then recommended to address the identified barriers.

2.1 Current status and business as usual scenario

In Australia, AD has been used primarily for treating organic waste and wastewater. Biogas is a by-product and is used to generate electricity and/or heat. Thus, to date, the current AD market has been restricted mostly to landfill operation or behind-the-meter operation where there is a localised demand for electricity and/or heat or when biogas is produced. As a result, a portion of current AD projects in Australia are economically unviable when considering only the revenue from energy sale. The payback period of the ReWaste AD plant at Yarra Valle Water would be 130 years if the sale of electricity is only source of revenue against the initial capital investment of $27 million AUD (Carlu, Truong, & Kundevski, 2019). This example highlights the need to capture non-energy revenue such as carbon credits and green gas certificates and explore new market for the produced energy where the premium value (transportable, storable, and dispatchable) of biomethane can be fully realised rather than electricity production in competition to wind and solar.

There is also a scope to co-locate large-scale biogas production with energy intensive and hard to abate industries (e.g., cement production and aluminium refinery). The behind-the-meter market is inherently restricted by the misalignment between supply and demand in terms of location, time, and scale. For example, a major advantage of gas for industrial applications is the ability to provide large and precisely controlled thermal energy over a short period of time. Thus, large scale production and co-location are both essential to ensure the supply of a large quantity of biogas or biomethane over a short period of time. Large scale storage and grid connection for demand equalisation can also alleviate the misalignment between supply and demand.

Under the business as usual (BAU) scenario, the above-mentioned market bottlenecks will not be resolved. The AD section will continue to be restricted to behind-the-meter operation and low value energy production. Contribution of the AD to the Australian energy mix will be insignificant (well below 1%).

The full potential of biogas can only be realised with the creation of new and high value markets. As of 2022, these emerging markets have been demonstrated or explored overseas. They represent the accelerated scenario for Australia and include (1) injection into gas pipeline network or Bio-LNG/CNG production; and (2) power-gas exchange for energy storage. The potential for expansion and their commercial readiness of these current and emerging biogas market are summarised in Table 32.

Table 32. Potential for major biogas markets and their technological, commercial, and legal readiness in Australia.

Biomethane market	Potential for expansion	Technological readiness	Commercial readiness
Behind-the-meter	Moderate	High	High
Grid injection and Bio-LNG	High	High	Moderate
Power-gas exchange	High	Low	Low

2.2 Behind-the-meter operation

Behind-the-meter operation is defined as biogas production for onsite consumption to replace fossil gas or electricity purchased from the grid. Behind-the-meter operation is an established biogas market. It is financially favourable where there is the co-location of high energy biomass and high energy demand such as in intensive livestock farming, crop processing, and sewage treatment. A major driver for many of these operations is waste management to comply with environmental regulations. This market is well supported by existing technologies. There are also opportunities to expand this market in the immediate and medium terms.

AD technology for behind-the-meter applications can be very simple or highly sophisticated depending on performance and reliability requirements. Sophisticated engineering control is required when an application needs to collect and pre-process the substrate, operate the digester, manage the digestate and utilise the produced biogas. Due to the high labour cost for routine servicing and maintenance in Australia, biogas production is financially viable only at a certain scale. For example, for a piggery, the current estimated cut-off value is about 1,000 sows for viable operation.

Here, opportunities exist to reduce the CapEx and OpEx of biogas operation through the increase in market size and creating a market for new technologies. In this context, the opportunity to scale up, manage risk and reduce business costs offered by the Emissions Reduction Fund's Aggregation processes may be worth further examination. Subject to eligibility, "aggregation" under the Emissions Reduction Fund may enable individuals or organisations to draw together multiple sources of carbon abatement into single registered project or bundle small biogas projects into a single bid at the Clean Energy Regulator's bi-annual Carbon Abatement Contract auctions. For example, multiple small volume biogas production sites could be aggregated to achieve the necessary volume to offset transaction costs and/or bid into auctions. Further exploration of the impacts of recently introduced 2022 biomethane method package variations under the Emissions Reduction Fund (the 2022 Biomethane Package) for aggregation of biomethane projects and associated carbon credits is warranted.

Electricity generation from biogas is currently achieved through internal combustion or turbine engines. These engines are inherently complex with many moving parts, and thus, require regular servicing and maintenance. Fuel cell technology can potentially and drastically simplify biogas utilisation and achieve much higher energy conversion efficiency compared to combustion technology, expanding the market. Demonstration plants using solid oxide fuel cell technology to convert biogas from wastewater treatment to electricity and thermal energy have been reported in Europe and Japan. Funded by the EU Horizon 2020 program, a demonstration fuel cell plant has been installed at a wastewater treatment facility near Turin, Italy since 2017. During normal operation, the plant generates 110 kW of electricity and 45 kW of thermal energy (Gandiglio et al., 2020). In Oct 2020, a 200 kW solid oxide fuel cell plant was installed at an Asahi Brewery to convert biogas to electricity and thermal energy. Small scale fuel cell generators are also available. For example, in June 2020, Panasonic has launched a fuel cell system called ENE-FARM that can be used even for a single household with the combined heat and electricity conversion efficiency of 97%.

In the immediate and medium terms up to 2030, environmental issues will continue to be a major driver of the biogas industry. The viability of biogas projects will be sensitive to policies and incentive at both the Commonwealth and State government level. In particular, waste management and climate change policies will directly impact on the future of biogas development in Australia.

The 2019 National Waste Action Plan set a target to halve the amount of organic waste sent to landfill by 2030. This target can be partially achieved through waste reduction; however, a significant portion of organic waste (e.g. banana peel and coffee ground) is unavoidable. In October 2018, the NSW EPA revoked the exemption for land application of mixed waste organic outputs (MWOO) (NSW EPA, 2019). While other state governments have not finalised their position about MWOO, no new composting facilities for MWOO treatment have been constructed in Australia since 2018. In effect, the decision from NSW EPA has excluded composting as an approved treatment method of MWOO. Thus, a significant expansion of the biogas market biogas is expected by 2030 if the target of halving organic waste to landfill in the National Waste Action Plan is to be realised. It will be necessary to develop or adapt new technologies for source separation and managing specific contaminants in MWOO or digestate from MWOO treatment.

Climate change policies and laws in Australia have evolved significantly over the last decade. In 2011, the Australian Federal Government introduced a legislative carbon offset scheme, referred to as the Carbon Farming Initiative (CFI). Established through the Carbon Credits (Carbon Farming Initiative) Act 2011 (the Carbon Credits Act), the CFI was designed as a voluntary, broad project-based, baseline and credit carbon offset certification scheme. The CFI sought to incentivise emission reduction projects (including anaerobic digestion and biogas capture from landfills) through tradable carbon credits known as Australian Carbon Credit Units (ACCUs). The Carbon Credits Act was amended in 2014 and the carbon tax was repealed. In 2014 the Emissions Reduction Fund (ERF) was introduced to replace the CFI with broadly similar functions. As part of the 2014 amendments to the Carbon Credits Act, the criteria for assessing which emissions reduction activities would be eligible to receive credits under the Act were also amended. Consequently, in 2015, the Federal Government's Carbon Credits (Carbon Farming Initiative—Superseded Methodology Determinations—Revocation and Transitional Provisions) Instrument 2015 came into effect. Relevantly, this legislative amendment resulted in the revocation of six landfill and alternative waste treatment methods developed under the Carbon Farming Initiative. Since then, other methods have also been varied or revoked. In January 2022, a range of new methods were introduced, including relevantly, the Biomethane Package. Subject to being approved as an Emissions Reduction Fund project, the recent ERF Biomethane Package (January 2022) is likely to generate additional potential non-energy revenue through the crediting of Australian Carbon Credit Units (ACCUs) to a broader range of emissions abatement projects involving biomethane. Likewise, the ability to trade ACCUs and other carbon credits through the proposed Australian Carbon Exchange, introduces a further possibility for biomethane projects to attract higher non-energy revenue streams of this kind. Currently in its pilot establishment phase, the Australian Carbon Exchange is expected to take effect in or around late 2023.

Accordingly, the future revenue stream impacts of the 2022 Biomethane Package and the Australian Carbon Exchange on biomethane generation and use warrant further consideration by all stakeholders of the AD industry. The additional financial revenue from ACCUs is particularly important. When first introduced, the issued value of one ACCU was $16 and carbon credits accounted for 2-6% revenue in a biogas project. In February 2022, the market value of one ACCU has risen to $56.90, prompting the government to allow developers of emissions reduction projects to sell their carbon credits to the open market instead of the government as initially stipulated in their contract with the Commonwealth. As a result, the value of one ACCU has dropped to $30 as of April 2022. Despite this fluctuation in the market, ACCUs are expected to account for 10% to 50% of the total revenue from a biogas project. Additional revenue from ACCUs might change the financial outlooks of some behind-the-meter projects from loss making for environmental compliance to highly profitable.

With the exception of organic waste from municipal origins, there is considerable seasonal variation in feedstock availability, and thus, biogas production. As a result, supply security is a major issue for large scale behind-the-meter operations. The outlook of behind-the-meter market is significantly improved when the produced biogas can be stored on site or biomethane from an external source (e.g. via grid connection or bio-LNG) is available to ensure supply security. In this aspect, the three markets in Table

32 do not compete, instead, they can complement one another for a diverse and cost-efficient biogas sector.

2.3 Grid injection

Biomethane can be readily obtained from biogas and injected into existing gas infrastructure networks without major upgrades. Australia has extensive gas infrastructure for both export and domestic consumption. The Australia Gas Vision 2050 has also identified biogas as a key element for converting the current gas network to zero-emission (Australia & APGA, 2017). The current gas infrastructure in Australia can store 27,000 PJs, dwarfing the storage capacity of all other technologies, for examples, the Snowy Hydro 2.0 (360 PJs), Battery of the Nation (140 PJs), and Tesla Big Battery (0.2 PJs). Utilisation of the gas infrastructure to deliver energy also reduces emissions at half the cost to customers compared to electrifying the services provided by gas (Australia & APGA, 2017).

Technologies for purifying biogas to biomethane and grid injection are readily available but still expensive, especially for small scale operations. In Australia, biogas upgrade, transmission, and injection would result in an addition of 5.9 AUD to 9.5 AUD to the cost of each GJ of gas in the pipeline (Guerin, 2022). The CapEx for additional infrastructure to inject biomethane to the grid is also significant. This infrastructure typically includes pipeline extensions and a remote automated flow unit or RAF (see section 1.6.2). As of 2022, Australia has had no or very limited grid injection experience. A $12 million demonstration project to produce biomethane at Sydney Water's Malabar wastewater treatment plant for injection into Jemena's gas network is due for commissioning at the end of 2022 and grid injection of biomethane will start in March 2023. Compared to behind-the-meter operation, grid injection is more technologically demanding and can be economically viable only at a sufficient scale. Further work to develop new technologies and suitable legal framework to govern grid injection will be needed for commercial scale grid injection in Australia. As discussed in 1.6.2, the cost of biogas purification and infrastructure for injecting into the grid is expected to significantly decrease as the grid injection market increases in size and becomes mature over time.

The current market setting does not allow biomethane to compete with fossil gas in both production cost and capital investment for accessing the gas grid. Figure 14 depicts major components of the potential supply chain for biogas from anaerobic digesters or landfill to finally entering the grid. The first three steps, namely biogas production, pre-treatment, and onsite utilisation, have reached commercial maturity. However, they are currently confined to the behind-the-meter operation market which has limited scalability as described above. There are significant challenges in all subsequent steps from biogas upgrade to grid injection in Figure 14. There are also opportunities for technological and market breakthrough for cost reduction in each of these steps. For example, biomethane can be injected either to the distribution grid (<4 bar) or transmission line (<40 bar). Injection into transmission lines allows biomethane to reach long term storage facilities, but it is technologically demanding and only suitable for a major hub. Injection into the distribution grid is the default choice when biogas production is close enough to the gas grid. Injection capacity into the distribution grid is limited by maximum grid capacity, gas pressure and flowrate in the grid, customer demand, and number of injection points. These factors could lead to situation where biomethane producers cannot inject into the grid. Thus, it is essential to develop technologies for flow reversibility and matching supply and demand.

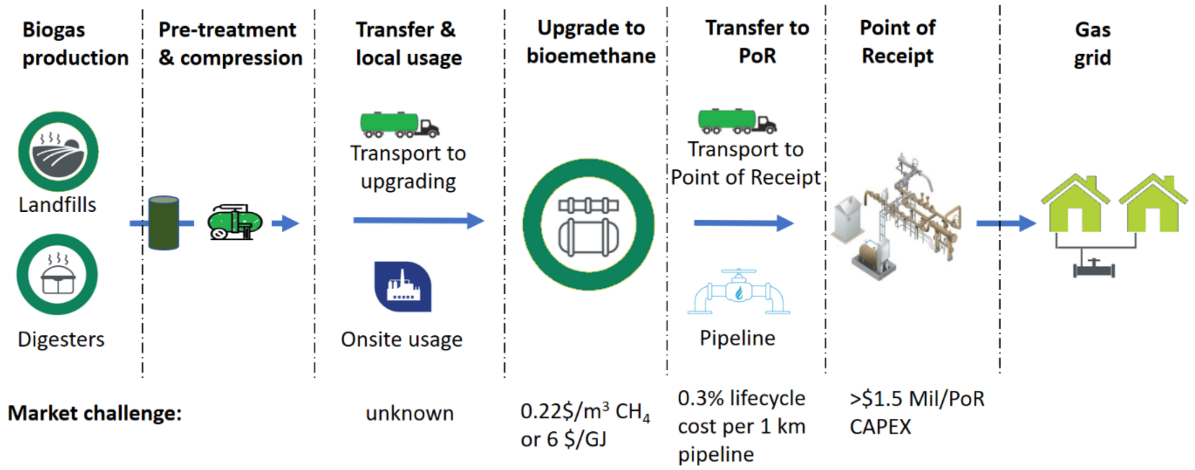


Figure 14. Schematic illustration of biomethane grid injection.

High infrastructure cost is a primary barrier to biogas producers accessing the gas grid. In 2020, the US EPA estimated that the cost of pipeline extension and construction of point of receipt for gas injection is between $1.5 to 3 million per site, depending on the design capacity and location (US-EPA, 2020). Here, there are opportunities for standardised and modular design of grid injection units and market development to substantially reduce the unit cost. Grid injection requires a comprehensive legal framework to regulate the interaction between grid owners and gas injectors. Such a legal framework has not been developed in Australia.

New technologies will be needed for gas storage and the transfer of biogas from small scale digesters to a centralised location, biomethane upgrade, quality monitoring, compressing, bottling, dispensing, and network optimisation to achieve a viable injection capacity. There are also market opportunities to (i) inject near large gas users such as a cement production or aluminium refinery facility; and (ii) development of micro-bottling technologies to export biomethane beyond grid injection capacity.

Biomethane can be converted to liquefied natural gas (bio-LNG) using existing technologies and gas infrastructure. Bio-LNG is biomethane that has been cooled to -160^{0}C, changing it from a gas into a liquid that is 1/600th of its original volume. Biomethane can also be compressed to 25 bar for storage as bio compressed natural gas (bio-CNG) that is 1/100th of the original volume. In the context of biomethane, further technology development will be needed to lower the cost of LNG or CNG conversion at micro scale and manage operational risks associated with flammable methane gas. In November 2021, a consortium of Optimal Group, BOC and Elgas announced a plan to build a $55 million waste-to-biogas plant to provide biomethane for bio-LNG production. The plant will use BOC micro-LNG technology (<50 t/d) that is modular and can achieve the same price per tonne as a conventional plant with 200 t/d capacity.

As part of the 2021 National Gas Infrastructure Plan, biomethane was considered in the accelerated review of the National Gas Law framework (Department of Industry Science Energy and Resources, 2021a) and in 2022, the National Gas Law and Regulations were changed from covering natural gas only to now included "covered gases" such as natural (fossil) methane, hydrogen, biomethane, synthetic methane and blends. As of 2021, the Clean Energy Regulator was also working on an ERF method for biomethane to support further investment in grid injection and micro-bottling technologies. At State

Government level, the NSW government has announced a pilot renewable gas certification scheme (GreenGas) to open a voluntary market for industrial gas users to buy renewable gases. In addressing regulatory complexities associated with jurisdictional-based differences across the Commonwealth, States and Territories, the overlap and market competition between Renewable Gas Certificates and Renewable Energy Certificates will need to be addressed through a homogenised policy framework. Additional work will also be needed to clarify and regulate access to gas distribution network and LNG/CNG facilities to support long term investment in these infrastructures.

2.4 Power – gas exchange for energy storage

Renewable methane presents a new and exciting opportunity for whole system decarbonisation. As a versatile fuel, methane can be cheaply transferred and stored, and efficiently converted to electricity (Ghaib & Ben-Fares, 2018). Surplus electricity from wind and solar can also be used to produce synthetic biomethane via the production of renewable hydrogen and then methanisation to form methane (Figure 15). The bidirectional transformation between synthetic methane and electricity together with extensive gas infrastructure offer a new and significant market to biogas industry in Australia. When realised at commercial scale, power to methane conversion can support the electricity grid during times of high and low demand to provide secure, lowest cost and low emissions electricity for use across the economy.

Pilot demonstrations of power to methane conversion have been built overseas (Ghaib & Ben-Fares, 2018). However, significant investment in R&D and pilot testing will be needed to reach technological maturity for large scale power to methane operation. Energy loss from the conversion from electricity to methane is still very high, at about 40%. In addition, there have yet been any long-term operational experience beyond pilot demonstration. Despite several technical and economic challenges, commercial scale of power to methane is expected given its capability to transfer energy between the electricity and gas grids. A comprehensive regulatory framework that integrates the electricity and gas market will also be needed to support market development of power to methane.

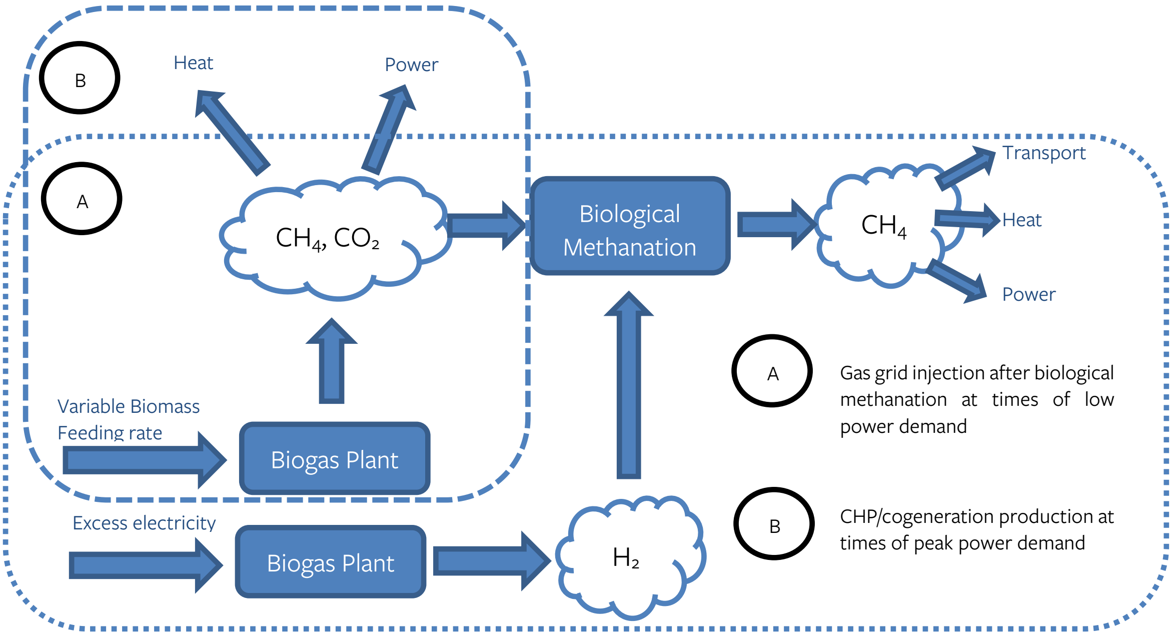


Figure 15. Power to gas exchange system that can supply or store energy at time of low and high demand, respectively. Adapted from (Persson et al., 2014)

3 System transitions

This section explores the expansion of biogas production with AD technology through a socio-technical transition lens. Firstly, it categorises biogas production as a socio-technical system within the broader field of complex adaptive systems. It then explores the application of the multi-level perspective (MLP) to explain where biogas is situated in Australia's renewable energy transition. Finally, it places biogas production within the Technological Innovation Systems (TIS) framework and summarises the functional strengths and weaknesses of the AD system.

3.1 Conceptualising socio-technical transitions

For AD (Figure 16), drivers of change at the landscape level include anticipation of more intense impacts of climate change, global movements towards decarbonisation and circular economy principles, fossil fuel divestment strategies, burgeoning consumer preferences for renewable forms of energy, and threats of action in international markets to implement trade barriers to carbon intensive products. However, at the niche level, unlike other technologies such as roof top solar PV, which is a relatively standardised technology producing a single form of energy (i.e., electrons), AD is better described as an ecosystem (Walrave et al., 2018). AD is made up of multiple technologies (covered lagoons, closed digestors, landfill gas collection etc.) delivering a range of products (biogas, biomethane, green CO_2, digestate etc.). Only some of these are energy products (e.g., biogas and its derivatives), most require further processing with additional technology (e.g., biomethane), and could be considered as technology niches in their own right. The AD ecosystem is further complicated because some AD applications are 'mature' technologies in some business contexts, while others are nascent (see Markard (2020) for a detailed discussion of innovation lifecycles). For example, biogas from AD is generated using a range of technologies (CAL, landfill gas capture and closed vessels) and is commonly used in behind-the-meter applications to satisfy site energy requirements for heating and electricity, both mature applications. However, production of biogas or its derivatives for distribution to commercial off-site energy users is an emerging application of the technology currently struggling to obtain a place in Australia's energy system.

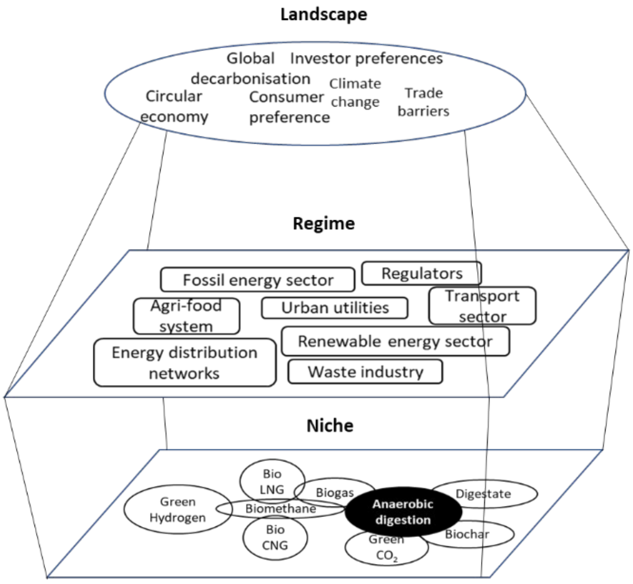


Figure 16. Multi-level perspective (MLP) framework applied to anaerobic digestion

In addition to the complexity inherent at the niche level in the AD ecosystem, how AD and its outputs interact with the regime level is also highly complex. Actors at the regime level include the agri-food system, the waste industry, urban utilities, the transport sector, energy generators and distributers, and the manufacturing sector. Some sectors are involved in supplying inputs to AD and are also potential users of AD outputs, such as the agri-food sector. AD relies on organic feedstocks that are inherently variable in properties (density, moisture and chemical composition) and in geographical and temporal availability of supplies from a broad range of providers, such as farms, food processors, wastewater utilities, and municipal waste collectors. Equally, as farming moves to more regenerative practices, agricultural carbon wastes may be needed on farm to create more regenerative farming systems, as was noted by an agricultural IRG member. New sources of urban food waste are also being explored, as ways of supplementing more traditional feedstocks. For example, the 2018 Melbourne Sewerage Strategy suggested the use of the sewerage system as a vehicle for collecting food waste from households to produce biogas and reclaim nutrients, while reducing the emission of methane from landfill (Melbourne Water, 2018).

