Clarifying biomethane and small-scale biogas options for Australian piggeries

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Executive Summary

The purpose of this project was to carry out cost benefit analyses on a number of biogas production and use options for Australian piggeries.

Biogas is a fuel gas mixture of mostly methane and carbon dioxide that is produced naturally when organic matter (e.g. pig manure) decomposes biologically in the absence of oxygen, such as in effluent ponds. Biogas can be captured and used on-farm as an energy source to heat, cool or generate electricity, or can be purified into compressed/liquified methane for higher-end uses.

To date biogas use on-farm has been most economical for larger piggeries (1000+ sows farrow-to-finish) due to economies of scale and higher energy costs. The current project sought to clarify true biogas feasibility at a medium sized piggery, by conducting a real biogas case study on a 535-sow farrow-to-finish piggery in Victoria, Australia. The results showed that economic feasibility of biogas was moderate at this piggery size (Table 1), with an estimated 6.4-year simple payback period. The producer considered the investment in biogas as good, provided that the on-going maintenance requirements remained largely the same as they had been since commissioning of the biogas system in 2017. The producer also significantly valued the social-license benefits, having observed notable improvements in community relations due to odour reduction achieved by the on-farm biogas system.

Table 1 Summary of cost-benefit-analysis results. Not including debt finance, so excluding interest payments.

Biogas-use scenario		Estimated capital spend[1]	Estimated NPV (20 years)[2]	Estimated Simple Payback Period
(A – Real case study) 535-sow farrow-to-finish, Victoria, biogas used to generate electricity and to produce hot water		$615k	$621k	6.3 years
(B – Scenario) Same as A, but with: • grower-finisher pigs on deep litter • conventional effluent from breeding herd converted into biogas in smaller covered anaerobic pond • grower spent litter converted into biogas in a new in-ground digester		$626k	$485k	7.1 years
(C - Scenario) Same as A, but with the addition of an absorption chiller unit to supply chilled drinking water to sows during summer months, increasing sow feed intake, milk production and piglet weaning weight		$658k	$644k	6.4 years
(D - Scenario) Large piggery, 57,400 Standard Pig Units (SPUs), all conventional, piggery sells biogas to separate entity that produces biomethane and bio-CO_2, to sell to existing clients at current local market prices	for the producer that sells the raw biogas	$2.4M	$4.1M for producer	4.5 years
	for the third-party commercial gas manufacturer-supplier that buys the biogas and produces and sells biomethane and bio-CO_2	$3.3M	$5.8M	4.5 years

[1]Initial capital investment for biogas systems.

[2]Net Present Value (NPV) assumes a 5% per annum discount on future cash flows.

The project extrapolated the results of the real piggery biogas case study into a set of subsequent scenario analyses of biogas production and use options for piggeries that would produce low levels of biogas and piggeries producing excess biogas.

Some piggeries would produce low levels of biogas because all or part of their herd is on deep litter, thereby providing less piggery effluent (or none) for biogas production in covered anaerobic ponds.

Options considered for such piggeries included importing and use of other safe organic matter sources from external industry for biogas production in existing covered ponds, or the conversion of spent piggery litter (also an organic matter source) into biogas. However, spent piggery litter is unsuitable for treatment in covered anaerobic ponds, so a different dedicated anaerobic digestion system would be required to utilise the spent litter for biogas production. A cost benefit analysis (CBA) showed that an in-ground litter digestion concept could be only marginally less profitable than the base case piggery case study (Table 1), specifically with an estimated 7.2-year simple payback period. However, the batch-wise operation of the litter digester would require periodic mechanical emptying and reloading with an excavator/front-end loader. This is expected to significantly increase manual handling of the litter and labour requirements as compared to a typical deep litter piggery. There are currently no such digesters in Australia, and a future trial is recommended to clarify true cost-benefit.