Economics limits long distance transport of feedstocks. Therefore, selecting the most appropriate AD technology within place-based feedstock constraints entails business risk. Furthermore, situating AD processing according to availability of feedstocks, may not optimise the use of the range of outputs (energy and non-energy), considering for most outputs, markets are currently absent, transport costs prohibitive, and opportunities for networked distribution of biogas derivatives currently unavailable and subject to resolution of technical issues. Additionally, the regulatory environment is inconsistent across jurisdictions and can vary with type and source of feedstock and intended use of the outputs.

It is hard to determine at present if the difficulties faced by proponents in establishing AD as a viable part of the energy sector result from passive or active resistance by the regime. It is likely that in seeking to demonstrate net zero emissions by 2050, policy actors and regime activity have prioritised 'low hanging fruit', like electrification of domestic residences and businesses driven by existing capacity and ongoing investment in solar PV and wind energy generation. Some industrial processes are difficult to electrify, such as steel and aluminium processing, and will likely require gas as a substitute for coal. However, at present, hydrogen appears to be favoured as the putative energy source. While renewable (green) hydrogen is a derivative of AD-produced biogas, alternative processes exist for its generation from renewables; proponents of alternatives pose one potential source of active resistance through industry lobbying of policy makers.

3.1.1 Anaerobic Digestion as an Innovation System

While the MLP is a useful tool to examine key socio-economic factors shaping development pathways, another framework, Technological Innovation Systems (TIS), allows a qualitative analysis of the structure and functional strength of a technology. TIS can reveal barriers to the success (Table 33) (Jacobsson & Bergek, 2011), and identify blocking and inducement mechanisms and how they are linked to functional patterns (Bergek et al., 2008) in a sustainability transition, such as establishment of a biogas industry. TIS has been used in Switzerland to analyse the drivers of biogas technologies in mature markets (Nevzorova & Karakaya, 2020) and identify technological and organisational development options for biogas, and in Rwanda to investigate adoption of bio-digestion in an emerging innovation system (Tigabu et al., 2015).

In Australia, Cox et al. (2021) used TIS to explore the coordination and legitimacy of the Australian biofuels innovation system 1979 – 2017.

Table 33 shows the range of issues identified through industry stakeholder engagement processes in association with each of the TIS functions in the Australian AD innovation system. While there are some strengths, such as active expansion of AD capacity and a relatively small but informed and well-connected network of AD actors, many weaknesses were identified. The weaknesses are discussed in detail in 4.1, 4.2, 4.3, and 4.4, and include the need to expand the local AD skills-base, the need for engagement with the agriculture sector on collection and use of crop residues, lack of policy cohesion, coordination and recognition of AD energy outputs, the need for access to gas networks, and limited public understanding of renewable energy from AD compared with roof top solar PV.

Table 33. The functions of a technological innovation system applied to AD in the Australian energy system (adapted from Jacobsson and Bergek, 2011)

Function	Description	Australian AD innovation system
F1. Entrepreneurial experimentation	Pursuit of commercial aim	On-going expansion of AD capacity Integration into local clean energy initiatives
F2. Knowledge development	Development of new knowledge including R&D activities	Industry developed standards for biogas Expansion of local AD skills-base Agri-tech development for collection of crop residues
F3. Knowledge diffusion	Enablement of knowledge sharing among actors	Small but well-developed AD knowledge networks in place Knowledge deficits among policy actors
F4. System guidance	Guidance toward selection of particular technologies	Lack of interest from European tech providers Landfill organics-removal policy
F5. Market formation	Development of niche markets and their expansion	Economic relativities of range of renewables Uncertain policy environment on government priorities and incentives Lack of policy recognition of biogas Inability to attract investment for implementation Need for certainty in feedstock supply and quality Opportunities for 3rd party value-added commercialisation of AD outputs (digestate)
F6. Resource mobilisation	Promotion of availability of resources to overcome blockages	Gas network connection issues Circular Economy initiatives
F7. Legitimation	Increased acceptance of technology	Limited public understanding of biogas benefits Community engagement on place-based development issues

4 Barriers

AD is a well-established technology with significant potential to achieve environmental, social and economic gains for organisations, however uptake is limited (Ackrill & Abdo, 2020). This section of the report details key barriers acting against the widespread adoption and diffusion of AD technology. Four types of barriers are discussed: social license and responsible innovation; technical; economic; and regulatory.

4.1 Social license and responsible innovation

Social capital is a key component to any energy transformation project, not least those associated with anaerobic digestion. When it comes to the socio-cultural barriers that can have an impact on the adoption and diffusion of AD technology, many factors are at play. For instance, religious beliefs, traditions and the level of education (among other demographic factors) appear to impact biogas adoption Socio-cultural barriers appear more prevalent in developing economies compared with developed counterparts though some barriers still persist (Nevzorova & Kutcherov, 2019). For example, some EU member states are grappling with the financial impact of biogas on end-users, together with a "not in my backyard" (NIMBY) mentality, reducing the political will to support AD projects (O'Connor et al., 2021). This also extends to the US, where biogas facilities are often located in rural communities where there may be greater social disparities (Gittelson et al., 2021). This may be less of an issue in Australia where there are already existing sites, such as landfills or wastewater treatment plants, that have achieved social acceptance as part of a sustainable energy, waste and land-use strategy.

The lack of trust in the Australian population about fossil gas more generally is high. This has arisen from simplistic messaging and recent public experience with the fossil gas industry's actions and reluctance to move to greener energy alternatives. Biogas proponents need to ensure that the Australian public do not see biogas as a way to support fossil gas, while ensuring that they do not oversell how much can be produced, and how it fits into the broader sustainability aims.

International experience is informative in this context. For example, in Germany, anti-biogas sentiment has increased in recent times, leading to a reduction in biogas project investments on farms (Hjort-Gregersen, 2015). Part of this negative view is associated with the widespread understanding that over the first 15 years of biogas production increases in Germany (which led to it being the largest biogas producer in Europe) (Gustafsson & Anderberg, 2022), the relative price of other renewables drastically reduced. Thus, the positive incentives to put farmland into maize crop production to make silage for AD biogas production for electricity generation have been reduced. It is likely that these economic drivers are having a bigger downward impact than any social barriers. The broader sustainable land use requirements both in Germany and the EU have led to a rethink of how much biogas is needed for electricity supply and targets have moved downwards because of this. Considerations including place, referring to "cultural, economic, environmental, historical, political, social, and technological characteristics", aesthetics, proximity all have a potential impact on public perception (Peterson et al., 2015). Whilst individuals may appreciate the importance of renewable technologies on a global scale, when certain technologies, and AD in particular, are being deployed in a community, the public perception is often negative. Just because individuals fully support the notion of renewable energy does not necessarily mean they will be accepted in a particular community (Bourdin et al., 2020). Specific issues facing AD technology include odour, explosion risk, increases in traffic and devaluing of property (Bourdin et al., 2020). This is also evidenced by a response from one participant in the meat processing focus group:

> *"Every family, every mum and dad can be part of the solar energy revolution that is taking Australia by storm, but it is very hard for them to get their head around the job that digest does, it smells, it doesn't look very good how do they participate in that?"*

Trust is also a core theme, as communities grapple with the likelihood of a negative impact whilst navigating the intentions of developers, which can lead to a perception of a particular technology not being environmentally friendly (Bourdin et al., 2020). This is a common barrier for organisations that rely on decentralised modes of operation that depend on effective collaboration between value chain members. It is for this reason that some organisations prefer to capture value internally to the firm and avoid external collaborative efforts, as is the case for AD adoption in Irish farms (O'Connor et al., 2021).

A significant factor in shaping public opinion of technologies such as AD revolves around the manner in which a community is involved in the process (Peterson et al., 2015). For AD in particular, community engagement seems to be particularly problematic, if it is conducted at all (Bourdin et al., 2020). In the Australian experience, social acceptance issues are not so pervasive given that projects seem to be located outside populated areas (Carlu, Truong, & Kundevski, 2019). Nonetheless, effective community engagement is still recognised as a critical first step (Carlu, Truong, & Kundevski, 2019). While there are many different ways in which community engagement can be achieved, it would appear a collaborative approach where the community is actively involved in design and policy matters can prove helpful (Jami & Walsh, 2017). This was mentioned by one of the respondents in the meat processing focus group:

> *"We come from a regional area and we want the local community to be involved in the concept. Bring in stakeholders that range from councils to other food processors to be a part of the process and doing their part for the environment and climate…"*

However, not all energy technologies are the same and the way the public perceives the adoption of thesetechnologies is also impacted to varying degrees. It is for this reason that the public views such technologies as a "highly complex socio-technical system" (Scheer et al., 2017) – the likes of which is not so straight forward to unpack and leverage.

Summary of key social barriers:

- Negative public perception and stigma is an ongoing and persistent barrier in AD adoption. However, this may not be as strong in Australia, though it should still be considered for each project in case it becomes more prevalent.
- Community engagement is a critical first step to AD projects. However, because of the potentially complex nature of AD operations, there is no one-size-fits-all approach to this.

4.2 Technical Barriers

The technical barriers acting against AD adoption are relatively well understood, with global experiences yielding similar insights (Hasan et al., 2020; Nevzorova & Kutcherov, 2019; Norouzi & Dutta, 2022). Some of the recurring themes that appear in technical barrier reports include infrastructure constraints, technical failures, transportation issues, after-sales support, specific characteristics of the biogas, feedstock selection and supply as well as knowledge-related barriers. The strongest of these are discussed further here.

Infrastructural challenges relate to upgrading existing infrastructure and achieving viable scale. One of the key constraints relates to the characteristics of existing infrastructure, particularly for AD producers looking to inject gas into the grid. Because a lot of the existing infrastructure is quite old, there is an inherent need for biogas producers and associated energy entities to upgrade existing infrastructure to meet the needs for a viable gas injection operation. Another prominent infrastructural barrier relates to achieving viable scale. In this case, there are minimum requirements by way of biogas output that need to be met for an AD operation to become and remain viable in the long term. For smaller producers, this would mean, for instance, developing novel collaborative methods to foster the required scale via centralised storage. Such a collaborative effort would indeed require significant capital outlay in terms of infrastructure requirements, among other design and technical considerations.

Another technical barrier relates to the availability, security and characteristics of feedstock. Indeed, AD requires measured and consistent feedstock supply and characteristics in order to function effectively over time. This challenge is compounded by the diverse nature of AD operations and the site-specific characteristics for each AD operation. In Australia, feedstock supply is a particularly acute obstacle, especially in regional areas, with the potential to significantly impact the financial viability of AD adoption. As was mentioned during the municipal and landfill focus group:

> *"In regional areas, security of feedstock is quite important as waste volumes are not huge. If another facility opened up and cut us on price, it could ruin the return on investment. We need to secure the feedstock; long term contracts are helping."*

However, there is sometimes a reluctance on the part of feedstock suppliers to sign long-term agreements. This feedstock insecurity is exacerbated by the physical distance between the AD plant and feedstock suppliers, driving feedstock prices upward (Carlu, Truong, & Kundevski, 2019). Another challenge relates to the viability of feedstock suppliers to produce feedstock specifically suited to AD, which is the case for energy crops in Europe. In the UK, this reluctance to participate in AD markets is exacerbated by the long-term uncertainty regarding revenues from producing AD feedstock as well as the political climate. In such circumstances, international experience, such as that illustrated by the EU's incorporation of sustainability criteria into its renewable energy laws regulatory framework, can successfully address such concerns. This is considered further in the subsequent Opportunities discussion.

Technical barriers also stem from the fact that AD systems can vary in complexity and scale, from a bag that can be used to generate biogas for use in residential households to turnkey commercial solutions ranging in the tens of millions of dollars. In the case of commercial use of AD, engineering control structures, policies and technology are crucial to maintain an effective AD process. This requires a level of expertise to design, operate and maintain an AD system, which poses a considerable barrier in the Australian context. Given the nascent nature of AD adoption, there is a lack of domestic engineering experience in designing and operating biogas plants. This has the potential to incur construction risks, process failures, poor biogas quality and over/under capacity of CHP/cogeneration units. Thus, safety has remerged as a common theme in AD discussions in the EU, given heightened safety protocols have the potential to increase the cost of building and upgrading AD systems considerably.

Summary of key technical barriers:

- The technical barriers towards AD adoption include infrastructure, feedstock supply and characteristics as well as knowledge gaps in AD implementation.

4.3 Economic Barriers

Economic barriers to the adoption of technologies aimed at resource (energy) efficiency can generally be brought down to market failures or market barriers (Thollander et al., 2010). Market failures represent those barriers that seem to "[violate] the underlying axioms of mainstream economic theory" (Thollander et al., 2010, p. 50) including imperfect and asymmetric information, split incentives and others. On the other hand, market barriers represent those economic barriers that cannot necessarily be explained by market failures, but nonetheless contribute to the lack of adoption and diffusion of the technology including, upfront capital requirements and hidden costs (Thollander et al., 2010).

There appears to be some consistencies with market failures when it comes to the adoption of energy efficient technologies in general. For example, in the case of Ireland, where there is a lack of adoption of AD technologies despite the immense potential created by the size of their agriculture sector, the most significant barrier is a lack of information regarding the technology itself (O'Connor et al., 2021). Though a common theme amongst the European community in general (O'Connor et al., 2021) and an emerging theme in the Australian context (ENEA & Deloitte., 2021), this phenomenon applied only to those that had an interest in adopting AD into their operations in the first place. Other observed market failures associated with information and knowledge sharing include an uneven distribution of knowledge amongst key policy makers as well as between key AD value chain partners.

Market barriers are also commonly associated with the uncertain economic benefits of the AD technology adoption itself. Recent figures in the US, for instance, suggest the costs associated with AD adoption based on an on-farm model can outweigh the economic benefits that they bring for dairy producers (Lee & Sumner, 2018). In the Australian context, some earlier adopters of AD technology in piggeries have also voiced concerns over the economic benefits of AD adoption whereby internal value capture was preferred over revenue from selling biogas back to the grid (ABC, 2016). This approach seems to be persisting in recent times (ABC, 2021). The uncertainty over the profitability of AD adoption has also led banks and other lenders in the EU to impose strict preconditions on potential adopters, stunting further adoption of the technology, particularly for smaller producers (Hjort-Gregersen, 2015). A more comprehensive list of market failures and market barriers can be found in Figure 17.

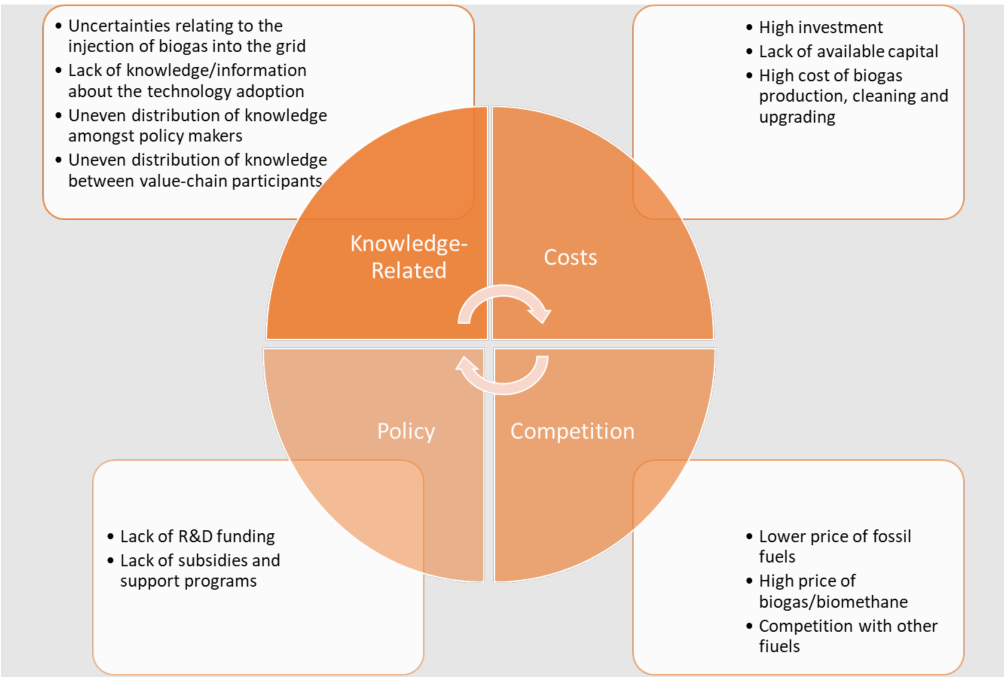


Figure 17. Economic barriers to AD adoption (Carlu, Truong, & Kundevski, 2019; Nevzorova & Kutcherov, 2019; O'Connor et al., 2021)

Despite the pervasive nature of economic barriers in the adoption of AD across sectors, there are indeed organisations that have managed to overcome such obstacles and work towards long-term sustainable growth. For instance, Germany has a projected 9,692 biogas plants with an annual turnover of €9 billion in 2021 (GBA, 2021). Whilst a significant portion of these successes can be attributed to favourable policy making (as will be discussed in the next section), organisations still have to find a way to create new opportunities for growth and capture the value from these opportunities in order to remain viable. As is forecast in the case of biogas production in Italy, for instance, the introduction of new plants and their output in terms of energy generated has, to some extent, stagnated off the back of radical policy changes in 2008 (Benedetti et al., 2021), with a lack of support for the construction of new plants in general (O'Connor et al., 2021). In such cases, there are calls for creating new opportunities for AD adopters to grow and better capture the value from these opportunities.

Summary of key economic barriers:

- Economic barriers can be split into two forms, i.e. market failures and market barriers.
  - The key market failure is knowledge-related, both in terms of leveraging the technology for generating and capturing value and the more technical know-how.
  - The key market barrier relates to uncertainty over the economic benefits of AD technology adoption. Other well-known market barriers include those related to costs and competition against other (often less expensive) technologies and fuels.
- A significant contributing factor towards the economic successes of AD technology in other regions around the world relates to favourable policy making. However, this may not be enough to sustain a market in the longer term.

4.4 Regulatory Barriers

"Regulation" is a generic term, which includes legislation, regulations and statutory rules, delegated legislation where decision-making or other powers are given by government to someone else, industry codes and other regulatory tools created at national, state/territory and even local levels (Australian Government, 2010). Behind and shaping regulations are policy frameworks, within which regulation is developed and implemented. These can encourage or hinder the development of biogas and biomethane as contributors to the renewable energy resource pool. This section on regulatory barriers includes relevant policy frameworks in the generic scope of the term "regulation", unless otherwise indicated.

Regulation can impact upon the biogas/biomethane industry at the planning, production, distribution and end-use stages. Some of the areas where existing regulation can impact include:

- planning regulations relating to location;
- environmental and technical regulation, both for storage and production;
- transportation of feedstock and finished products;
- safety regulation in gas and feedstock handling; and
- market regulations in the gas and electricity markets.

Currently, regulations covering most aspects of biogas and biomethane are complex and multilayered. They provide a confounding and complicated policy and legal backdrop to achieving a greater role for these energy sources in the new low carbon energy mix. They also impact in diverse ways on all existing and emerging barriers and opportunities. For example, current regulation often creates barriers to market entry when biogas is used to generate electricity and it is complicated to sell it into the electricity grid. Another barrier relates to use of biogas or biomethane as part of the existing gas pipeline network. In addition to technical issues, there are regulatory issues with injecting biomethane into the established gas pipeline network.

This summary provides only a snapshot of the general groups of regulatory barriers, and in turn, highlights potential regulatory opportunities. While suitable regulatory frameworks are pre-requisites to establish, support and operate viable AD biogas and other renewable gas businesses, regulation on its own is not sufficient to achieve such ends. The regulatory framework may require positive incentives or actions to overcome key market, social, environmental, and technical barriers.

Currently, a wide range of regulatory barriers arise at various stages of the AD biogas and biomethane production, supply, and end-use transactions. This review looks at regulatory barriers that relate to two general production processes: The AD biogas process (AD-Biogas); and the AD biogas renewable natural gas process (AD-Biogas-RNG).

The AD-Biogas process includes the entire chain of production, supply, and consumption: from primary inputs (feedstocks) for biogas generation, through storage, transportation, distribution, and to final end-use, usually as a fuel to produce electricity and heat onsite, or for direct use in other processes or appliances. As discussed previously, the AD-Biogas digestate may also have an additional commercial use as fertiliser (IEA, 2020). Key recognised regulatory barriers include those impacting on primary production and supply of AD-Biogas, regulatory issues around the location of anerobic digestor and feedstock (sustainability, land use, seasonality, storage, transportation) and regulatory barriers to end-use applications and waste.

The AD-Biogas-RNG process covers the production of RNG by upgrading biogas into biomethane or the 'thermal gasification of solid biomass followed by methanation' (IEA, 2020). Upgrading biogas into biomethane for grid injection entails a range of known regulatory issues relating to the transportation and distribution of biogas to upgrade facilities, as well as legal and technical constraints on injection of RNG into gas pipelines and distribution network, and incompatibility with many end-use applications. AD-Biogas-RNG also raises by-product/waste disposal issues, most notably CO_2 resulting from upgrading processes.

Many of the regulatory barriers relating to the AD-Biogas and AD-Biogas-RNG processes are well known; others are emerging with new potential uses. For example, AD-Biogas-RNG's varied applications as a potential energy source gives rise to further regulatory complexities. Potential uses, which include vehicle fuels, gas grid injection for domestic and/export gas markets, or localised application as an additional fuel carrier in domestic or industrial electricity generation and end-use, bring their own regulatory complexities (ARENA, 2020; Carlu et al, 2019).

4.4.1 Different kinds of regulatory barriers

Generally, the nature of the regulatory barriers for each of these processes fall into three main types:

1. Non-existent regulation where its existence would be helpful for the development of an AD biogas/biomethane industry;
2. Existing regulation is inadequate or not fit for purpose; and
3. Regulatory complexity and confusion.

4.4.1.1 Non-existent regulation

There are some "missing pieces" in the regulatory and policy landscape, which could encourage or facilitate the broader used of biogas and biomethane to accelerate the move to low carbon energy production and away from fossil fuel sources. These include the absence of:

- a comprehensive national renewable energy law that incorporates a renewable gas target;
- an effective and comprehensive carbon pricing mechanism (Garnaut, 2011); and
- mandated sustainability criteria for bioenergy production.

A comprehensive renewable energy law including targets, could be of significant assistance to the growth of the AD biogas and biomethane industry and provide greater policy certainty for investors and industry developers.

There are several reasons why this situation has occurred in Australia, but the main one has been a paucity of political leadership by previous Federal Governments and a lack of integrated climate-energy policy and laws. Drawing on international experience, by contrast, the EU has embedded this kind of policy and legislative framework into the EU economy over the past 30 years. As such, EU efforts in relation to renewable energy and accompanying societal transition provides a useful example of the cooperation required between governments to develop and implement the necessary changes to support the development of an Australian biogas sector, e.g., clear, constant regulatory progression that provides legal and investment certainty. Further details on this are set out in Appendix G – EU Renewable Energy Regulation Case Study.

The absence of a national carbon pricing scheme since 2014 has also impacted the Australian decarbonisation transition. A pilot under the auspices of the Clean Energy Regulator of an Australian

Carbon Exchange, expected to be fully launched sometime in 2023, warrants further consideration in relation to future opportunities for AD-Biogas and AD-Biogas-RNG.

4.4.1.2 Inadequate regulation

Most existing regulations were designed principally for fossil fuel industries, some of which are now creating barriers to entry to new players. These include many of the regulations covering existing national gas and electricity markets. For example, constraints on grid-injection of gases other than fossil "natural gas" in existing national gas laws and rules and other laws include:

- the previous narrow interpretation of "natural gas" in the National Gas Laws (NGL);
- natural gas Australian Standards;
- the application of economic regulation of gas pipeline infrastructure and distribution networks to AD-Biogas-RNG blending facilities; and
- related site-specific issues such as the location of upgrading/blending facilitates and grid injection processes.

The current Australian Energy Ministers' agreement to reform the national gas regulatory framework seeks to enable renewable gases, including AD-biogas and AD-Biogas-RNG, to come within the regulatory scope of the NGL, and where necessary, the National Energy Retail Laws (Australian Government, 2022). The consultation period was extended to 19 May 2022. Regulatory proposals may come forward from this, including a draft legislative package and draft rules. The purpose of this work has been to support the transition in the national gas market to enable participation by the AD-Biogas and AD-Biogas-RNG sectors. In October 2022, Energy Ministers agreed to amendments to the NGL and Regulations to allow biomethane, hydrogen and other renewable gases to be included in the national gas regulatory framework, and now refers to "covered gases" rather than "natural gas". Similarly, the National Energy Retail Law now refers to "natural gas equivalents" and "prescribed covered gases". Energy Ministers tasked the Australian Energy Market Commission with leading work to "identify and develop amendments to the National Gas Rules and National Energy Retail Rules", and AEMO with leading work to "amend the Procedures and other AEMO-made instruments required for settlement and metering in the … retail gas markets". Consultation on proposed legislative changes to incorporate an emissions reduction objective into the national energy objectives was commenced in December 2022 by the Energy Ministers, as part of the National Energy Transformation Partnership priority.

Another example of inadequate regulation has been the history of the Emissions Reduction Fund (ERF) methodologies for measuring the carbon advantages in various industries, which do not adequately measure biogas and biomethane benefits. Biomethane projects were expressly excluded from the EFR for seven years between 2015 and 2021, which resulted in a marked decline in the number of such projects during this period. While the introduction of the new biomethane package in early 2022 will certainly go some way towards remediating this, progress will not be instantaneous, with the benefits of these reforms taking months or perhaps years to flow through to positive outcomes.

The 2020 King Review, which looked at additional sources of low-cost abatement, recommended 'allowing ERF methods to award ACCUs over a shorter, compressed timeframe and ahead of when abatement is achieved' (Department of Industry Science Energy and Resources, 2020). Depending on the nature of an ERF project, the "regulatory additionality requirement", which is the offset test in the ERF legislation, may also create a regulatory barrier by prohibiting the award of ACCUs for activities that are already legally required. The Clean Energy Regulator's change of approach in 2020 enables a broader interpretation of what activities may satisfy the "regulatory additionality" requirement, for example, where existing legal requirements are exceeded (Clean Energy Regulator, 2020). Whether this will overcome the barrier is yet to be seen.

4.4.1.3 Regulatory complexity and confusion

Overly complex, repetitive, inconsistent and/or different policy and legal mechanisms across Commonwealth, State/Territory, and local levels of government, result in different regulatory frameworks across Australia. These include:

- complex regulatory instruments relating to energy sector stakeholder authorities, including permissions, licenses and permitted or prohibited activities;
- multiple environmental, water, and land use constraints and protections, arising from different levels of government;
- complex safety and technical regulation, including multiple industry codes, and transport and storage regulation; and
- policy and statutory changes to end-use applications, such as emerging mandates against gas connections to new residential developments.

The complexity and confusion were vividly illustrated in a recent high-level review of primary and secondary legislation and standards relating to renewable gases (hydrogen, biogas, and biomethane) by the Future Fuels CRC. This identified over 250 instruments across the nine Australian jurisdictions (Future Fuels CRC, 2020). This includes state, territory and federal acts, regulations, rules, codes, standards, and other instruments relating to economic, environmental and land use, safety, and technical regulation, and end-use, as well as business and corporate law requirements. While the Future Fuels listing is extensive it is not legally comprehensive. Rather it provides confirmation of what is well understood across governments and industry, namely, the complexities and confusion of existing regulation in this area. The 2020 King Review proposed as one of its principles that "Policy responses would be coordinated between federal, state and territory governments and undertaken in collaboration where possible" (King Review, Principle 7) (Department of Industry Science Energy and Resources, 2020). While this is important for future policy development, the complexity and confusion are already a substantial barrier. The absence of a nationwide uniform regulatory scheme and regulatory inconsistencies between jurisdictions in relation to biogas and biomethane markets, as well as existing and emerging regulatory constraints on end-use of gas in certain settings raise further questions about the long-term viability of the sector.

Other key barriers include the absence of dedicated national renewable energy policy and legislation and national renewable gas targets for the National Gas Market. In terms of environment and planning restrictions, noted regulatory barriers include constraints on the location of anaerobic digestor, upgrader facilities and/or co-digestion, inadequate or non-existent statutory land-use/feedstock sustainability criteria, responsibilities for dealing with waste/by-products of anaerobic digestion (digestate and biosolids, e.g., PFAS – water pollution and other waste concerns – in landfill waste).

4.5 AD opportunities

There are a number of research opportunities that could help overcome the barriers to adoption and widespread diffusion of AD technology in Australia. The market size for biogas in Australia was projected to be upwards of $AUD 5bn in 2020 (Carlu, Truong, & Kundevski, 2019). Given that about half of Australia's gas consumption is used in the manufacturing and mining industries, sectors accounting for a considerable portion of Australia's total GDP, there is certainly significant potential for biogas in this context (Guerin, 2022). This section of the report focuses on research that could unlock additional market opportunities that may prove lucrative for organisations participating in the AD value chain (Figure 18). In doing so, we highlight not only specific opportunities for value chain partners to create and capture value from AD operations, but also outline some innovative business models that may help provide a holistic perspective of the market potential that AD adoption can create.

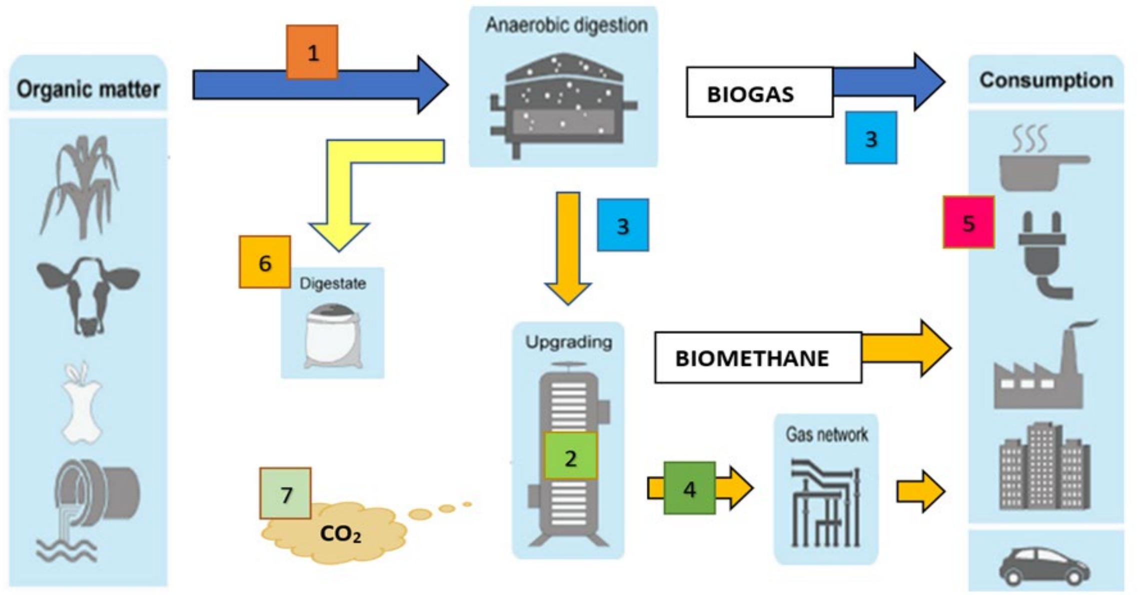


Figure 18. Simplified AD value chain including key processes

4.5.1 Feedstock supply

From the input side, feedstock supply and security has proven to be both a challenging exercise and a source of considerable opportunities for further value creation when it comes to participants in the AD value chain. Here, formalised contracts for the supply of feedstock in AD operations are favoured, based partially on the perceived reduction of uncertainty they may bring, as one respondent from the municipal and landfill focus group mentioned:

> *"Long-term contracts offer a best outcome for the customer, provider, community and the environment"*

However, these often hotly contested formalised contracts benefit from a wider engagement with the local community in which operations are proposed as well as their partners in the value chain. Informal contracts thus are also a critical component in capturing value from feedstock supply where mutually beneficial engagements, such as sharing technical knowledge and other quid pro quo arrangements seem to bolster more effective supply and foster collaborative behaviour amongst value chain participants. An example of this in the Australian context is the free supply of paunch from a meat processor to a local piggery for use in the on-site AD operation. Paunch is quite difficult to sell and, as a waste, also incurs a fee for disposal. This collaborative effort resulted in reduced costs for the feedstock supplier and helped maintain efficient operations for the AD in the piggery, helping a move towards energy independence.

Given the geographically distributed nature of feedstock, another opportunity discussed during the barriers and opportunities workshop was that of the development of specific technologies for feedstock collation and transfer. Tools for mapping and predicting feedstock availability, as well as determining the most economic transport options, were also discussed as potential opportunities required to help with a growing AD market.

4.5.2 Upgrading and cleaning

When it comes to processing and related outputs, the opportunities are seemingly more visible and quite well established. One such opportunity that has emerged from the increased interest of biogas is biogas upgrading. Biogas has not only been found to be useful in generating heat and electricity, but also as fuels in the transportation sector and as a supplement to fossil gas in existing gas pipeline grids. However, unprocessed biogas often contains impurities which limit its use in these domains including a reduction of its calorific value and its corrosive nature, creating challenges in, for example, gas engines. To effectively make use of biogas, it needs to go through an upgrading process (and, potentially, other cleaning processes too).

Biogas upgrading technologies are well established, with many variations – though such technologies generally require significant capital outlay to design, install, operate, and maintain. One novel opportunity stemming from the increased interest in upgraded and cleaned biogas is that of upgrading-as-a-service. Here, considering the potential cost constraints for implementing upgrading and cleaning technologies for smaller AD adopters, organisations in Europe have begun to offer various financing mechanisms to help support upgrading adoption. These arrangements can be in the form of a monthly payment scheme where the upgrading technology provider is responsible for all operational and maintenance duties of the upgrading equipment whilst retaining ownership (c.f. Green Lane Biogas Finance joint venture).

4.5.3 Grid injection

Grid injection is one of the more significant opportunities for biogas. Given an overview of the potential opportunities of biomethane injection into the gas pipeline grid has been provided in the Market Status Review, this section will focus on the opportunities that emerged as part of the barriers and opportunities workshop (results shown in Appendix F) conducted during this research project. Here, 32 potential opportunities (including both market and research-based opportunities) were identified across four key areas: technology, regulatory, economic and consumer.

In the technological realm, one of the more significant opportunities discussed stemmed from the need to build local capabilities in the development of large-scale biomethane projects. Here, industry and training partners could work together to develop expertise in Engineering, Procurement, Construction and Management (EPCM) capabilities. Another key technological factor pertained to the barrier of economic cost. In this case, standardisation and modular solutions came to the fore as potential opportunities. Despite the inherent need for more affordable technologies, the development of new, more efficient, and scalable digesters and add-on technologies has also been discussed as a necessary precondition to support a much larger biogas market.

From a regulatory standpoint, there is a significant opportunity for Australia to learn from the international community to urgently develop policy and regulation for certifying renewable gas. Compliance standards for overseas imported OEM equipment has also emerged as a significant need to ensure quality standards for the Australian market. The creation of dedicated government agencies proved an additional opportunity to support the development of a "level playing field", thus enabling biogas to compete with other sources of energy, as well as to drive the creation of cost sharing and innovative investment options to help lower the economic barriers to entry for grid injection. Finally, a government scheme to help underwrite the supply of feedstock and guarantee feed stock security presents itself as potential opportunity. Such a scheme could be similar to the guaranteed feed-in-tariffs that many state and territory governments in Australia have used to encourage the uptake of small-scale roof top solar PV in the early 2010s.

In the economics realm, the opportunities for a biogas market were stated to be significant. Such a market will provide pricing incentives and investment mechanisms to support biomethane projects. Along these lines, there is also an opportunity to develop mechanisms to reward gas users who purchase biomethane from the gas pipeline grid. This can be accomplished in the form of a virtual power purchasing agreement in the same way green electricity is being distributed through the electricity grid. In the immediate future, however, there is said to be an opportunity to supply biomethane or biogas directly to large commercial gas users – considered to be an important transitional market before grid injection can become financially sustainable. Along the same vein, the development of a transport fuel market, especially in the case of hard to abate transportation sectors such as maritime shipping and long-distance freight in Australia, emerged as a prominent theme. Such an opportunity can leverage the already significant LNG infrastructure available in Australia.

From the consumer point of view, there is said to be a great need to educate the public and consumers about the distinction between biomethane, a renewable gas, and fossil gas. There is a consensus that once this distinction is clear to the public, there will be grass root support for biomethane projects – echoing the general recommendations brought forward in the discussion of social barriers earlier. For large scale commercial gas users, there is an opportunity for collaboration amongst biowaste generators, biomethane producers and end-users to co-invest, de-risk upstream investment, secure a reliable energy supply, and achieve decarbonisation.

An additional opportunity in this space, and one that spreads across multiple areas mentioned above, concerns the use of Blockchain renewable gas certification. Cited as one of the most significant opportunities for the biomethane industry in Australia, this solution must be realised across all four areas of technology, regulation, economic and consumer considerations for effective implementation. For instance, it requires blockchain technology, a regulatory framework for renewable gas certification, market setting for renewable gas trading and consumer participation. Blockchain renewable gas certification is expected to open international voluntary markets for decarbonisation using biomethane. It is noted that components of this proposed system are already available, and the realisation of this opportunity will involve the assembling of these individual components (such as blockchain technology, renewable gas certification regulation, market mechanisms, and renewable gas trading).

4.5.4 Digestate

As the potential for AD adoption, and biogas in particular, continues to generate interest in the global community, this also brings forth significant opportunities for generating value from so-called secondary outputs i.e., digestate. Digestate, as "a mixture of microbial biomass and undigested material", is a useful biproduct of the AD process (Monlau, Sambusiti, Ficara, et al., 2015). In agricultural settings, the digestate is most often mechanically separated into hard/soft fractions where the harder fractions are commonly processed to produce, i.e., effective bedding for animals and soil conditioners, whilst the softer fractions can be used to produce products such as fertilisers. Indeed, it is also important to mention that on-site production of such co-products proves rather challenging given the seasonal nature of fertiliser use. As AD is operated year-round, large quantities of digestate are also being produced. The fertiliser being produced from the digestate may need to be stored – something which appears to come with significant environmental and practical challenges. This phenomenon has also created a further push for the valorisation of digestate in the commercial sphere through the production of eco-products (e.g., plant seeding pots and commercial-quality fertilisers) as well as in other domains including the production of algae, bioethanol and as a fuel for other combustion-based processes. The digestate can also undergo further processing for use in energy generation, building materials, bio-adsorbents, bio-plastics and many other co-products (see Kapoor et al. (2020), Logan and Visvanathan (2019), Monlau, Sambusiti, Ficara, et al. (2015), Tsapekos (2021) for a fuller review of potential digestate coproducts). A graphical representation of the various opportunities stemming from the use of digestate is provided in Figure 19.

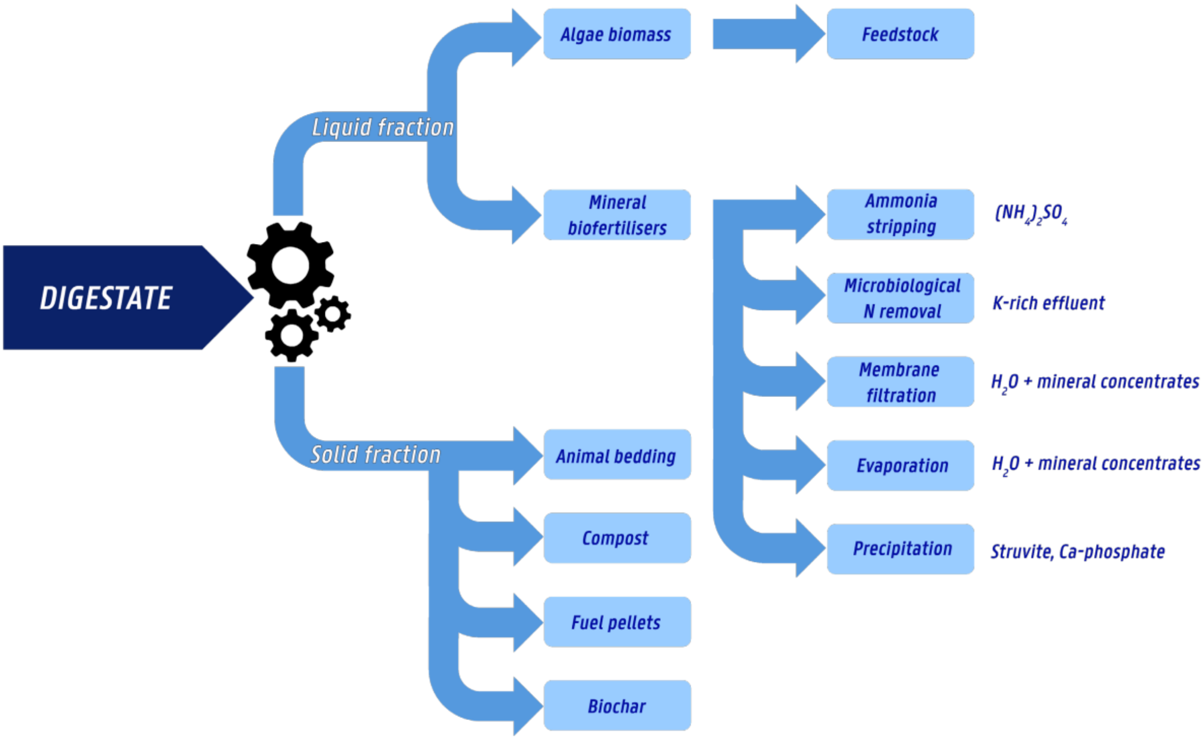


Figure 19. Digestate opportunities. Adapted from (Reuland et al., 2019)

Given such significant potential to generate and capture value from digestate and coproducts, this was also a key focus of the barriers and opportunities workshop as a secondary value-add from AD adoption (primary value-add being grid injection). The discussion revolved around, firstly, the main motivations, value, and impact, as well as key stakeholders (found in Appendix F). This was followed by a discussion of the potential enablers stemming from technology, regulatory/policy, economic/market, and social-related factors (Appendix F).

In terms of the motivation to make use of digestate in the first place, the barriers and opportunities workshop highlighted several key factors. Here, digestate was viewed as a significant contributing factor for value generation in rural settings e.g., digestate is said to help reduce overproduction, return nutrients to the soil, avoid GHG emissions, and, perhaps more prominently, reducing the purchase of inorganic fertilisers, the price of which has increased significantly in the latest months. In addition, a key opportunity for digestate stems from its reclassification as a valuable product (rather than waste). This opens the door for its use in rapid composting operations and other commercial endeavours, a potential reduction in transportation costs as well as a reduction of administrative concerns for AD adopters. The diversion of waste from landfill was also listed as a motivation. This will potentially generate a reduction in gate fees for many industries, as well as the management of waste streams such as FOGO.

In terms of value creation and capture, different stakeholder groups appeared to hold varying conceptualisations. For instance, Government organisations mentioned the creation of value-adding co-products to be a potential area of value creation. Engineered biofertilisers and a reduction in dependence on inorganic fertilisers were stated as key value creation mechanisms. Along the same vein, this is also seen as a potential solution to address water pollution issues from farmers applying unregulated manure to fields. Technology-based value creation could be realised through pelletisation of bioengineered fertiliser administered via existing spreader mechanisms. Resource recovery principles and creation of

ACCU's through waste diversion summed up discussions in the government context. However, a key question was raised in the creation of new markets – more revenue for whom?

Energy providers, on the other hand, cited the treatment of solid digestate to achieve contaminant inactivation, destruction, or encapsulation. Market opportunities taken into consideration could include reuse, recycling and upcycling for conversion of organics waste to AD digestate e.g., nutrients and soil conditioning, whilst agri-businesses appear to be interested in easily transportable by-products to contribute to markets for soil fertilisers from smaller producers.

Other potential contributions for value-add that were mentioned include the effective separation of solid and liquid fractions to help identify suitable digestate co-products in the first place. In addition, the development of a certification body/logo for co-products has been mentioned as a key mechanism for enhancing the recognition of such products both nationally and overseas.

The key sustainability benefit discussed was carbon sequestration in order to return organic carbon into the soil by application of digested streams, which at the same time aligns with the motivation of the creation of ACCUs. Key stakeholders that can help enable value creation and capture from digestate products included farmers, piggeries, meat processors, hatcheries, dairies, regional councils, compost processors, engineered biofertiliser producers, environment waste management providers and food manufacturers. Indeed, it is generally acknowledged that any purchasing organisation that presents a market opportunity for digestate product represents a key customer e.g., councils, landscapers, developers, farmers, agricultural organisations, and stakeholders involved in land rehabilitation / remediation (e.g., mining industry).

The discussion into the key enablers began within the technological realm. In this case, there are a considerable number of technologies that can help with further processing of digestate for value-adding – depending on the specific characteristics and strategic goals of the AD plant or digestate processing facility. As a potentially lucrative endeavour, the commercial development of digestate coproducts has been a key point of concern for AD adopters that are operating in an environment where revenue from e.g., electricity generation is comparatively small. Along these lines, the potential opportunities for the commercialisation of digestate coproducts has spurred on a raft of research and development towards the creation of patents in this space, thus also making it one of the more sensitive topics amongst the AD community (Gorrie, 2014). During the discussions, the technological enablers mentioned include the likes of ammonia stripping and scrubbing, pyrolysis, solid-liquid separation, sludge dryers, gasification, and palletisation technologies. The economic considerations of the add-on technologies required to upgrade the digestate and the lack of understanding of the land applications of digestate were also presented as a key discussion point. Another point of concern was that most of the technology providers that could enable value creation from digestate were from Europe. It was mentioned that these European suppliers may not be so keen in participating in the Australian market – their "hands being tied" by Australian regulations. This presents a significant opportunity for Australian technology providers to fill gaps in technology required for treatment of digestate.

Despite such potential for significant opportunities to leverage digestate for AD market creation and growth mentioned thus far, it is also important to note that regulatory and legislative considerations should be directed towards the use of digestate in e.g. commercially produced products (Logan & Visvanathan, 2019). When it comes to the outcomes of the barriers and opportunities workshop, as with the previous discussion on motivation and value generation and capture, the key regulatory/policy enablers for digestate were a core theme. Here, the implications of digestate as a waste product and safety concerns, whereby a consideration of local digestate streams to allow local applications, need addressing. The emergence of contaminants including PFAS, microplastics, AMR organisms etc. formed part of the impetus behind the regulatory discussions.

Moving towards an economic perspective, access, supply, and logistics considerations are deemed to be key issues – linking AD feedstock suppliers, AD producers and digestate end-users. Pricing considerations were also considered, whereby the cost of alternatives to digestate disposal options for the producer seem to reign over the worth they actually are to a re-user (i.e., how does the cost of creating value-added coproducts compare to disposal?). The wholesale price of gas is also mentioned as an additional market driver, by virtue of the AD process in general, leading towards the production of digestate. Carbon sequestration and soil conditioner alternatives round-up the key economic/market considerations, whilst cost-effective cooperative approaches between the digestate producer and the key customers also presented a key talking point for opportunities.

Along similar lines to the discussion associated with grid injection earlier, public engagement and acceptance of digestate as a soil conditioner appear to be some key enablers in this space. One way of helping could include demonstrating the environmental benefits of the beneficial reuse of digestate solids.

4.5.5 Bio-CO_2

In addition to the digestate, another secondary coproduct of the AD process is the CO_2 extracted after the biogas upgrading and cleaning process. In this regard, common uses of the Bio-CO_2 from on-premise AD includes greenhouses (e.g. Stoknes et al. (2016)). In addition, Bio-CO_2 from AD operating in meat processing plants can potentially be cycled back for use in stunning animals prior to processing. Generally, however, the CO_2 method of stunning animals has animal welfare considerations that are resulting in a review of its use in this context with the European Commission conceding that it may not be the most appropriate method under all circumstances. However, with a lack of any other practical alternative, CO_2 stunning remains a mainstay in this industry and thus another opportunity for AD coproducts for the present time.

Whilst these opportunities paint a picture of AD technology as holding the potential to generate value for the producers, the flexibility of the technology itself brings forth added complexities concerning the manner in which value is generated and captured by AD adopters. Lazarevic and Valve (2020) and Valve et al. (2021) describe this phenomenon in great depth. Here, for instance, it is suggested that in the case of large-scale dedicated AD plants that operate based on gate fees, the economic frame is primarily that of "waste management". In this regard, the focus is on moneyed wastes that gain economic value once they are transported and arrive at the AD site. Because the emphasis is on waste management, the AD operator may not place so much emphasis on what happens to the digestate – this is often treated as an externality that needs to be removed quickly and cheaply, forfeiting the potential to close the loop. Likewise, when on-farm operations adopt AD to deal with manure surplus or to help support rural energy consumption, the economic frame is that of manure management in the first instance and energy generation in the second, both of which may place proverbial blinders on other opportunities. It is also important to note that these economic frames are further reified by dominant players in the market as well as the political landscape at the time that may incentivise some modes of value creation over others – potentially making it difficult for AD adopters to explore new opportunities to capitalise other opportunities from AD adoption. Along the same vein, as was found during this Opportunity Assessment, technical limitations and social acceptance also remain key factors in stalling widespread diffusion in the Australian context. Indeed, there are other areas of opportunity that move beyond the value chain that should also be considered.

From the technical front, advanced processing and monitoring technologies can help reduce the impact of a knowledge gap through automation and remote maintenance activities. Research and development in biogas fuel cells and biomethane bottling can also prove useful in increasing accessibility and reducing running costs. The specification of biomethane for fuel cell operation differs from that for conventional combustion engines. Fuel cells are highly susceptible to catalytic poisoning caused by hydrogen sulphide but can tolerate most other gas impurities in biomethane. In terms of economic and market-based considerations, novel business models that push the boundaries of generating and capturing value from the AD value chain can help improve adoption rates. These can include the likes of different ownership and control structures that enable effective collaborative efforts amongst AD value chain participants and work towards more symbiotic value creation and generation mechanisms (e.g., third party owned and operated digestors, network-based business models, AD-as-a-service and so on). Careful consideration of community engagement, as a recurring theme, can also yield dividends for the wide-spread diffusion of AD, whilst regulatory and policy considerations are required to provide the backbone that helps make all this possible.

4.5.6 Regulation opportunities

The move away from fossil gas and the emerging role of renewable gas can present opportunities for biogas and biomethane, especially where regulatory reform or policy change recognises the potential of biogas and biomethane as alternative low carbon energy sources.

For example, the Australian Capital Territory (ACT) Government removed the mandate for gas connections in new residential developments in 2020 and removed the gas connection initially proposed for stage 3 of the new suburb of Whitlam in April 2021. While this reduces the likelihood of any regulatory encouragement for injecting renewable gas into the gas pipeline in the ACT, at the same time, the ACT has encouraged and permitted the creation of a Landfill Gas Power Plant, using biogas at its Mugga Way landfill to produce electricity to power 5,700 homes (ACT Government, 2022). With an electricity generation model in existence and any regulatory barriers overcome in this prototype, it may be easier to look at other similar developments, such as using agricultural, food and organic garden waste and sewage as feedstocks for AD biogas and biomethane, as part of the ACT's transition to a zero-carbon jurisdiction.

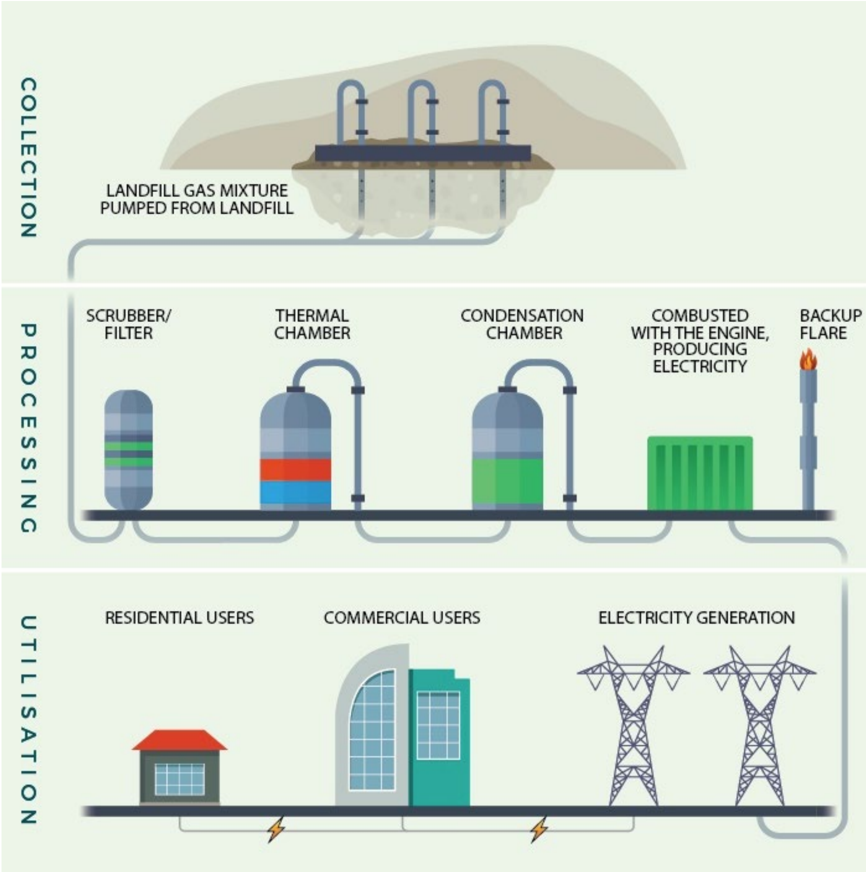


Figure 20. Diagram from ACT Landfill-Gas Factsheet

Another example of the regulatory opportunities for biogas and biomethane is occurring in Victoria. As part of its exploration of 'sustainable alternatives and pathways for the gas sector to transition to net zero emissions', the Victorian Government's *Gas Substitution Road Map* consultation paper recognises the need for 'a strategic framework for decarbonising natural gas in Victoria' (Victoria Government, 2022). Currently, Victoria uses gas for both domestic and industrial purposes. As the Roadmap generally proposes that domestic uses would be more appropriately met through electrification, opportunities for biogas and biomethane seem to be mainly in the industrial sphere, particularly in areas where heat and power are required. It may also be useful for firming capacity for the electricity grid, if it is designed to go into a generator, rather than simply being used for injection into the gas pipeline network. The roadmap provides a decarbonisation pathway which includes AD-Biogas-RNG, but not as a direct substitute for fossil gas in the main gas pipeline network. The roadmap expressly recognises both the advantages associated with 'switching from gas to renewable electricity sources and adopting more sustainable gaseous fuels such as hydrogen and biogas'. More specifically, like the ACT, Victoria's proposed decarbonisation pathway acknowledges that 'residential gas use and some commercial and industrial gas use can be readily electrified' while also pointing out 'existing examples of commercial operations in Victoria that utilise heat onsite made from biogas, which can also be upgraded into biomethane for injection into the existing gas network.

The NSW Government's decarbonisation plans include the 2021 pilot renewable gas certification (RGC) scheme (GreenPower, 2022; NSW Government, 2021). This scheme currently only allows the sale of GreenGas to industrial users, but in future may enable increased uptake of renewable gas by allowing 'households to voluntarily opt-in to buying gas produced from renewable and zero-emissions sources'.

Future exploration and greater understanding of what features define the success of this and other pilot programs and roadmaps will be highly beneficial to advancing the AD-Biogas and AD-Biogas-RNG sectors. Other opportunities could be enhanced if the range of pathways for incentivising emissions abatement activities, and formal recognition and recording of emissions abatement throughout Australia, were improved to enable better interoperability between existing and new systems and that accounting of emissions reductions could be streamlined.

During 2020-2022, the Australian Federal Government conducted industry consultation on a proposed Guarantee of Origin (GO) scheme for hydrogen, which was a priority action item in the National Hydrogen Strategy. At present, the scheme is generally aligned with the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) methodology for determining the greenhouse gas emissions associated with the production of hydrogen. The GO scheme is managed by the Clean Energy Regulator and the December 2022 policy position paper only covers the production pathways of electrolysis, steam methane reformation (SMR) with carbon capture and storage (CCS) and coal gasification with CCS. In theory, SMR could use fossil methane or biomethane, and biomass gasification is similar to coal gasification. The November 2022 version (Ver2) of the IPHE methodology allows for 6 production pathways – the three included in the GO, and industrial by-products, biomass gasification with CCS and auto-thermal methane reforming with CCS – and allows feedstocks from both fossil (coal, fossil methane) and renewable (biomethane, biomass) sources. It is unclear when the Australia GO will be updated to align with the current version of the IPHE method and the current definition of "covered gases" in the National Gas Law which includes biomethane. When the scheme is expanded to include renewable feedstocks such as biomethane, it may replace the GreenGas scheme, as it has national coverage rather than being limited to the gas pipeline network in the eastern states.

5 RESEARCH ROADMAP

5.1 Australia's biogas potential

Bioenergy provides approximately 47% of Australia's current renewable energy output. In 2019-20, biogas production was 16.7 PJ and accounted for 4% of Australia's current renewable energy production of 418.8 PJ (Australian Energy Statistics, 2021). Biogas accounted for 0.5% of 265,178 GWh/yr Australia's total electricity generation in 2019-20 (Australian Energy Statistics, 2021). However, the potential for biogas in Australia is significantly larger. The biogas potential in Australia was modelled in this study and is presented in Figure 21. The data is presented based on the estimated and projected sustainable biomass availability in Australia between 2030 and 2050. The analysis shows that available and sustainable biomass in Australia is estimated to be 62 Mt TS by 2050, which could generate 371 PJ of biogas per year (103 TWh/yr). This represents 64% of the east coast domestic gas supply of 580 PJ in 2020 (Australian Energy Regulator, 2021). Thus, biogas could account for more than 50% of all gaseous consumption in Australia by 2050 once the decrease in fossil gas consumption is factored in.

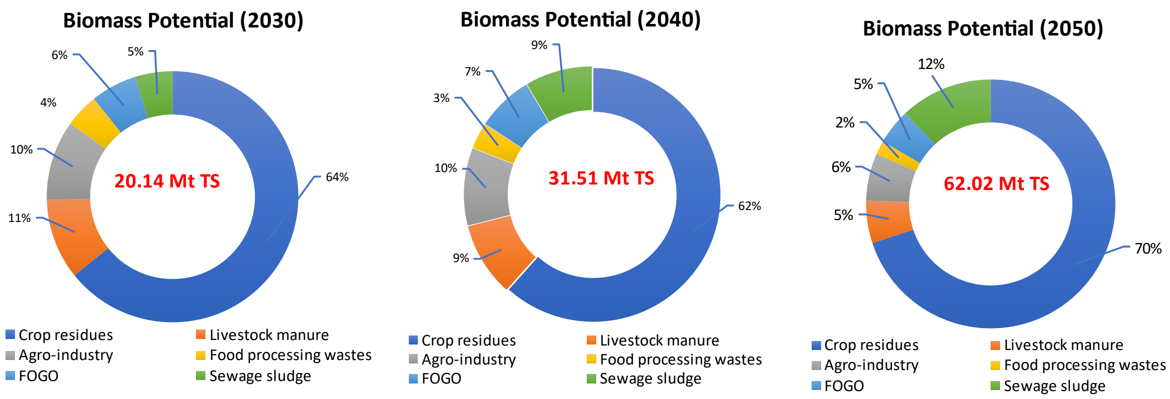


Figure 21. Estimated total biomass potential in Australia

The cheapest biogas feedstocks, such as sewage waste, livestock manure and FOGO, are currently sufficient to meet around 14% of energy used from biogas. Interestingly, agricultural waste offers the greatest potential and, if fully utilised, could account for around 69% of the total biomass and 86% of total biogas potential by 2050. However, usable agricultural resources are often located in rural areas, which can make it difficult to access as a feedstock.

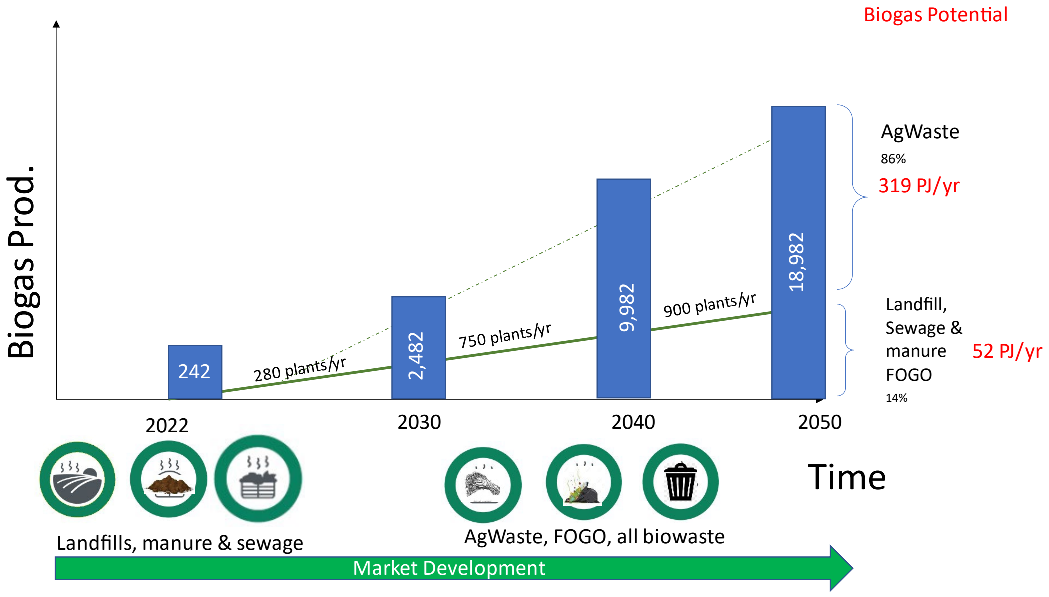


Figure 22. Development of the number of biogas plants and biogas production by 2050

Figure 22 presents the projected growth of the biogas industry in Australia based on the amount of sustainable biomass available from 2022 to 2050. Of the total biogas potential of 371 PJ/yr, agricultural waste accounted for 319 PJ/yr (86%) whilst landfills, sewage sludge, livestock manure and FOGO accounted for the remaining 52 PJ/yr. On this trajectory, biogas has the potential to provide up to 6.2% of Australia's total energy consumption of 6,013 PJ or replace 22.5% of the current fossil gas consumption of 1,647 PJ by 2050. The adoption of biogas technologies in organic waste management could also add $50 billion to Australia's GDP by 2050 and create 18,100 full-time jobs, mostly in regional areas.

The growth in installation of new biogas plants per year is based on the current average biogas facility size of 0.64 MW_{el}, which is similar to the average biogas plant size of 0.61 MW_{el} in Europe (EBA, 2018). However, financial analyses showed that the average biogas plant size in Australia should be 6.6 MW_{el} to be economical viable, if AgWaste is used as feedstock (see section 1.8). Thus, the number of biogas plants shown in Figure 22 might be less than the projected numbers if the size of plant is >0.6 MW_{el}. Moreover, the market development is dependent on the evolution of support mechanism and policies.

Supportive policies and regulation are critical for the biogas industry to achieve this trajectory. For instance, diversion of FOGO from landfills would stimulate the source separation of food waste and its use as feedstock for biogas production. Similarly, development of an AgWaste Methodology for calculating ACCUs is a critical milestone under the ERF to develop agricultural biogas plants based on crop residues. See Section 5.3 for details on the impact of policies and regulations on biogas market development in Australia.

Biogas provides a significant opportunity for the fossil gas industry to dramatically reduce its carbon intensity and offer a lower carbon product to consumers that is not currently available in Australia. This is critical to secure long-term investment and job security in that sector. As outlined in Deloitte's "Decarbonising Australia's Gas Network" report, Australia has significant volumes of biomass that could be harnessed to support decarbonisation of Australia's gas pipeline network (Deloitte Access Economics, 2017). The analysis in this report demonstrates that the biogas industry could help avoid 13.26 Mt CO_2-e

GHG emissions by 2050, or 28% of the 74 Mt CO_2-e of Australia's total emissions from fossil gas use in Australia (Deloitte Access Economics, 2017).

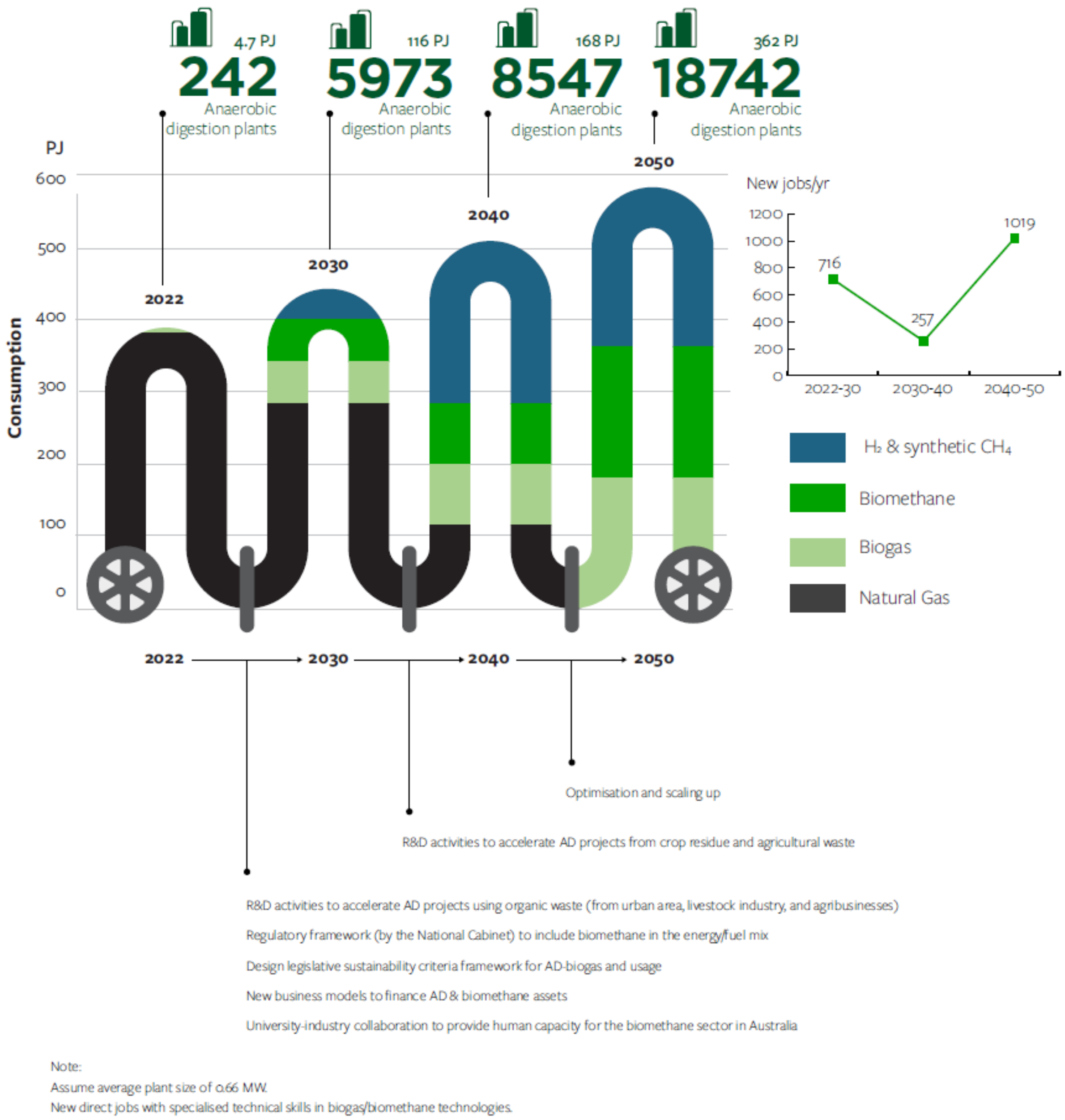


Figure 23. Infographic showing the share of biogas/biomethane in renewable gas by 2050.

A quantitative analysis of an accelerated scenario for Australia suggests that biogas and biomethane can contribute to more than half of all gaseous consumption in Australia by 2050 (Figure 23). To achieve the complete phase out of fossil gas in the gas pipeline network, the remaining balance is projected to be provided by green H_2 and synthetic methane (produced from H_2 and CO_2). The data in Figure 23 is derived from a comprehensive survey of available feedstocks in Australia, with the assumption of an expected increase in feedstock utilisation, as well as collection efficiency (Table 34). Baseline gaseous demand in 2022 is from an analysis by ENEA and Deloitte (2021), taking into account all current consumptions but excluding gas fired electricity generation. The model assumes a maximum contribution from electrification to the energy mix, thus gaseous fuels will be used mostly by hard-to-abate industries where electrification is not technically or economically viable. Improvements in energy efficiency and further growth in economic activities are considered, however due to the expected population increase in Australia, there will be an overall increase in gaseous consumption of 1.5% per annum. The assumptions are consistent with the projection of gaseous consumption by Victoria toward net zero emission by 2050 (Victoria Infrastracture, 2021).

Table 34. Biogas and biomethane potential (PJ) from available feedstocks in Australia toward 2050.

Year	2020	2030	2040	2050
	Energy potential (PJ)			
Landfill	12.2	8.5	5.2	2.5
Crop residues	-	88	132	320
Livestock manure	1.2	3.5	4.1	4.9
Agro-industry	-	9.1	13.6	18.5
Food processing wastes	2.4	2.8	3.4	4.3
FOGO	-	3.5	7.0	9.8
Sewage sludge	0.1	0.4	1.0	3.1
Total	16	116	166	364

Figure 23 also shows a significant potential to scale-up behind-the-meter AD within the next decade to take advantage of the readily available landfill gas and organic waste (mostly sewage sludge, food processing waste, animal manure, and FOGO). Behind-the-meter AD is economically competitive in the medium term given the regulatory requirement to treat organic wastes, existing operational experience in Australia, and the localised energy demand from waste generators themselves or neighbouring businesses. The treatment of organic wastes by AD is currently a major source of revenue, as the cost of biogas production from landfills and existing wastewater treatment plants can be as low as 1.4 $AUD/GJ (Guerin, 2022). In fact, many current behind-the-meter AD projects have been developed without or with very little subsidy or financial benefit from green energy production.

5.2 Research opportunities and priorities

The projections in Figure 23 show several critical and immediate work packages that are required within the next decade to realise the full potential of AD for biogas and biomethane production. Initially, significant R&D investment is required to accelerate behind-the-meter AD projects and to prepare for large scale implementation of gas pipeline network injection. These R&D activities should focus on adapting technologies and technical-know-how from overseas, especially Europe and the USA, and adoption in the Australian context to increase biogas production and reduce costs. Unlike solar and wind (from which electricity is the only output), AD operation is much more complicated and due consideration must be given to feedstock (collection, transportation, and storage), biogas production (quality, storage, transportation, utilisation), and digestate utilisation (compliance for safe disposal or beneficial applications).

Critically, there is an urgent need for a nationally accepted regulatory framework to include biomethane from AD in the energy/fuel mix and manage all relevant aspects (as discussed above) of the AD process. Since early 2022 the NSW government commenced a 2-year pilot program to establish mechanisms for renewable gas certification. This renewable gas certification scheme expects to unlock a voluntary market for gas users to purchase biomethane, which is produced from wastewater and organic waste (e.g., food waste, animal manure, and FOGO). The scheme is also an important transition to scale up behind-the-meter operation to regional and nationwide energy trading. Once finalised, adaptation of this scheme is expected by other states and territories in Australia. Further regulatory work is required to explicitly recognise the role of biomethane in Australia's effort to achieve net zero emission by 2050, create a renewable gas market that is inclusive of biomethane, and establish mechanisms to evaluate sustainability in terms of biomethane utilisation, feed stock selection and digestate management. The projections outlined in Figure 23 can only be realised in full when the value of biomethane as a renewable gas, transition fuel, and industry grade energy source can be recognised with suitable financial mechanisms.

New business models will also be needed to finance AD projects. Biogas assets, including digesters, biogas upgrade facilities, biomethane storage and transmission network, are capital intensive with a long payback period. These include multi-partner agreements, private public partnerships, and AD cooperatives. As an example, the AD cooperative model has been successfully applied in several European countries (e.g., the Netherlands and Switzerland) to pull resources and investment together to scale up AD operation (Henly, 2021; Yazan et al., 2018). In Australia, using a similar concept, a group of 18 dairy farmers together with Innovating Energy and partners have formed a consortium to build and operate a 2.2 MW, $17 million biogas facility in Nowra (Nowra BioEnergy Facility, https://www.nowrabioenergy.com.au/).

Significant capacity building will also be required to achieve the projected industry growth. The emerging biogas sector in Australia will demand a rapidly increasing workforce with specialised technical competency to manage key aspects unique to the biogas supply chain. By 2030, up to 6,000 AD plants will be operational. The design, construction and operation of these plants will require 6,000 new jobs with technical qualification specific to the biogas sector. In other words, 750 technicians must be trained each year between now and 2030 to fill in this gap in human capital to support the biogas sector in Australia (Figure 23).

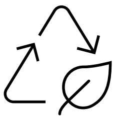
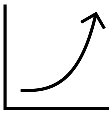
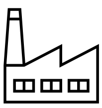
Research is also required to facilitate the transition of the biogas industry from behind-the-meter operations to large-scale grid injection, which is expected during the 2030-2040 period. As the production of landfill gas decreases and the sector has maximised the utilisation of organic waste feedstock, agricultural waste (Ag waste), such as sugarcane bagasse, silage, and other crop residues, will become the dominant feedstock for biogas production. By 2030, it is also expected that the renewable gas market has matured and biomethane from Ag waste can compete with other forms of renewable fuel and energy. R&D activities during this period will need to focus on the selection, collection, and storage of Ag waste feed stocks as well as digestate utilisation to improve soil carbon balances.

Biomethane from Ag waste is expected to be the dominant renewable gas in Australia by 2040 if key technologies can be supported to maturity. The period of 2040-2050 will see rapid growth in Ag waste-based AD projects and consolidation of the biomethane industry in Australia. By 2040, there will be sufficient clarity if green H_2 can be exclusively used as a renewable gas by itself in the gas pipeline network or must be blended with biomethane and synthetic methane at a certain ratio. Technology for synthetic methane production is currently at TRL7, with several pilot demonstrations in Europe expected to reach commercial maturity (TRL9) by 2040.

Research questions were tabulated from feedback through the project's industry reference group (IRG), market analysis conducted within this project, and a comprehensive review of the literature.

Research questions (Table 35) were divided into four main areas: (1) growth of the feedstock supply; (2) scaling-up and increasing efficiency; (3) improve economics for new infrastructure; and (4) markets for new AD products. These themes represent the issues critical to the development of the biogas / biomethane industry in Australia over the next decade, namely scale, market, feedstock availability, and technology adaptation and development. In the next decade, direct research investment of at least $10 million per year will be needed to support these projects, representing less than 1% of the potential revenue that these projects could generate. These research projects will also provide research and technical training to create the necessary work force for the biogas industry in Australia.

Table 35. Research questions identified from the Opportunity Assessment Project of RACE for 2030

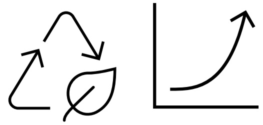
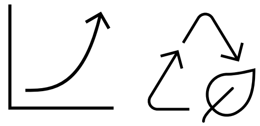
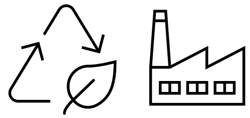
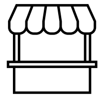
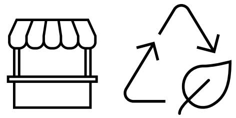
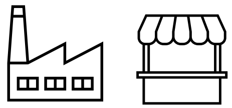
Theme/ Research Area		Research questions
	Growth of the feedstock supply	To what extent can food waste or FOGO be treated by AD? Can FOGO be co-digested with sewage sludge and other feedstocks in existing sewage biogas or AD plants?
		What is the appropriate management of livestock manure at feedlots?
		How can AD digestate be used? Can digestate be sold in the market? What regulatory and digestate quality parameters must be developed for sale of digestate?
		Why are more than 50% of landfills in Australia are not currently producing and/or capturing biogas for electricity generation?
	Scaling-up and increasing efficiency	How can we improve the biogas production from sewage sludge at WWTPs?
		What are other AD technologies than can be used to enhance biogas production from food processing industries such as the dairy and meat industries?
	Improve economics for new infrastructure	What infrastructure is required to manage manure at feedlots and use it as feedstock for AD?
		Is AD viable for AgWaste? What should be the scale of AD technology to make it economically viable for AgWaste and/or other feedstocks? How can we assess the techno-economic viability of AD for new feedstocks?
		How can biogas be captured and optimised from landfills?
		To what extent can biogas plants and microgrids be integrated?
		What should be the ideal biogas plant location from biomass and gas pipeline network for biomethane injection?
		What kind of sustainable biomass collection and logistics should be developed for developing biogas market?

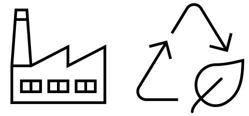
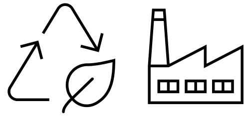
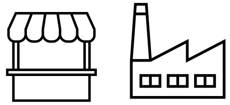
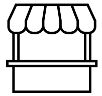
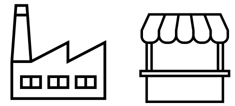
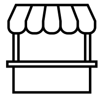
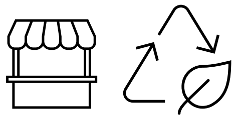
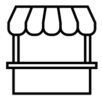
	Markets for new AD products	What are the biomethane quality standards required for injection into gas pipeline networks? What is the digestate composition required to sell into the market? What are the potential markets for sale and use of $BioCO_2$? What technologies are required for improving biogas production from existing AD facilities? What regulatory frameworks are required for sale of AD products? How will the public engagement facilitate in developing AD in Australia?

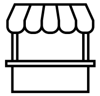
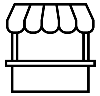
Key research projects to realise the full potential of biogas in Australia are described in Table 36. These projects are not intended to be exhaustive and only cover opportunities within the next decade, with a focus on behind-the-meter operation and preparation for the scaling-up of biogas production and/or biomethane for gas pipeline network injection.

Some research activities have already commenced but further investment and collaboration for successful systems approaches and transitions for scaling-up are required. Examples of existing projects include research on anaerobic co-digestion of food waste and sewage sludge currently undertaken or commissioned by several Australian Water utilities, a grid injection trial by Sydney Water and Jemena, and several scoping projects funded by the Future Fuel CRC.

Table 36. Research opportunities in the next decade to develop scale, market, technology and regulatory framework to support the biogas/biomethane industry in Australia.

No	Project title	Description	Themes
1	Food waste co-digestion at WWTPs	Develop: new tools to assess the viability of co-digestion; ways to collect and manage food waste; co-digestion demonstration projects	
2	Demonstrating advanced AD technologies	Demonstrate AnMBR and CSTR technologies for dairy, food processing wastewater and municipal waste industries to increase biogas production and reduce costs	
3	Manure collection at feedlots	Develop techniques to collect manure, including new pen designs, to minimise contamination and improve biogas production	
4	Biomethane quality specification	Standardise the biomethane specification for common behind-the-meter applications (20 Mt TS of biomass = 6.0 billion Nm^3 of biogas)	
5	Digestate assessment and standardisation	Develop standards to manage digestate from specific feedstocks and for specific economical reuse options (digestate 33 Mt @ $20/t)	
6	Demonstration of small-scale partial biogas upgrading	Demonstrate technology and assess the techno-economic viability of partial biogas upgrading, storage and transfer	

No	Project title	Description	Themes
7	Techniques to enhance landfill gas production	Develop techniques to enhance landfill gas production and accelerate landfill maturity (1 ton of OF-MSW = 50 Nm^3 CH_4)	
8	Biogas production from FOGO	Develop and demonstrate technology for biogas production from FOGO including source separation, collection, and mechanical bioreactor for high-rate and high-solid AD (Dry AD).	
9	Integrating AD into microgrids	Integrate AD into a microgrid to demonstrate energy reliability and efficiency	
10	BioCO_2 utilisation	Assess new options for utilising BioCO_2 from biogas upgrading (e.g. greenhouse operation, animal slaughtering @ $200/t Bio$CO_2$)	
11	Biological methanation using existing AD facility	Demonstrate biomethanation to enhance biogas production and enrich CH_4 content in biogas by using RE-H_2 (Power to gas).	
12	New business models to finance and support biogas project	Develop new business models to allow for long-term and large capital investment in biogas projects	
13	National framework to regulate AD material flows	Develop a national framework to promote the most beneficial use of feedstock, digestate, and biogas	
14	Inclusive renewable energy market	Develop a framework to acknowledge the role and value of renewable biomethane in the national energy mix e.g. through a renewable gas target and/or a renewable gas certificate	

No	Project title	Description	Themes
15	National sustainability criteria	Develop a national framework to assess and evaluate the sustainability of AD projects against specific criteria considering carbon credits, soil organic carbon, and land use regulation	
16	Social licensing and system transition	Undertake consultative knowledge and capacity building engagement with the public/community, with a view to enhancing understanding and promoting support for the social benefits of biogas/biomethane market and the regulatory changes needed to achieve positive outcomes.	

Note: AnMBR: Anaerobic membrane bioreactor; CSTR: Continuously stirred tank reactor; BioCO_2: Carbon dioxide from biogas upgrading; BioLNG: Liquefaction of biomethane. Assume current market price of biomethane at S10/GJ; Digestate value is assumed at S20/t (33 million tons/yr); current market price of BioCO_2 is S200/t.

5.3 High impact research areas and its metrics

The major users of biogas in Australia are commercial and industrial businesses. Industrial businesses need heat and gas for running their own operations (behind-the-meter) with some businesses replacing their gas and electric power with bioenergy.

Impact measurements from the high impact research areas (section 5.2) are presented in Table 37. Impacts of research projects are measured in terms of energy generation, GHG emissions avoided, and expected number of jobs to be generated by each research project. In total, 16 research projects have been identified through IRG meetings in this Opportunity Assessment project of RACE for 2030. These projects covered technology, market development, regulatory and social license. The estimated budget for the implementation of these 16 projects along with the project impacts is shown in Table 35.

Table 38 presents a brief overview of research projects, stakeholders/beneficiaries and potential industry partners from RACE for 2030.

Table 37. Metrics for high impact research areas identified from the Opportunity Assessment Project of RACE for 2030

No	High Impact Research Themes	Approximate annual research budget ($mill)	Metrics			
			Market value ($mil/yr)	Energy production (PJ/yr)	GHG emissions avoided (Mt CO_2-e/yr)	Expected jobs per year
1	Food waste co-digestion at WWTPs	0.5 to 0.6	82	8.2	1.49	51
2	Demonstrating advanced AD technologies	1.2-1.4	100	10	1.82	62
3	Manure collection at feedlot	0.6-0.8	3	0.3	0.05	2
4	Biomethane quality specification	0.4-0.6	109	10.9	1.97	67
5	Digestate assessment and standardisation	0.8-1.0	660	N/A	N/A	N/A
6	Demonstration of small-scale partial biogas upgrading	2-3.5	155	15.5	2.82	96
7	Techniques to enhance landfill gas production	1-2.5	85	8.5	1.55	52
8	Biogas production from FOGO	0.8-1.2	35	3.5	0.64	22
9	Integrating AD into a microgrid	1-1.4	N/A	N/A	N/A	N/A
10	BioCO_2 utilisation	2-3.5	1.22	6,108 Mt BioCO_2/yr	N/A	N/A
11	Biological methanation using existing AD facility	2-2.4	0.06	305.4 Mt BioCO_2/yr	N/A	N/A
12	New business model to finance and support biogas project	0.6-0.8	N/A	N/A	N/A	N/A
13	National framework to regulate AD material flows	0.4-0.5	N/A	N/A	N/A	N/A
14	Inclusive renewable energy market	0.4-0.5	N/A	N/A	N/A	N/A
15	National biogas sustainability criteria	0.3-0.4	N/A	N/A	N/A	N/A
16	Social licensing and system transition	0.25-0.3	N/A	N/A	N/A	N/A

Table 38. Stakeholders and beneficiaries identified from high impact research projects for the Opportunity Assessment Project of RACE for 2030

No	Projects	Description	Stakeholders and Beneficiaries	Possible RACE for 2030 industry partners[2]
1	Food waste co-digestion at WWTPs	Develop: new tools to assess the viability of co-digestion; ways to collect and manage food waste; co-digestion demonstration projects	• Water utilities • Waste collectors • Food processors/manufacturers, who currently pay for waste disposal • Gas users • State and territory governments • Local governments	Ausgrid, AGL, SA Power Networks, AMPC, QFF, Agrifutures, Singh Farming, Sydney Water, State governments (NSW, VIC)
2	Demonstrating advanced AD technologies	Demonstrate AnMBR and CSTR technologies for dairy, food processing wastewater and municipal waste industries to increase biogas production and reduce cost	• Dairy Industry • Meat industry • Water utilities • Triple bottom line investment funds • Technology providers	FIAL, QFF, Sydney Water, AMPC, Singh Farming, Visy, Agrifutures, State governments (NSW, VIC)
3	Manure collection at feedlot	Develop techniques to collect manure, including new pen designs, to minimise contamination and improve biogas production	• Meat and livestock industry incl. MLA	QFF, AMPC, Visy, Climate KIC, Agrifutures, State governments (NSW, VIC, QLD)
4	Biomethane quality specification	Standardise the biomethane specification for common behind-the-meter applications (20 Mt TS of biomass = 6.0 billion Nm^3 of biogas)	• EPA • ARENA • Australian Gas Association • Australian Energy Market Commission • Energy Networks Australia • Gas grid operators • Equipment suppliers	Visy, Ausgrid, AGL, Sydney Water, State governments (NSW, VIC, QLD)

[2] RACE for 2030 partners were selected based on participation in IRG meetings; however, the list could be extended to include other RACE for 2030 partners and other stakeholders.

Continuation of Table 38. Stakeholders and beneficiaries identified from High impact research projects for the Opportunity Assessment Project of RACE for 2030

No	Projects	Description	Stakeholders and Beneficiaries	Possible RACE for 2030 industry partners[3]
5	Digestate assessment and standardisation	Develop standards to manage digestate from specific feedstocks and for specific beneficial reuse options (digestate 33 Mt @ $20/t)	• EPA • Standards Australia • Biosecurity regulators • Compost suppliers • Fertiliser manufacturers • Existing composters • Farmer/agricultural organisations	Visy, QFF, Agrifutures, State governments (NSW, VIC)
6	Demonstration of small-scale partial biogas upgrading	Demonstrate technology and assess the techno-economic viability of partial biogas upgrading, storage and transfer	• Dairy industry • Meat and livestock industry • Transport companies with CNG vehicles • Gas engine suppliers e.g. Clarke Energy • ARENA • Small landfills • Local governments	Visy, FIAL, Sydney Water, AGL, State governments (NSW, VIC)
7	Techniques to enhance landfill gas production	Develop techniques to enhance landfill gas production and accelerate landfill maturity (1 ton of OF-MSW = 50 Nm^3 CH_4)	• State/territory/local governments who manage/ license landfills sites • Companies that benefit from increasing collection efficiency	Climate KIC, Waste management companies, State governments (NSW, VIC, QLD)
8	Biogas production from FOGO	Develop and demonstrate technology for biogas production from FOGO including source separation, collection, and mechanical bioreactor for high-rate and high-solid AD (Dry AD)	• Local governments	State governments (NSW, VIC, QLD)

[3] RACE for 2030 partners were selected based on participation in IRG meetings; however, the list could be extended to include other RACE for 2030 partners and other stakeholders.

Continuation of Table 38. Stakeholders and beneficiaries identified from High impact research projects for the Opportunity Assessment Project of RACE for 2030

No	Projects	Description	Stakeholders and Beneficiaries	Possible RACE for 2030 industry partners[4]
9	Integrating AD into a microgrid	Integrate AD into a microgrid to demonstrate energy reliability and efficiency	• Gas engine suppliers • Energy companies • ARENA	Ausgrid, AGL, SA Power Networks
10	BioCO_2 utilisation	Assess new options for utilising BioCO_2 from biogas upgrading (e.g. green-house operation, meat processing @ $200/t Bio$CO_2$)	• Gas engine suppliers • ARENA	Ausgrid, AGL, SA Power Networks, AMPC, Sydney Water
11	Biological methanation using existing AD facility	Demonstrate biomethanation to enhance biogas production and enrich CH_4 content in biogas by using RE-H_2 (Power to gas)	• Gas engine suppliers • ARENA	Ausgrid, AGL, SA Power Networks, Sydney Water, AMPC
12	New business model to finance and support biogas project	Undertake an economic assessment and fuel standard testing for trucks and farm machineries to operate on biogas/B85/biomethane	• State government energy agencies • Clean Energy Finance Corporation • Corporations with net zero targets • Social impact funds • Banks	Visy, FIAL, Sydney Water, AMPC, AGL, Singh Farming, EPRI, State governments (NSW, VIC, QLD)
13	National framework to regulate AD material flows	Develop a national framework to promote the most beneficial use of feedstock, digestate, and biogas	• ARENA • State government energy agencies • Life cycle assessment specialists • Local governments	FIAL, QFF, Climate KIC, State governments (NSW, VIC, QLD)

[4] RACE for 2030 partners were selected based on participation in IRG meetings; however, the list could be extended to include other RACE for 2030 partners and other stakeholders.

Continuation of Table 38. Stakeholders and beneficiaries identified from High impact research projects for the Opportunity Assessment Project of RACE for 2030

No	Projects	Description	Stakeholders and Beneficiaries	Possible RACE for 2030 industry partners[5]
14	Inclusive renewable energy market	Develop a framework to acknowledge the role and value of renewable biomethane in the national energy mix e.g. through a renewable gas target and/or a renewable gas certificate	• National cabinet • Property council specifying "green buildings"	All
15	National biogas sustainability criteria	Develop a national framework to assess and evaluate the sustainability of AD projects against specific criteria considering carbon credits, soil organic carbon, and land use regulation	• State/territory governments • EPAs • Australian Government • ARENA	FIAL, Climate KIC, Agrifutures, State governments (NSW, VIC, QLD)
16	Social licensing and system transition	Undertake public engagement to gain social and regulatory support for a biomethane market	• Future Fuels CRC • State/territory and federal governments • Gas developers	FIAL, Agrifutures, State governments (NSW, VIC, QLD)

[5] RACE for 2030 partners were selected based on participation in IRG meetings; however, the list could be extended to include other RACE for 2030 partners and other stakeholders.

5.4 Industry development opportunities and priorities

While research opportunities have been identified in the preceding section, additional industry development activities are required to realise the full potential of biogas in Australia. Industry feedback and market analysis have also informed the following list of industry development opportunities and priorities.

Figure 24 presents the timeline and impacts of potential projects identified in this Opportunity Assessment to realise the full biogas potential in Australia. Feed-in tariffs, renewable gas certificates and ACCUs are considered as important policies that will support the market development of biogas industry in Australia. In Australia, green energy certificates are only available for electricity generation, which is a disincentive to generate biomethane for blending into gas pipeline networks. This is one of the fundamental reasons why biogas collected at landfills and through AD facilities is used to generate onsite heat and electricity. The electricity can be exported and generates revenue from the electricity price and the value of renewable energy certificates. Similarly, a general biomethane methodology should be introduced to allow the creation of ACCUs to produce biogas, or biomethane, which can either be transported to a large gas consuming facility, injected into a gas pipeline network for end-use or used as a transport fuel. A general biomethane methodology, rather than a waste/feedstock specific version, will support the growth of an emerging biogas and biomethane market, helping large fossil gas consumers to decarbonise their businesses. The current biomethane methodologies do not cover the scenario where a stand-alone AD facility receives a combination of organic waste streams to produce biogas and/or biogas is upgraded to biomethane.

Demonstration of manure collection at feedlots, technologies to improve biogas production and/or quality at landfills and the development of advanced reactor technology such as AnMBR and CSTR technologies for dairy, food processing wastewater and municipal waste industries would improve and increase biogas production and thereby the economics of biomethane production. Similarly, technology to demonstrate partial biogas upgrading (e.g. 65% for brick plant), storage and transfer directly by a pipeline from the AD facility to an end-user facility, or injection and blending into a nearby fossil gas pipeline network will enable the economics to improve.

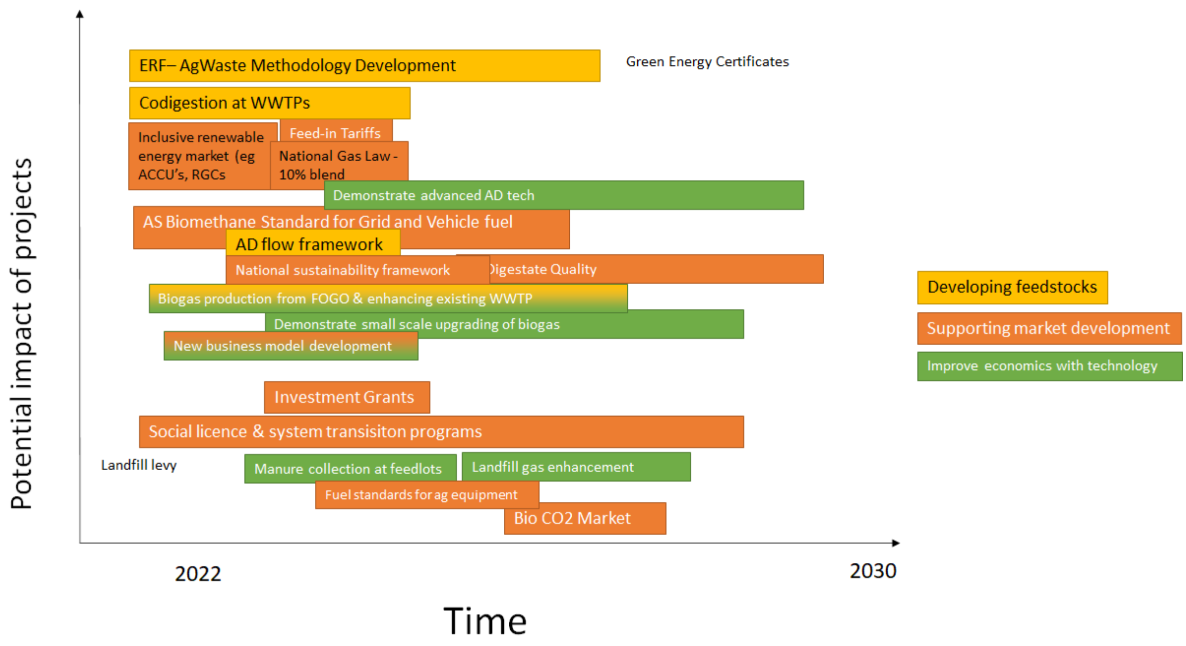


Figure 24. Timeline and impacts of potential projects identified in this Opportunity Assessment for RACE for 2030 to realise the full biogas potential in Australia

1. Setting a Renewable Gas Target

The Commonwealth and state/territory governments could consider setting short-term and long-term renewable gas targets, similar to the Renewable Energy (Electricity) Amendment Bill in 2015. As part of that amendment bill, a renewable energy target of 33,000 GWh was set to be achieved by 2020. In addition, biomethane targets could be set in the capacity market to ensure that the supply security of electricity should also be considered. Such targets with clear mandates will encourage renewable gas production and consumption. Both biogas and hydrogen can be considered under this Renewable Gas Target. Even non-binding targets, as seen overseas, can give impetus to industry growth.

2. Establishing an intergovernmental apex body for coordinating waste management, climate change and renewable energy generation

At Commonwealth and state/territory governments, there is a need for an apex body for coordination and synchronisation in achieving the national Renewable Gas Target through the coordination of Minister for Climate Change and Energy, and Minister for Environmental and Water, Minister for Infrastructure, Transport, Regional Development and Local Government, Minister for Agriculture, Fisheries and Forestry and Minister for Industry and Science.

3. Establishing a "single window" for biogas/biomethane project approval mechanisms

Project proponents need to work with consultants, local/state/territory authorities such as EPA and electricity and gas network businesses to develop projects. Currently, project development and approval is a complex process and takes a very long time. This red tape could be avoided if there was a government body with technical and regulatory experts that could review and approve the projects and provide solutions, develop guidelines and information packs for supporting the biogas industry. This mechanism could be applied to both the biogas and hydrogen industries.

4. Creation of industry stakeholder consultation group and technical coordination group for policy design and implementation of biogas projects

The Commonwealth and state/territory governments could create a new Renewable Gas Australia or use the existing Bioenergy Australia for detailed consultation with industry stakeholders to gather their insights on the barriers for developing the biogas industry, how existing policies could be improved or adapted and how new polices could be designed to support the biogas sector. Such an organisation could enable the harmonisation of the required policies at national and state/territory levels. Existing and new mechanisms include feed-in tariffs, ACCUs, investment grant support, tax rebates, infra-structure grants/loans, contracts-for-difference and import tax exemption for technology.

5. Development of support mechanisms for use of different wastes, technologies and biogas/biomethane generation and use should be encouraged such as:

- A basic feed-in tariff for biogas generation and upgrading to biomethane for gas pipeline network injection;
- A premium allocated for higher biogas quality, which is dependent on feedstock characteristics and the AD process;
- Additional incentives for using organic waste or diversion from landfill;
- Providing support to target the injection of biomethane into the gas pipeline network as the distances from the biomethane production and potential gas pipeline injection site can vary;
- The development of BioCNG or BioRNG retail products for gas users in Australia; and
- Providing support for large-scale and small-scale R&D pilot biogas projects.

6. Establishment of Australian National Gas Technology Development and Implementation Task Group

Industry and research experts working in hydrogen and biogas production, health and safety, gas quality for injection and use should be drafted into a national technical task group to oversee the industry's development and implementation including (for AD) the:

- Development of biomass harvest, logistics and storage technologies;
- Development of AD technologies for feedstock specifications and biogas processing; and
- Development of national biomethane standard for gas pipeline injection and vehicle fuel use.

7. Introducing waste management strategies to support feedstock quality and quantity

Facilitating the harmonisation of waste levies across all states/territories by the Commonwealth Government will ensure that organic waste is diverted from landfills and also prevent unnecessary waste transport between states/territories with high levy to lower levies.

State/territory and local Governments should work together to introduce more uniform and standardised waste collection mechanisms. Especially, source separation of food organics and garden organics should be supported and encouraged through incentives. This would make it easier to use household and community organic waste as feedstock for anaerobic digestion.

Diversion of organic waste and reduction in landfilling will support the recycling and resource recovery industry. International examples have shown that appropriately targeted landfill taxes have encouraged the organic waste diversion, reduction in waste to landfill, adoption of anaerobic digestion and reduction in the number of landfills.

Government and industry stakeholders should also work on establishing long-term feedstock supply contracts especially from the agricultural sector.
Logistics on crop residues collection and storage without affecting the agronomic benefits of crop cultivation should be investigated to develop farm-scale biogas plants in regional areas.

8. Development of support mechanisms for existing biogas plant operators to improve biogas production and quality through co-digestion and technology adoption

The Commonwealth and State/territory governments could introduce financial mechanisms, taxes or financial incentives, to encourage landfill operators to maximise the use of landfill gas. Approximately 50% of the 122 landfills currently operating in Australia do not use their landfill gas for electricity generation owing to the poor gas quality, but instead flare it. Technology and R&D incentives should be provided to improve biogas quality and use. Similarly, incentives should be provided to encourage sewage treatment plants to co-digest food waste with sewage sludge. Finally, CAL technologies should be upgraded to improve the biogas production and effluent quality.

9. Development of biomethane for vehicles

The use of biomethane as an alternative vehicle fuel, particularly for heavy freight and farm machinery, should be developed. This should be prioritised by the Commonwealth Government with greater support mechanisms as it can decarbonise the transport sector.

Currently, both CNG and LNG are taxed in the same way whether the gas is of fossil or renewable origin (BioCNG and BioLNG). Mechanisms to reduce or remove the excise duty on BioCNG and BioLNG produced from biomethane should be developed. Passenger vehicles and taxis running on BioCNG and BioLNG should have similar incentives to electric vehicles. Likewise, the current Diesel Fuel Rebate Scheme to support farmers should be extended to include BioCNG and BioLNG.

10. Harmonising national digestate quality for agricultural use

Each state/territory has a different regulation on the production and use of digestate. In the future, the Commonwealth and state/territory governments could develop a national standard and regulatory framework on digestate production and quality for use in agricultural and horticulture. Uncertainties around digestate regulation is seen as the major regulatory hurdle for industry development. Especially, the commercial use of digestate and its quality specifications needs to be addressed.

11. Developing social license through awareness and inclusion

Recognising the importance of securing the engagement of local communities in the establishment and long-term success of renewable gas (biogas/biomethane) markets, knowledge and capacity building programmes and activities that encourage participation in waste management and biogas use, can employed to facilitate and enhance social licence features and the benefits of renewable energy markets. Government and industry initiated “social licence” campaigns that focus on increasing community understanding and participation in biogas opportunities and the positive impacts of renewable gas in decarbonising Australia's energy and transport sector would be of immediate and long-term benefit. Examples of inclusive community engagement include:

- Inclusive knowledge building, educational consultations with a range of local community members – school children, farmers, residents, local businesses, etc. – to secure public engagement in project development and awareness raising campaigns; and/or
- Capacity and knowledge building activities organised by researchers and industry that include visits, workshops, and community meetings on biogas production and use, regulatory considerations, and environmental benefits of renewable gas (biogas/biomethane).

12. Development of a National Energy Sustainability Policy

This will provide a vision and certainty to foster investment and ensure that all potential decarbonised energy sources are developed for their best use. Experiences in Europe and other places make it clear that such a policy needs to accommodate the need for certainty to create urgent action, as well as flexibility to accommodate emerging changes as the world makes the decarbonising journey.

This policy should consider what regulatory instruments, if any, are needed to incentivise production and end-use of biogas and biomethane, such as taxation, carbon price and trading, feed-in tariffs, renewable gas and renewable energy targets.

13. Development of a uniform/harmonised national Renewable Energy Regulatory System

States, territories and the Commonwealth governments all need to work together in a collective collaborative way to create nationally harmonised and simplified laws across Australia to ease the urgent transition to renewable energy for communities and industries.

An agreed nationwide, uniform renewable regulatory scheme should provide a holistic, comprehensive policy, governance, and legal framework, with clear incentives (such as an effective and efficient carbon pricing/trading mechanism, and renewable gas target). It should promote and support current and potential AD-Biogas and AD-Biogas-RNG transactions across the country, within a broad framework of sustainability, and social and environmental responsibility.

A simplified regulatory system will require greater alignment and streamlining of regulations across and between all levels of government (federal, state/territory and local governments). An integrated approach also requires consistency between existing policy, governance, and regulatory frameworks and instruments (mandated and voluntary) relating to, for example, environment and planning obligations, as well as other safety, health, and technical regulatory constraints arising throughout the AD-Biogas and AD-Biogas-RNG transactions. In jurisdictions where work is already proceeding independently, these efforts should be brought together, and lessons learned from each should be incorporated as part of the national effort.

14. Removal of unnecessary barriers to the use of the range of potential energy sources in safe and sustainable ways within a National Energy Sustainability Policy

One part of this will be to support the AD-Biogas and AD-Biogas-RNG sectors by accelerating the current plans to remove or minimise existing constraints around gas pipeline network injection (where this is appropriate) and economic regulation provisions of the national gas and electricity laws, rules, and other relevant instruments to remove distortions within and between renewable energy sources.

Appendices

A. Summary of process instability cases in medium- and large-scale biogas plants

Table 39. Summary of process instability cases in medium- and large-scale biogas plants. Adapted from (Wu et al., 2021)

Operational information	Performance of instability	Cause of instability	Counter measures and results	Ref
Farsø biogas plant in Denmark. Feeding substrate: mink manure.	Extremely high concentrations of VFAs.	High concentration of ammonia (> 10 g N/L) in Mink manure. NOTE – mink industry in Denmark no longer exists.	Decrease the loading rate and dilution of reactor contents.	(Angelidaki et al., 2005)
Snertinge biogas plant in Denmark.	Dramatic increase in VFAs in reactors RII and RIII.	Heavily increased loading occurred in reactors RII and RIII since they were available for feeding. Reactor RI was closed down for modification from mesophilic to thermophilic operation.	The process did not recover. The reactors were eventually emptied and re-inoculated.	(Angelidaki et al., 2005)
Hashøj biogas plant in Denmark.	High and fluctuating VFA levels.	High hydraulic loading.	No counter measures taken.	(Angelidaki et al., 2005)
Blaabjerg biogas plant in Denmark.	Relatively high VFA levels.	Addition of a particular organic waste, product from the medical industry with a high protein and sulphur content.	Terminated feeding the medical industry. VFA concentration dropped to a much lower level.	(Angelidaki et al., 2005)
Three thermophilic reactors of 7,600 m^3 and 3 reactors (53°C with HRT of 17–18 d). Feeding substrate: manure (362 t/d) and organic industrial waste (75 t/d).	Sudden sharp increase in ammonia and VFA levels. Decrease in biogas production by 32%. Severe accumulation of LCFAs.	Organic industrial waste consisted of blood from pigs with a high biodegradability and a low C/N ratio, increasing the OLR and causing ammonia accumulation.	Removed the blood from the feedstock. Biogas production recovered after approximately 2 weeks.	(Angelidaki & Ellegaard, 2003)
Mesophilic conditions	Frequent foaming. Loss of 32% biogas production.	Inexpedient mixing of different waste types led to CO_2-stripping, but the reason for foaming inside the reactor remains unknown.	Constructed more pre-storage tanks. Foaming inside the reactors ceased suddenly.	(Angelidaki & Ellegaard, 2003)

Note: VFAs: Volatile fatty acids; HRT: Hydraulic retention time; C/N: Carbon to nitrogen ratio; LCFAs: Long chain fatty acids; OLR: Organic loading rate; PFR: Plug-flow reactor; CSTR: Continuous stirred tank reactor.

Continuation of Table 39. Summary of process instability cases in medium- and large-scale biogas plants. Adapted from (Wu et al., 2021)

Operational information	Performance of instability	Cause of instability	Counter measures and results	Ref
Three thermophilic reactors of 7,600 m^3 and 3 reactors (53°C with HRT of 17–18 d). Feeding substrate: manure (362 t/d) and organic industrial waste (75 t/d).	Significant increase in VFA and ammonia levels. Decrease in biogas production. Occurrence of foaming.	Addition of waste from a mink farm rich in ammonia. No analysis of the waste was performed by the plant.	Terminated the feeding of mink farm waste immediately and replaced it with fresh manure, while continuing to feed with industrial waste. The ammonia concentrations gradually decreased through effluent wash out.	(Nielsen & Angelidaki, 2008b)
Thermophilic temperature: 52°C. Primary reactors: PR1, PR2, and PR3 under the same HRT of 23 d. Second-stage reactor: SR. Feeding substrate: manures (75%) and industrial waste (25%) for PRs and effluent from the PRs for the SR.	Excessive foaming in PR3 with a maximum foam formation of approximately 1,065 m^3/d.	Addition of acidic industrial waste (containing acidic whey) feed mixture and a large amount of chicken manure rich in protein content. Low-mixing speed in PR3.	No counter measures taken.	(Kougias et al., 2014)
Hybrid between a PFR and a CSTR. Feeding substrate: manure (produced by approximately 3,000 cows/wk) and cheese whey (35,000 Gal/wk).	VFA concentration was 9 times that of the baseline. Decrease in biogas production by 70%.	One pump located in the influent pit was out of service for 2 weeks, making the influent material highly inconsistent and stratified. Almost twice the volume of cheese whey was received for co-digestion and the corn silage was also doubled.	No counter measures taken.	(Labatut & Gooch, 2012)
Three on-farm co-digestion plants in Germany.	Decrease in biogas production. Formation of foam and small-sized bubbles.	Addition of thick stillage, a by-product of the ethanol distillation process. Changed the feedstock to slaughterhouse waste. Proteins were denatured through prior hygienisation, and partly or completely hydrolysed, leading to protein enrichment on the surface and stabilisation of the foam.	No counter measures taken.	(Moeller & Görsch, 2015)

Note: VFAs: Volatile fatty acids; HRT: Hydraulic retention time; C/N: Carbon to nitrogen ratio; LCFAs: Long chain fatty acids; OLR: Organic loading rate; PFR: Plug-flow reactor; CSTR: Continuous stirred tank reactor.

Continuation of Table 39. Summary of process instability cases in medium- and large-scale biogas plants. Adapted from (Wu et al., 2021)

Operational information	Performance of instability	Cause of instability	Counter measures and results	Ref
A reported wastewater treatment plant in Germany. Feeding substrate: contents of grease separators.	Foam formation inside the biogas reactor.	Substrates contained active surface agents, which led to a reduction in the surface tension of the biogas reactor contents. The produced biogas could not escape and was encapsulated in the form of bubbles on the surface of the liquid.	No counter measures taken.	(Moeller & Görsch, 2015)
A reported wastewater treatment plant in Germany. Feeding substrate: waste from a paper mill.	Formation of foam with large bubbles.	Very high viscosity and a dry matter fraction of approximately 15%.	No counter measures taken.	(Moeller & Görsch, 2015)
A biogas plant in Saxony – Anhalt, Germany. Feeding substrate: corn cob mix silage.	Foam formation.	Maize kernels contain a large amount of starch, which increased the viscosity of the biogas reactor contents.	No counter measures taken.	(Moeller & Görsch, 2015)
Feeding substrate: liquid manure and maize.	Persistent foam layer over several months.	Tiny particles of the added rye groats offered a greater surface area for the microorganisms than coarsely ground grain. The microbes reproduced quicker and produced more proteins and polysaccharides (mucilage), which promoted foam formation once released after cell death.	Added several litres of anti-foaming agent daily to control the foam layer. Foam layer was considerably reduced by reducing the amount of groats to 0.25% (W/W) of the total feedstock.	(Moeller & Görsch, 2015)
Full-scale biogas plants in Germany. Four mesophilic reactors (8,000 m^3 each) operating in line-forming cascades. Agitation: recirculation. Feeding substrate: primary and surplus sludge. OLR: 2.5–3 kg VS/m^3/d; HRT: 20 d.	Foam formation in Reactor 3. VFA: 17% higher than the other 3 reactors. Slight accumulation of NH_3 in the foam fraction.	Reactor 3 additionally loaded with a high proportion of fat, oil, and grease.	No counter measures taken.	(Moeller & Görsch, 2015)

Note: VFAs: Volatile fatty acids; HRT: Hydraulic retention time; C/N: Carbon to nitrogen ratio; LCFAs: Long chain fatty acids; OLR: Organic loading rate; PFR: Plug-flow reactor; CSTR: Continuous stirred tank reactor.

Continuation of Table 39. Summary of process instability cases in medium- and large-scale biogas plants. Adapted from (Wu et al., 2021)

Operational information	Performance of instability	Cause of instability	Counter measures and results	Ref
Full-scale biogas plants in Germany. Feeding cycle: once per hour. Feeding Substrates: cattle manure (30 m^3/d), sugar beet (8 t/d), corn silage (6 t/d), grass silage (1 t/d), rest feed (2 t/d), and coarse wheat (1.5 t/d).	Temporary foaming incident. Significantly higher acetate, propionate, and ammonium-nitrogen concentrations and a lower pH.	Seasonally added sugar contains easily digestible sucrose, which led to overloading; its particle size enhanced the formation of foam. Poor mixing.	Added anti-foaming agents, plant oils, and acetate. Prolonged the stirring cycle.	(Moeller & Görsch, 2015)
Two-stage with two hydrolysis digesters and two main digesters operated mesophilic. Agitation: continuous stirring with two paddles. Feeding substrates: swine and cattle manure (50,000 t/a) and biogenic industrial waste (30,000 t/a). OLR: 2–2.5 kg VS/m^3/d. HRT: 25 d.	Slightly higher calcium, phosphorous, and sulphur levels. Occurrence of foaming.	An abrupt temperature increase caused higher mortality of microbial cells. Enhanced addition of cooking oil contributed to foam stabilisation.	Part of the digestate was pumped out to lower the level in the digesters, such that the foam could be stirred in by fixed-position agitators. The foam disappeared after 1 week.	(Moeller & Görsch, 2015)
One full-scale biogas plant with one-stage reactor (3,600 m^3) under thermophilic conditions in Germany. Agitation: recirculation. Feeding substrate: waste and sludge from potato processing (36,500 t/a). OLR: 2.8 kg VS/m^3/d; HRT: 36 d.	Long-term foaming at the start-up stage with decreased biogas production. Excessive foam formation during the full-load stage.	Due to new digestate processing, the phosphate concentration in the sewage sludge fed to the digester increased. Pumping water into the digester led to a considerable reduction in temperature.	Used a starvation diet and pumped water into the digester. Excessive foaming was so serious that the reactors had to be pumped out and reinoculated.	(Moeller & Görsch, 2015)

Continuation of Table 39. Summary of process instability cases in medium- and large-scale biogas plants. Adapted from (Wu et al., 2021)

Operational information	Performance of instability	Cause of instability	Counter measures and results	Ref
Two full-scale biogas plants with one-stage (1,000 m^3 each) under mesophilic conditions in Germany. Agitation: recirculation and pneumatic. Feeding substrates: commercial food waste (8,320 t/a), vegetable materials (3,070 t/a), grease separator contents and flotation tailings (3,040 t/a), pastry waste (1,400 t/a), and miscellaneous (dairy wastewater, potato waste, old bread grain sieving waste, 170 t/a). OLR: 2.8 kg VS/m^3/d; HRT: 29 d.	Excessive foaming event accompanied by a decrease of 50% in biogas production. Higher concentrations of propionate, butyrate, and calcium.	Prohibited chloride-containing disinfectants were used in the restaurant, which entered the grease separator contents.	No counter measures taken.	(Moeller & Görsch, 2015)
Full-scale biogas plant with two-stage (with open mash and hydrolysis stage) process in Germany. Mesophilic conditions. Agitation: hydraulic. Feeding substrates: grain waste products (22,800 t/a) and grease separator contents (1,200 t/a); HRT: 30–35 d.	Very high concentration of ammonium-nitrogen. Occurrence of foaming at all process stages.	Grain waste products are rich in protein, and the recirculation of digestate may have contributed to the accumulation of ammonium in the reactor.	The application of anti-foaming agents was not successful; therefore, all stages were equipped with stirrers that operated continuously.	(Moeller & Görsch, 2015)

B. Process parameters for characterising the AD process at full-scale biogas plants

Table 40. Process parameters for characterising the AD process at full-scale biogas plants

Parameter	Analytical method/ Instrument/Technique	Sampling Frequency	Interpretation
Mass of feedstock input (liquid, solid)	N/A	Daily (online)	Mass or volume of feed fed to the reactor has to be established using pump flow rates and/or volumes fed or removed from the reactor.
Characterisation of new feedstocks (pH, TKN, TS, VS)	pH: APHA 4500-H+ B (APHA, 2017) TS: APHA 2540 B (APHA, 2017) VS: APHA 2540 E (APHA, 2017)	New feedstock or feed or batch of feed	The characterisation of new feedstocks can help to prevent destabilisation of the process, especially during load changes and co-digestion; Not required if same or similar feedstocks are always used.
Biogas potential of new feedstock (Biochemical methane potential (BMP))	Lab-scale BMP testing VDI 4630 (VDI, 2006) ISO 11734:2017 (ISO, 2017) (Angelidaki et al., 2009) (Angelidaki & Sanders, 2004)	New batch of feedstock and prior to testing co-digestion of different substrates.	BMP testing gives information about the feedstock biodegradable and realistic methane potential of the feedstocks can be obtained. In addition, optimal co-digestion ratios and a first hint of toxic substances in a feedstock can be obtained.

Note: VDI – Verein Deutscher Ingenieure (Association of German Engineers)

N/A: Not applicable

Table 41. Process parameters, sampling frequency and thresholds limits for monitoring AD process for CSTR reactor operated under mesophilic conditions

Parameter	Sampling Frequency	Individual components	Range of the parameter	Interpretation
pH	daily (min. 2x per week)		7 – 7.5	Stable biogas process is normally operated between pH 7 and 7.5. If the pH value is above or below this range, then the process is already unstable. Therefore, pH cannot be used as an early indicator of process imbalance. In practice, temperature, sampling and storage can have an influence on pH measurement. Further, pH itself influences the dissociation of ammonia, hydrogen sulphide (H_2S) and volatile fatty acids (VFAs) and by that their inhibitory effect.
			< 7	Increased acidity is due to accumulation of VFAs due to an organic overload exceeding the buffering capacity. At pH < 7, microorganisms which degrade VFAs is reduced and thereby biogas production decreases/ceases.
			> 8	Increased alkalinity will lead to process instabilities. This is due to the pH-influence on the dissociation equilibrium of NH_3 and NH_4. High pH values and increased temperature conditions favour the accumulation of NH_3(aq). Free ammonia is able to pass through microbial cell membranes and affect the cellular osmoregulation and thus inhibit microbial performance.
Temperature in the reactor	continuous		37°C	Ideally operate the reactor at the designed temperature and should be kept stable in a biogas process. If AD process is operated under ambient conditions, temperature measurement is still necessary to understand the seasonal variation in temperature and its influence on biogas production.

Parameter	Analytical method/ Instrument	Sampling Frequency	Individual components	Range of the parameter	Interpretation
Ammonium nitrogen (NH_4-N)	APHA, 1998	1-2x per month		<5,000 mg/L	In some cases, NH_4-N concentrations of 3,000-5,000 mg/L can already pose stability problems. A stable process up to 5,000 mg/L is commonly achievable especially if the nitrogen concentration is increased slowly to allow microorganisms to adapt or an inoculum already adapted to high nitrogen concentrations is used for inoculation.
				>5,000 mg/L	It is possible to operate stable degradation processes beyond 5,000 mg/L, however, it is often not an easy task. Microorganisms have to be adapted and in good condition (e.g. no lack of trace elements). The exact limit up to which a stable degradation process is possible depends on temperature, pH and the performance of the microorganisms. VFA will often be accumulated in the biogas plant, although the degradation process operates in a stable manner. High amounts of NH_4-N increase the buffering capacity which supports a stable process. Nevertheless, the process is less robust against additional process problems and if an imbalance emerges it can be more drastic than at low nitrogen concentrations.

Parameter	Sampling Frequency	Range of the parameter	Interpretation
Biogas quality (CH_4, CO_2, H_2S)	daily (min. 2x per week)	CH_4 content: 50-55% (Carbohydrate rich) 60-65% (Protein rich) 65-70% (Lipid rich)	Changes in CH_4, CO_2 or H_2S concentration in biogas can give additional information for investigating process instabilities. A decline in CH_4 concentration, for example, may indicate an upcoming process imbalance if the feedstock mix has remained unchanged. The recommended measuring frequency depends on the infrastructure. If on-line gas composition analysis is available, measurements can be carried out more frequently.
Biogas production	Daily		If neither a sudden change in feedstock quantity nor quality has occurred, a decrease in biogas production can indicate process instability. In any case, as biogas volume has to be measured daily to understand the biodegradability and VS conversion to biogas. If the process becomes unstable, a decrease in biogas production will ultimately occur.
Total VFA (mg/L)	2-4x per month	<1,000 mg/L	Stable process.
		1,000–4,000 mg/L	Range in which stable as well as unstable processes are possible. In biogas processes using feedstocks relatively hard to digest (e.g. energy crops with high TS content) where the rate limiting step is the hydrolysis step, the concentration of total VFA is normally lower than in reactors where the feedstock is readily degradable e.g. food waste. Increased VFA concentrations can also be an indication of a lack of trace elements.
		>4,000 mg/L	High VFA concentrations are normally an indication of process problems, especially if VFA concentrations are increasing rapidly. Yet, stable degradation processes are also possible at higher VFA concentrations, e.g. at higher ammonia concentrations. The concentration of VFA which will lead to a decrease in pH and consequently to process problems depends on the buffering capacity and is plant specific.

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Parameter	Analytical method/ Instrument	Sampling Frequency	Individual components	Range of the parameter	Interpretation
Individual VFA	Gas chromatography	1-2x per month	Acetic acid	<1,000 mg/L	Stable process.
				1,000–4,000 mg/L	Stable and unstable processes are possible. Start to take corrective measures at 2,000 mg/L.
				>4,000 mg/L	High probability of unstable process.
			Propionic acid	<250 mg/L	Stable process.
				250–1,000 mg/L	Stable and unstable processes are possible. Start to take corrective measures at 500 mg/L.
				>1,000 mg/L	High probability of unstable process.
			Longer chained VFA (butyric, valeric)	<50 mg/L	Stable process.
				>50 mg/L	If longer chained VFA (and especially branched isomers e.g. iso-butyric acid and iso-valeric acid) accumulate, severe process problems occur.
			Ratio acetic/ propionic acid	>2	Stable process.
				1-2	Stable and unstable processes are possible.
				<1	High probability of unstable process.
Alkalinity ratio (FOS/TAC)*	Alkalinity analysers	2-4x per month		<0.3	Alkalinity ratios below 0.3 indicate stable processes.
				0.3–0.8	As alkalinity ratios are not comparable between different biogas plants, it is very difficult to generalise. Stability limits must be defined for every specific biogas plant. The maximum limits reported in literature for stable processes range from 0.3 to 0.8.
				>0.8	Unstable process.
H_2 in the biogas	Gas chromatography	on-line		<100 ppm	Stable process.
				100-500 ppm	In practice, it is quite difficult to guarantee accurate H_2 measurements. For this reason, the range where stable or unstable processes are possible is assumed to be quite big. If at a biogas plant accurate H_2 measurements can be guaranteed, a smaller range of stability limits can be defined.
				>500 ppm	Unstable process.

*Note: In German called FOS/TAC. In English also called IA/PA ratio, VFA/bicarbonate, VFA/ALK or Ripley ratio

C. Chemical composition of anaerobic digestate obtained under different process conditions and feedstocks

Table 42. Chemical composition of anaerobic digestate obtained under different process conditions and feedstocks.

Substrates and co-substrates	pH	TS	VS	VS/TS	TKN	NH_4^+/ TKN	C/N	COD	Residual methane yields	Reference
		(%)	(%)		(% on TS)			(g/L)	(mL CH_4/g VS)	
Sludge based anaerobic digestates										
Waste Activated sludge (WAS) and vegetable wastes	7.6	3.4	2.4	70	6.4	79	6.1	26.7	–	(Tampio et al., 2016)
Manure based anaerobic digestates										
Cow manure (100%)	–	7.4	–	–	4.6	65	10	–	–	(Risberg et al., 2017)
Cow manure (99%), fodder and silage wastes		6.1	–	–	6.7	68	6.3	–	–	(Risberg et al., 2017)
Manure (95%), organic wastes (5%)	–	3.1	–	–	14.5	82	2.4	–	–	(Risberg et al., 2017)
Cow Manure (90%), food wastes (10%)		4.3	–	–	8.1	69	4.8	–	–	(Risberg et al., 2017)
Manure (81%), slaughterhouse wastes (15%), food wastes (3%), energy crops (1%)	–	4.8	–	–	7.9	63	5.3	–	–	(Risberg et al., 2017)
Cow manure (80%), organic wastes (20%)	–	4.1	–	–	13.9	74	2.8	–	–	(Risberg et al., 2017)
Cow manure (75%), slaughterhouse wastes (20%), grease (3%), soybean and silage wastes (2%)	–	5.2	–	–	11	72	3.7	–	–	(Risberg et al., 2017)
Manure (cow and pig) (75%), industrial wastes (25%)	–	6.5	–	–	8.3	61	5	–	–	(Risberg et al., 2017)
Manure (cow, pig and chicken) (75%), food wastes (25%)	–	3.9	–	–	12.3	75	3.1	–	–	(Risberg et al., 2017)
Animal manure (70%), energy crops (20%), food industries by-products (10%)	7.9	9.6	7.4	77	4.4	46	–	–	38	(Menardo et al., 2011)
Animal manure (55%), energy crops (45%)	7.8	5.4	5	74	5.9	52	–	–	19	(Menardo et al., 2011)

Substrates and co-substrates	pH	TS	VS	VS/TS	TKN	NH_4^+/ TKN	C/N	COD	Residual methane yields	Reference
		(%)	(%)		(% on TS)			(g/L)	(mL CH_4/g VS)	
Animal Manure (37%), energy crops (47%), food industries by-products (16%)	8.0	3.7	2.5	67	14	58	–	–	4	(Menardo et al., 2011)
Cattle slurry (96%), glycerine (4%)	5.6	3.8	2.6	69	4.9	52	9.5	–	–	(Alburquerque et al., 2012)
Cattle slurry (84.1%), cattle manure (4.3%), maize-out silage (11.6%)	7.5	9	6.6	74	4.4	61	8.5	–		(Alburquerque et al., 2012)
Pig slurry (92.5%), sludge (1%), biodiesel wastewater (6.5%)	8.2	2	0.9	44	20.3	87	1.5	–	–	(Alburquerque et al., 2012)
Pig slurry (87%), energy crops (13%)	8.1	1.7	1.1	62	11.2	78	–	–	3	(Menardo et al., 2011)
Dairy manure, biowaste	7.4–7.9	2.8–4.4	2.1–3.3	69–76	5–6.2	52–63	–	–	–	(Paavola & Rintala, 2008)
Liquid fraction of dairy manure	7.7–7.9	3.8–4.5	2.2–2.8	59–61	7.7–8.5	58–72	–	29.3–36.9	15–103	(Rico et al., 2020)
Cattle slurry (12%), farmyard manure (31%), poultry manure (8%), maize silage (27%), drying maize residues (21%), rice chaffs (1%)	7.9–8.1	8.8–9.6	6.7–7.6	75–82	–	–	–	–	262 L methane/m^2 surface/day	(Gioelli et al., 2011)
Cattle slurry (50.5%), energy crops (49.5%)	8.1	5.7	4.3	76	6.3	51	–	–	–	(Riva et al., 2016)
Food wastes based anaerobic digestates										
Food wastes	7.7–8.0	6.7–7.9	4.6–5.1	68–77	9.3–11.6	26–52	3.3–4.5	–	80–135	(Tampio et al., 2015)
Food wastes (45%), slaughterhouse wastes (40%), organic wastes (15%)		1.7–6.1	–	–	12.5–20	66–82	2.1–2.5	–	–	(Risberg et al., 2017)
Food wastes and garden wastes	–	2.4	1.32	55	10	83	–	–	–	(Stoknes et al., 2016)
Organic wastes of food industry and WAS	7.6	2.4	1.6	69	–	–	–	24.6	169.4	(Boni et al., 2016)
Food wastes, slaughterhouse wastes, municipal wastes	8.4	3.9	2.7	69	22	63	1.3	–	–	(Köster et al., 2015)

Substrates and co-substrates	pH	TS (%)	VS (%)	VS/TS	TKN (% on TS)	NH_4^+/TKN	C/N	COD (g/L)	Residual methane yields (mL CH_4/g VS)	Reference
Food wastes, slaughterhouse wastes, source separated household wastes, kitchen wastes and garden wastes	7.9–8.2	1.4–6.1	0.5–4.3	38–71	11.2–15.7	46–69	2–4	–	–	(Sheets et al., 2015)
Lignocellulosic based anaerobic digestates										
Corn and wheat	6.9	2.03	1.15	57	20.3	70	–	19.1	–	(Meixner et al., 2015)
Maize silage (25%), sorghum silage (11%), olive waste (1%), cow manure (8%), pig manure (18%) and turkey poultry manure on coconut chips (26%)	8.1	8.3	6.03	73	6.4	76	–	74.8	70	(Sambusiti et al., 2015)
Grass (45%), cow manure (33%) and fruit and vegetables (22%)	7.4–7.7	7.1–15.3	4.9–11.6	69–76	–	–	–	–	–	(Ganesh et al., 2013)
Corn and wheat	6.9	2.03	1.15	57	20.3	70	–	19.1	–	(Meixner et al., 2015)
OFMSW based anerobic digestates										
OFMSW	8.3	3.2	1.9	59	14	71	2.3	30.6		(Tampio et al., 2015)
Organic fraction of residual household waste	8.2	–	–	–	1.9	22	–	–	–	(Zeng et al., 2016)
Organic wastes (78%), silage (12%), grease (10%)	–	5.9	–	–	9.3	64	4.4	–	–	(Risberg et al., 2017)
Organic wastes (75%), manure (25%)	–	1.1	–	–	23.6	81	1.7	–	–	(Risberg et al., 2017)
Slaughterhouse wastes based anaerobic digestates										
Slaughterhouse wastes (69%), cow manure (21%), whey (9%), others (1%)	–	3.3	–	–	20	80	2.3	–	–	(Risberg et al., 2017)
Other digestates										
Distillery wastes (100%)	–	6.6	–	–	8.5	55	5	–	–	(Risberg et al., 2017)
Distillery wastes (80%), cereals (10%)	–	3.7	–	–	17.3	64	1.4	–	–	(Risberg et al., 2017)

D. Characteristics of liquid fraction of digestate

Table 43. Chemical composition of liquid fraction of anaerobic digestate obtained under different process conditions and feedstocks.

Substrate	Feeding	OLR	HRT	Digester	Solid-liquid separation	T	pH	TS	VS	COD	sCOD	CORG	TC	TN	C/N	NH_4^+	TP (g/L)	sP	PO_4^{3-}	Mg^{2+}	K^+	Ref.
	(m^3/d)	(kg VS/m^3/d)	(d)			(°C)		(%)	(%)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)		(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	
Sludge and wastewater based liquid fraction of digestates																						
Sludge	NS	NS	NS	NS	Centrifuge and 0.45 mm filtration	NS	7.8	–	–	0.3	–	–	–	0.39	–	0.37	0.2	–	0.19	0.03	0.1	Huang et al. (Huang et al., 2015)
Swine wastewater	NS	NS	NS	NS	Centrifugation (4,000 rpm, 15 min, 5ºC	NS	8.4	1.1	0.5	3.97	–	–	–	1.7	–	1.65	0.17	–	0.15	0.01	2.1	Obaja et al. (Obaja et al., 2003)
Livestock wastewater	1.5	NS	NS	NS	Lab-scale centrifugation (2,000 rpm, 10 mm)	NS	NS	–	–	1.61	–	–	–	0.74	–	0.73	0.03	–	0.013	–	–	Kim et al. (Kim et al., 2016)
OFMSW based liquid fraction of digestate																						
Organic waste. Energy crops and animal slurry	NS	NS	NS	NS	Mechanical separation	NS	–	8	2.9	–	–	–	–	2.7	–	–	1.2	–	–	–	5	Vanden Nest et al. (Nest et al., 2015)
OFMSW	NS	NS	30	NS	NS	NS	8.2	1.9	1.1	–	–	7.4	–	2.5	8.3	1.7	–	–	–	–	–	Michele et al. (Michele et al., 2015)
Manure based liquid fraction of digestate																						
Pig manure	NS	0.4–0.8	35	Semi-continuous	Centrifugation	Ambient	7.5	1.9	0.4	5.6	3	–	–	–	–	1.36	–	0.05	–	0.08	–	Li et al. (X. Li et al., 2016)
Manure	NS	NS	NS	NS	NS	NS	–	NS	NS	7.5	–	–	–	3.6	–	3.3	0.12	–	–	–	–	Gong et al. (Gong et al., 2013)
Cattle slurry (90%) and corn silage (10%)	NS	NS	NS	NS	Roller press	NS	8.1	4.2	2.7	–	–	–	–	3.1	–	1.8	–	–	–	–	–	Perazzolo et al. (Perazzolo et al., 2015)
Liquid cow manure (77%), solid cow manure (19.8%), pellets (1.6%), maize flour (1%) and maize silage (0.7%)	55.3	NS	32	NS	Screw press	NS	–	–	–	–	–	–	–	3.4	–	1.7	0.69	–	–	–	–	Ledda et al. (Ledda et al., 2016)
Liquid cow manure (77%), solid cow manure (19.8%), pellets (1.6%) and maize flour	55.3	NS	32	NS	Screw press and centrifuge	NS	–	–	–	–	–	–	–	2	–	1.7	0.13	–	–	–	–	Ledda et al. (Ledda et al., 2016)

Substrate	Feeding	OLR	HRT	Digester	Solid-liquid separation	T	pH	TS	VS	COD	sCOD	CORG	TC	TN	C/N	NH_4^+	TP (g/L)	sP	PO_4^{3-}	Mg^{2+}	K^+	Ref.
	(m³/d)	(kg VS/m³/d)	(d)			(°C)		(%)	(%)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)		(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	
Cattle slurry (50%), pig slurry (35%), cattle slurry, poultry manure (5%), sorghum silage and corn flour (10%)	NS	NS	NS	NS	Screw press	NS	8.1	3.7	2.4	–	–	–	–	2.5	–	1.3	–	–	–	–	–	Perazzolo et al. (Perazzolo et al., 2015)
Cow manure (29%), cow slurry (29.7%), pig slurry (29.7%) and poultry manure (11.6%)	NS	NS	NS	NS	Centrifuge	NS	–	2.1	–	–	–	–	–	–	–	4.3	–	–	–	–	–	Limoli et al. (Limoli et al., 2016)
Swine manure (73.8%), corn silage (16.4%), triticale silage (8.2%) and maize flour (1.6%)	122	NS	NS	NS	Screw press	39	7.6–7.9	3.3–3.4	1.8–2.3	–	–	–	–	3.4–4.6	–	–	–	–	–	–	–	Chiumenti et al. (Chiumenti et al., 2013)
Cattle slurry (33%), farmyard manure (24%), maize silage (26%), triticale silage (11%), drying maize residue (3%) and kiwi (3%)	90	1.1	130	CSTR	Screw press	41	7.9–8.1	4.6–5.4	3.2–3.7	–	–	–	–	–	–	–	–	–	–	–	–	Giocelli et al. (Gioelli et al., 2011)
Pig slurry and corn	NS	NS	NS	NS	NS	NS	8	NS	NS	17.6	–	–	–	3.4	–	2.1	–	–	0.3	–	–	(Franchino et al. (Franchino et al., 2016), Tigini et al. (Tigini et al., 2016)
Cattle slurry (23%), farmyard manure (30%), energy crops (27%) and agricultural by-products (20%)	NS	1.55	105	CSTR	Screw press	41	8.8–9	5.9–6.7	3.8–4.7	–	–	–	–	–	–	–	–	–	–	–	–	Balsari et al. (Balsari et al., 2013)
Cattle slurry (50.5%) and energy crops (49.5%)	NS	NS	80	CSTR	Screw press and centrifuge	40	8.4	4.4	3.1	–	–	–	–	3.4	–	2.1	–	–	–	–	–	Riva et al.(Riva et al., 2016)
Pig slurry, glycerine, used oil, food processing waste and slaughterhouse waste	NS	3	22	CSTR	Centrifugation	NS	7.9	0.07	0.03	5.4	–	–	–	–	–	2.2	–	–	–	–	–	Gustin and Marinsek–Logar (Guštin & Marinšek-Logar, 2011)
Cattle slurry and maize	NS	NS	NS	NS	NS	NS	7.9–8.3	4.1–5.4	–	–	–	14.6–20.6	–	2.7–3.5	10.9–11.9	1.7–1.8	–	–	–	–	–	Cavalli et al. (Cavalli et al., 2016)
Corn stover	NS	NS	NS	Continuous	20-mesh sieve	NS	–	3	1.9	–	–	–	–	0.96	–	0.65	–	–	–	–	–	Hu et al. (Hu et al., 2015)
Corn stover	NS	NS	NS	NS	20-mesh sieve filtration	NS	NS	1.5	0.7	–	–	–	4.5	0.6	7.4	–	–	–	–	–	–	Wei et al. (Chadwick et al., 2015)

Substrate	Feeding	OLR	HRT	Digester	Solid-liquid separation	T	pH	TS	VS	COD	sCOD	CORG	TC	TN	C/N	NH_4^+	TP (g/L)	sP	PO_4^{3-}	Mg^{2+}	K^+	Ref.
	(m^3/d)	(kg VS/m^3/d)	(d)			(°C)		(%)	(%)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)		(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	
Corn and wheat	NS	3.5 kg COD/m^3/d	NS	CSTR	Centrifugation	NS	–	1.5–1.7	0.8–1	1.1 – 1.6	–	–	–	3.53	–	2.68–2.73	0.52	–	–	–	2.1	Meixner et al. (Meixner et al., 2015)
Lignocellulosic based liquid fraction of digestate																						
Leaf biomass	1 kg TS/m^3	NS	NS	Plug flow	Filtration at 50 μm and autoclaved	NS	NS	2.1	–	–	–	–	0.17	0.1	1.6	–	0.16	–	–	0.54	2.2	Malayil et al. (Malayil et al., 2016)
Maize silage, sunflower silage, cereal residues, grass silage and liquid manure	36.9–44.6	3.7–4.1	45–84	Fully mixed horizontal and vertical digester	Screw extractor and rotary screen	40	–	4.5	3.13	–	–	–	17.8	4.2	4.2	2.6	0.9	–	–	–	3.5	Bauer et al. (Bauer et al., 2009)
Food waste based liquid fraction of digestate																						
Source segregated food waste	NS	2	107	CSTR	Sieve	36	7.9	6.4–6.6	4.7–4.8	–	–	–	–	8.75	–	5.1		–	–	–	–	Serna–Maza et al. (Serna-Maza et al., 2015)
Food waste and garden waste	–	1.96	40	CSTR	Centrifuge	40	9.4	0.8	0.5	–	–	–	–	2	–	2	0.14	–	–	0.03	0.4	Stoknes et al. (Stoknes et al., 2016)
Organic biological waste produced by food industry (40%), animal manure (30%) and energy maize (30%)	NS	NS	NS	NS	Sieve ba-press	NS	8.6	3.3	1.5	–	–	–	–	5.3	–	4.6		–	–	–	–	Sigurnjak et al. (Sigurnjak et al., 2016)

E. System transition background

Complex adaptive systems

The generation, distribution, marketing and consumption of energy in Australia can be conceptualised as a complex adaptive system (CAS) (Figure 25). CAS are made up of a set of connected or interdependent agents or stakeholders (i.e., an organisation, department, team or individual) that respond to a dynamic environment in unpredictable, often non-linear ways (Palmberg, 2009). The control of the system is distributed across stakeholders, who adapt, learn and self-organise through co-evolution in response to drivers of change (Holland, 2006; McCarthy et al., 2007; Zimmerman et al., 1998). The system's ability to learn and adapt means that its behaviours emerge over time rather than through system design (Smith & Stirling, 2008). For example, Bale et al. (2015) considered stationary energy systems as CAS, and Pearson and Bardsley (2022) analysed the need for adaptation to climate change in stationary energy using a CAS approach. However, almost every biological, economic and social system is a complex adaptive system (CAS) (Ahmed et al., 2005).

Management of energy systems as CAS is problematical as there are no known mechanisms capable of mapping, in advance, the interdependencies among political (governance, legislative, policy and institutional arrangements), technical (production, distribution, storage and utilisation), environmental (resource, risk and climate), social (livelihoods, energy poverty and social practices) and economic (consumers and the energy market) elements (Di Maio, 2014; Pearson & Bardsley, 2022), which requires unique approaches that influence rather than control behaviour (Figure 25).

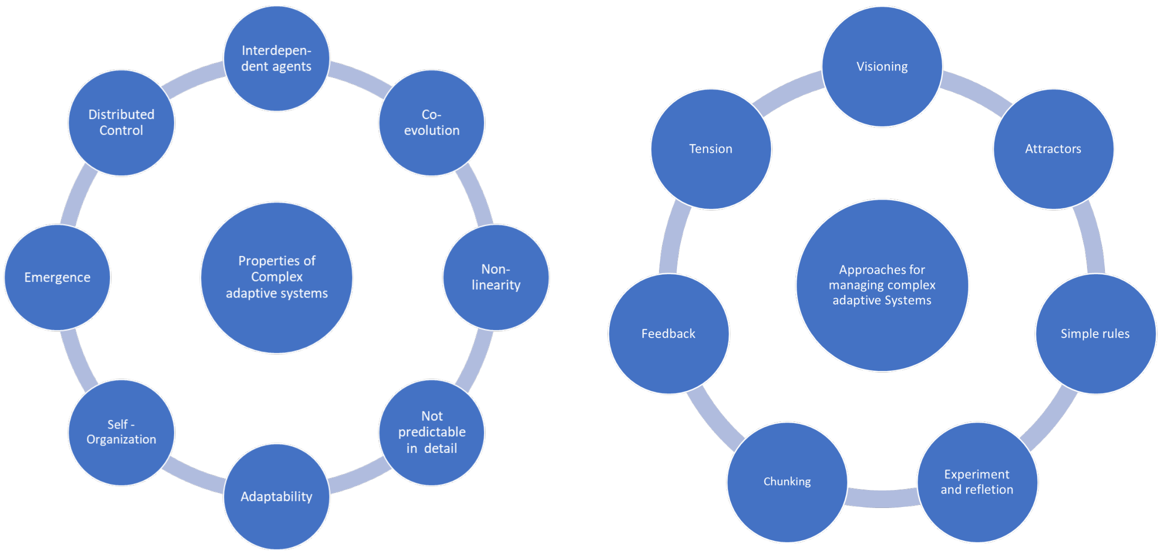


Figure 25. Properties of complex adaptive systems and approaches for their management (Zimmerman et al., 1998)

Socio-technical systems (STS)

The interaction of engineered systems with society, such as in energy systems, represents a particular class of CAS known as socio-technical systems (STS). An STS perspective is used to study the development and use of technology as a complex adaptive process where materials and people interact (Smith & Stirling, 2008). STS are open systems that may operate at a range of scales, and larger systems can be composed of interacting sub-systems (nested systems) meaning determining system boundaries is often problematical (Di Maio, 2014) (Figure 26). For example, Australia's energy system, is composed of multiple socio-technical subsystems (e.g., fossil-fuel, renewable energy and so on). While renewable energy can be conceptualised as an STS, it in turn can be considered as composed of several interacting socio-technical subsystems – solar, wind, geothermal and bioenergy – based on specific (sometimes multiple and competing) technologies. Given the properties of CAS described above, understanding the potential for rapid dynamic reconfiguration in STS (a process of transition) has been conceptualised through a number of methods like the technical-economic perspective (TEP) or the multi-level perspective (MLP) (Wilkinson et al., 2021).

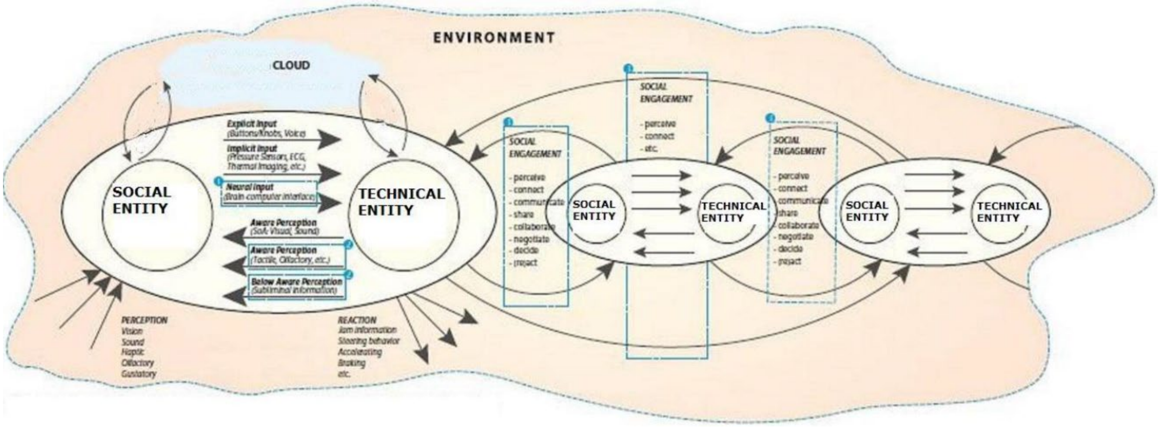


Figure 26. An example of nested, interacting socio-technical systems (Di Maio, 2014)

Conceptualising socio-technical transitions

The use of STS perspectives to explore sustainable technologies, such as for decarbonising energy systems, aligns with the recognition that there is no 'silver bullet' technological solution, rather, structural changes will be required in social, economic, political and infrastructure systems (Smith & Stirling, 2008). Because the stakeholders in an STS pursue a range of goals, strategies and plans, designing incentives and rules that influence adaptive behaviour may lead to tipping points or thresholds of adoption (Wruck, 2000) and, ultimately, system transformation. The process by which societal transformation occurs, either incrementally or abruptly, is defined as transition. Transition management, often driven by the desire to improve system sustainability, is a model of system governance that considers and incorporates an understanding of complex systems theory to deliberately intervene in an STS to promote change (Kemp & Loorbach, 2006; Shove & Walker, 2007). Table 44 contrasts the transition management approach with a market-based mechanism to promote sustainable energy transitions in Australia (Rosenbloom et al., 2020).

Table 44. Comparison of carbon pricing strategies and sustainability policy to promote sustainable energy transition in Australia (Rosenbloom et al., 2020)

	Carbon pricing strategies	Sustainability transition policy
Conceptual roots	Neoclassical economics	Innovation studies, evolutionary economics, institutional theory
Problem framing and solution orientation	Climate change as a market failure problem: price carbon to correct market signal	Climate change as a system problem: fundamentally transform existing sociotechnical systems
Overriding policy priority	Efficiency: reduce carbon emission while keeping the economy wide cost at a minimum	Effectiveness: drive down emissions as quickly as possible
Innovation approach	Incremental change, indirect simulation of innovation	Transformative change, direct stimulation of innovation
Contextual considerations	Universality: carbon pricing for all jurisdictions and sector	Tailoring: policies should be adapted to local and sectoral contexts
Understanding of politics	Revenue recycling to deal with political realities	Creation of alternatives and formation of supportive coalitions

While transition management appears to provide a mechanism to promote transition, the uncertainty and unpredictability of complex systems suggest that deliberate management to control all of the system elements (e.g. stakeholders, resources stocks and flows, shared vision, thresholds of change) and to ensure that the transformed system has desired attributes is at best extremely difficult (Shove & Walker, 2007).

Although other models of change exist (e.g. the Technological Innovation System approach, Strategic Niche Management and Transition Management) (Köhler et al., 2019), the MLP is a mature, heuristic framework (Geels, 2022) widely applied to empirical studies of change (such as deliberate transition management) in socio-technical systems across diverse knowledge domains (e.g., autonomous vehicles, Fraedrich et al. (2015); phosphorus circularity, Jacobs et al. (2017); and energy systems, Kanger (2021)). The MLP conceptualises transitions as occurring through processes of interaction within and among three analytical levels: niches (the sites of innovation), socio-technical regimes (networks and rules etc. of the incumbent system) and a socio-technical landscape made up of drivers of societal change (Figure 27). Arranz (2017) associates change at the regime level most often with new or visibly changed political manoeuvring (e.g., lobbying, election promises), socio-cultural understanding (e.g., lifestyle choices, fashion), or economic variables (e.g., prices, competition). It appears that the combined weight of multiple factors is more important to regime destabilisation than any single factor alone (Arranz, 2017). Pressure from the landscape level on the regime can open opportunities for niches to form around technological innovations. The potential for disruption or destabilisation by the innovation is generally resisted, actively or passively, by the existing regime (Arranz, 2017). However, over time, through a range of pathways (reproduction, transformation, dealignment-realignment, technological substitution, reconfiguration) change in the regime (Geels & Schot, 2007) may allow the technology to become established.

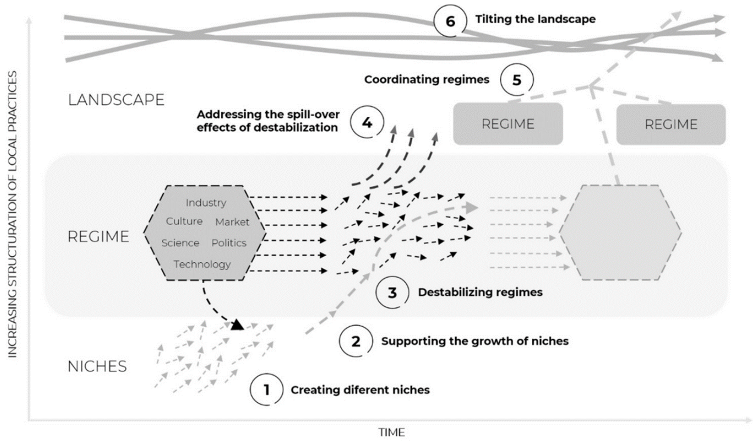
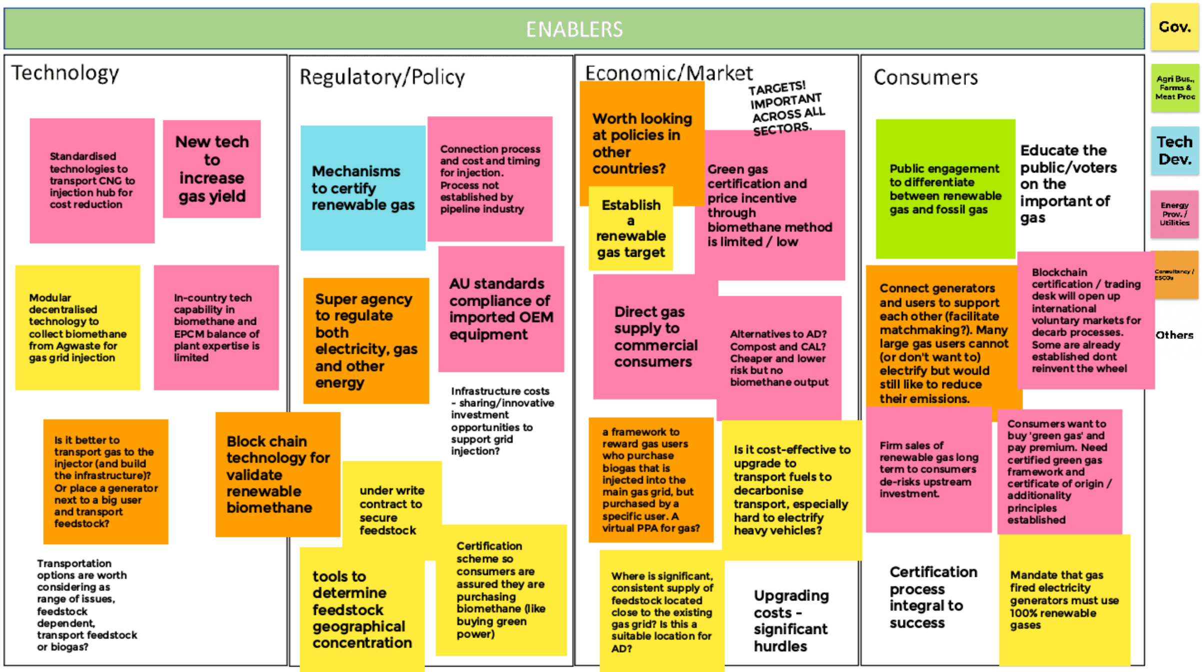


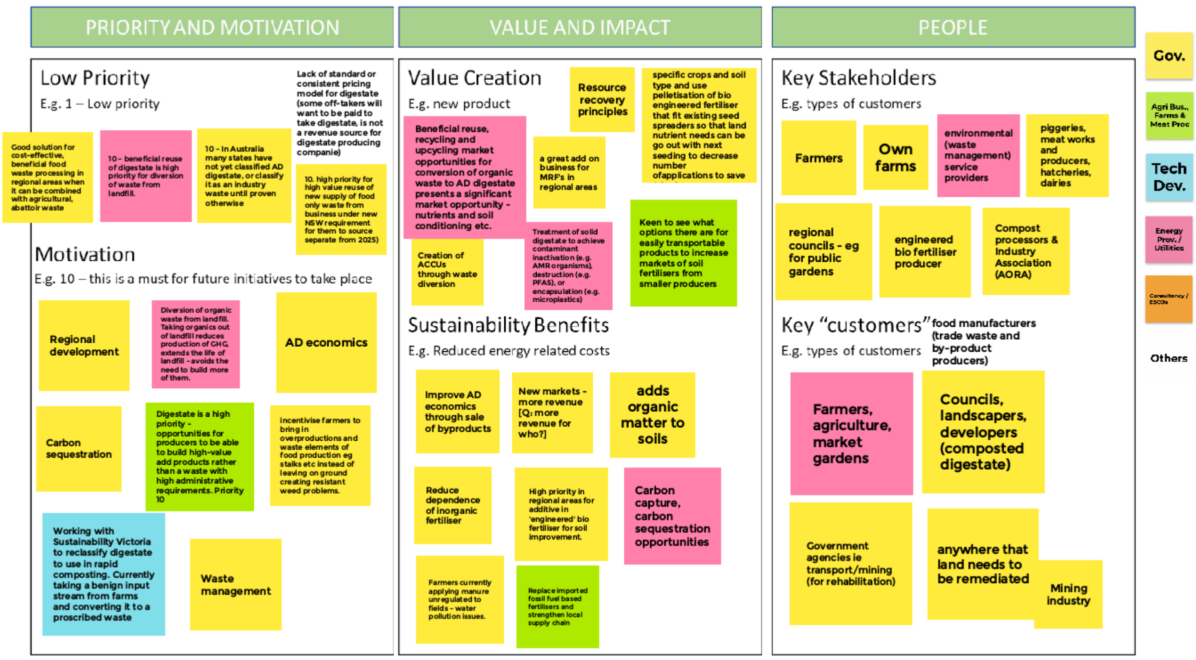
Figure 27. Process of influencing transition management in the MLP framework (from Kanger et al. (2020))

F. Results of the barriers and opportunities workshop

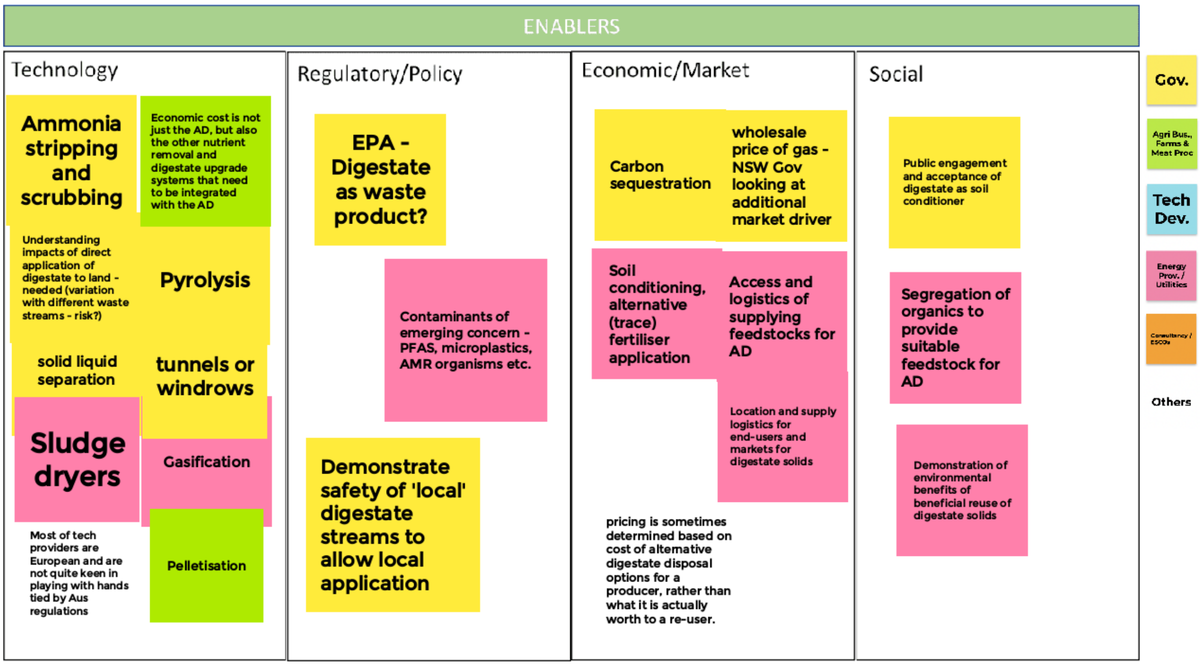
Results of the Barriers and Opportunities Workshop based on Gas Pipeline Network Injection – Key Enablers



Results of the Barriers and Opportunities Workshop based on Digestate - Motivation, Value and Key Stakeholders



Results of the Barriers and Opportunities Workshop based on Digestate - Key Enablers



G. EU Renewable Energy Regulation Case Study

As can be seen in Figure 28 below, the EU has over three decades of integrated approaches to energy-climate policy and laws.

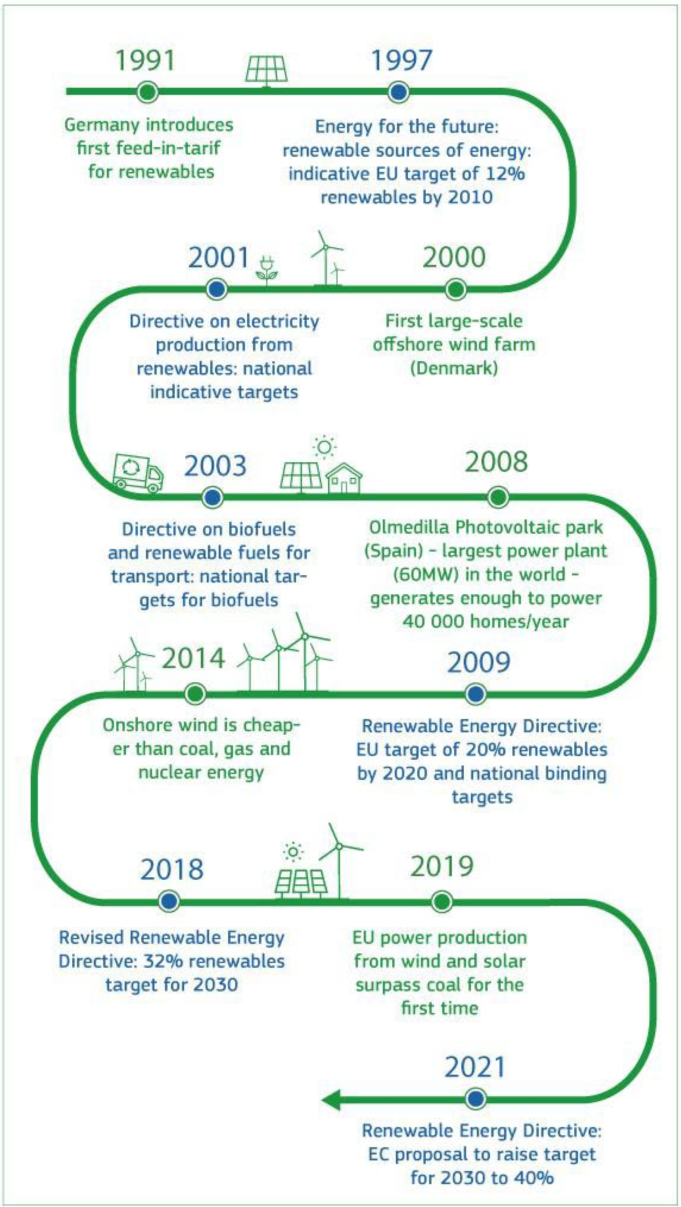


Figure 28. Timeline for Renewable Energy in the EU (European Union, 2020)

Within the renewable energy EU regulatory framework are both policies and legislation, and underneath these are the policy and regulatory actions of each EU member country. An example of this kind of policy and regulatory development is the German Renewable Energy Sources Act, first adopted in 2000. This Act initially introduced a planned process to manage the transition to a low-carbon economy, including a transition to biogas production as a renewable energy source. The German legislation required the encouragement of renewable energy production, but with a requirement that, in each case, this had to make ecological sense and not generate conflict with the sustainability objectives of environmental conservation schemes. Regulations which encouraged biogas production were introduced in German over time from 2004 (Thrän et al., 2020). The first stage of this process was 'the careful consideration of the overall conditions' in the geographic area. The Institute for Energy and Environmental Research in Heidelberg coordinated 'an analysis of the ecological impact of the generation and use of biogas in Germany taking into account legal and economic aspects, and recommendations were given to policy makers' (Bioeconomy BW, 2012).

The 2009 European Union Renewable Energy Directive 1 (Directive 2009/28/EC) established a mandatory 20% target for renewable energy consumption by 2020, including 10% renewables target for transport fuels.

The directive also mapped out various mechanisms that Member States could apply in order to reach their targets, such as support schemes, guarantees of origin, joint projects, and cooperation between Member States and third countries, as well as sustainability criteria for biofuels (European Union, 2021).

The first renewable target was then legislated in Germany in 2012 in the Renewable Energy Act and all EU members were expected to produce national renewable energy progress reports every two years. These targets were revised upwards, with the 2018 EU Renewable Energy Directive II (RED II) (Directive 2018/2001), which increased the binding renewable energy target for 2030 to at least 32% and increased the transport target to 14%. In addition, it introduced a number of changes in the biogas context. Among other thing, RED II:

- mainstreamed renewables in the heating and cooling sector, with an annual increase of 1.3% renewables for heating and cooling;
- strengthened the EU sustainability criteria for bioenergy;
- introduced a bio-fuels certification scheme, and a 7% cap on first generation biofuels like palm oil, which increased CO_2 emissions in road and rail transport; and
- introduced a 3.5% share in the transport sector for advanced biofuels and biogas by 2030, with an intermediary target of 1% by 2025.

The overall targets were modified again in 2021 to include an intermediate target of 55% net reduction in greenhouse gases by 2030. These changes were required to deliver on the European Commission Green Deal (European Comission, 2019) which seeks climate neutrality and they were:

- A new benchmark of 49% renewables use by 2030 for buildings;
- A new benchmark of a 1.1% annual increase in renewables use for industry;
- A binding 1.1% annual increase for the Member States in the use of renewables for heating and cooling;
- An indicative 2.1% annual increase in the use of renewables and waste heat and cooling for district heating and cooling;
- A target of a 13% reduction in the greenhouse gas intensity of transport fuels by 2030, covering all transport modes;
- A 2.2% share of advanced biofuels and biogas by 2030, with an intermediary target of 0.5% by 2025 (single counted); and
- A 2.6% target for renewable fuels from non-biological origin and a 50% share of renewables in hydrogen consumption in industry, including non-energy uses, by 2030 (European Union, 2021).

How these policy prescriptions are implemented nationally varies substantially, as does their use of different feedstock (Gustafsson & Anderberg, 2022). In this context, in the first 15 years of the renewable energy policy and legislative shift, Germany became the highest biogas producer in Europe, essentially through encouraging fuel crop production to produce biogas for electricity generation to feed-in to the electricity grid, but subsequent policy changes have sought to target biogas production differently, specifically towards biomethane production.

There are important lessons in the implementation of regulatory biogas incentives from the German experience, following the extensive development of the industry between 2000 and 2015. For example, the incentives to expand the production of corn to produce silage as feedstock for biogas production was assessed as problematic so far as sustainable use of land was concerned. The electricity supply contracts entered into by producers, which provided long term security financially, have tied them into this production. Many are unable to shift to biomethane production, which may well be more profitable. The use of biogas for electricity production was identified as economically inappropriate, as solar and wind energy resources have become much cheaper over that time. The goals for the industry are moving to focus biogas production as a peak load energy source to "fill in the gaps" when seasonal variation with solar and wind requires more energy from other sources for the electricity and sometimes heat supply (Willinger, 2020). Following this experience and the implementation of the revised EU Renewable Energy Directive (RED II) in 2018, further regulation was required (Thrän et al., 2020) and Figure 29 below sets the thematic representation which governs the German biogas industry.

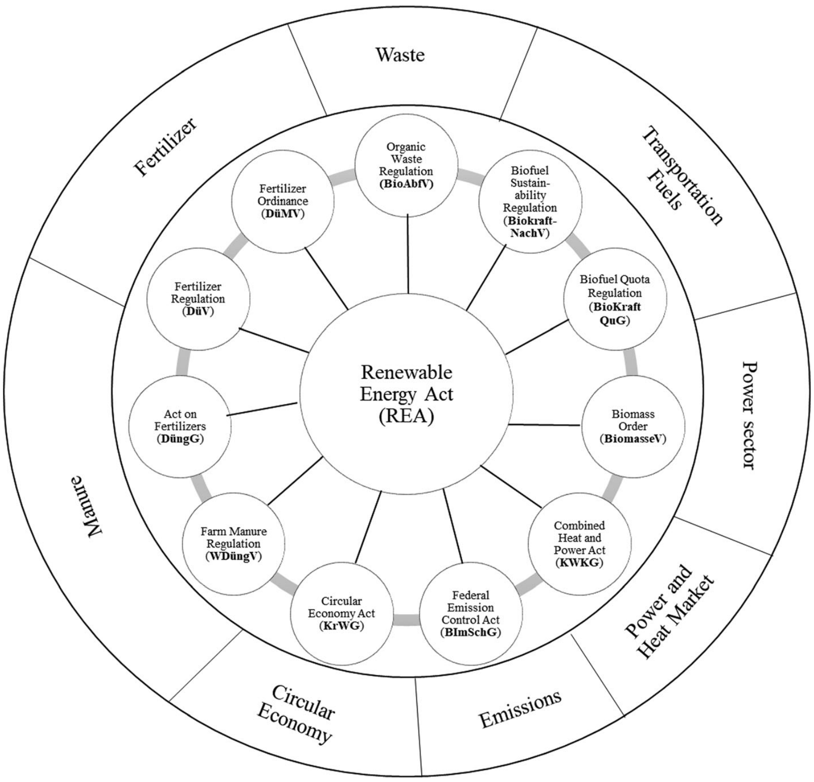


Figure 29. Thematic presentation of national legislation relevant to the German biogas sector (Thrän et al., 2020)

H. Addendum

Since the initial draft of this document, 2 major changes have occurred and are still in flux:

1) **Gas price rise and subsequent gas price** cap – the report was based on a gas price of $6/GJ. When Russia invaded Ukraine on 24 February 2022, the gas price in the eastern states and the Northern Territory rose to over $20/GJ. In response to this price rise, in December 2022 the Australian Federal Government introduced a temporary price cap of $12/GJ for gas sold in the east coast and Northern Territory gas markets, which will apply for 12 months. While the initial price rise provided a positive incentive for biogas projects, the gas price cap and lack of differentiation of biomethane has created uncertainty in the market, which anecdotal evidence suggests is making it difficult to secure the long term off take agreements needed to underwrite capital expenditure.
2) **New Federal Guarantee of Origin (GO) Scheme** – this scheme allows for certification of hydrogen and potentially other gases. In theory this is aligned with the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) methodology for determining the greenhouse gas emissions associated with the production of hydrogen, but the second version of the IPHE method allows for biomass gasification with carbon capture and storage (CCS) and is feedstock agnostic, meaning that steam methane reformation or auto-thermal reformation can use biomethane or fossil methane (natural gas). Additionally, the changes to the National Gas Law in late 2022 refers to "covered gases", which include biomethane. It is unclear when the GO scheme will be updated to align with the IPHE v2 and current National Gas Law.

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