Some piggeries produce excess biogas that they are unable to profitably utilise. An option explored for such piggeries was to use the biogas directly in an absorption chiller unit to supply chilled drinking water for sows under heat stress or for shed cooling applications. This may be particularly important into the future, with a likelihood of more extreme climates. Commercially available absorption chiller units were found that can directly run on natural gas, and it may be possible to retrofit these to instead run on biogas. Importantly, the commercially available absorption chiller units were able to simultaneously produce chilled water and hot water, thereby providing versatile energy options for a piggery. Such infrastructure may open future opportunities for piggeries unable to install a biogas electrical generator, then instead directly utilising the biogas energy in a retrofitted absorption chiller unit. A CBA compared the business case of (a) using biogas in both an onsite electricity generator and in a parallel operating absorption chiller unit, with (b) only using the biogas in an electricity generator with heat recovery. The results showed that adding an absorption chiller only marginally improved overall benefits from the biogas, because most of the cost savings were from electricity generation. However, the commercially available absorption chiller units considered in this study were more costly than expected, so that if a more cost-effective chiller unit could be found in future investigations, it may be possible to achieve a significantly better feasibility.

Another option explored for piggeries with excess biogas (in this case for larger piggeries with >250$m^3.hr^{-1}$ excess biogas) is to sell the biogas to a third-party commercial gas manufacturer-supplier who then purifies it to produce biomethane and bio-CO_2. These products are then sold instead of natural gas and commercial gaseous CO_2 to existing users and at the current market value. The involvement of a third-party gas manufacturer-supplier would complicate arrangements, but would also significantly de-risk the project for the producer. The CBA results showed that a scenario project would be highly economically favourable for both the producer and the third-party entity, with an estimated payback period of 4.5 years for both (Table 1). The economic feasibility was however highly sensitive to the sale of liquid CO_2 at the current market price, so the feasibility of distributing and selling CO_2 should be further explored in future studies.

Overall, the report has identified potential technologies, provided a real biogas case study, conducted feasibilities of real-life scenario projects, and provided a good evidence-based justification of various biogas concepts for Australian piggeries. Based on the observed cost benefits being moderately to highly feasible, future investigations and research are recommended to trial and pilot the spent litter digestion concept, the use of an absorption chiller unit for chilled and hot water production and a biogas to biomethane concept. Such work would help clarify real cost-benefit and practical opportunities and constraints for Australian piggeries.

Table of Contents

Nomenclature List

Anaerobic digestion	A natural biological process by which organic matter into biogas in the absence of oxygen (i.e. in an anaerobic environment).
AMPTS II	Automated Methane Potential Test System II (Bioprocess Control, Lund, Sweden), a commercial instrument used to measure BMP
AUD	Australian dollars
Biogas	A gas mixture of mostly methane and carbon dioxide, produced by anaerobic digestion
BMP	Biochemical methane potential, the maximum amount of methane that can be achieved by anaerobic digestion of an organic matter sample, under ideal laboratory test conditions
CBA	Cost Benefit Analysis
CH_4	Methane
CHP	Combined heat and power unit, an engine generator that produces both electricity and useable heat
CO_2	Carbon dioxide (bio-CO_2 is sourced from a renewable source)
d	Discount rate used in NPV analysis
ERF	Emissions Reduction Fund
HDPE	High-density polyethylene, a common commercial plastic
H_2S	Hydrogen sulphide, a trace gaseous ingredient found in biogas
kWe	Kilowatt electrical, a measure of electrical power
kWhe	Kilowatt hour electrical, a measure of electrical energy
NPV	Net Present Value, the difference between the present value of cash inflows and the present value of cash outflows over a period of time, accounting for the depreciation in the value of money over time.
LGCs	Large-Scale Renewable Energy Credits
LPG	Liquefied petroleum gas
Pork CRC	Cooperative Research Centres for High Integrity Australian Pork
PSA	Pressure swing adsorption, a commercially available technology used for purification of gases
Payback period	Time taken to recoup an initial capital investment with an annual net revenue stream (annual total gross revenue – annual total operating expenses)
QLD	Queensland
SPU	Standard Pig Unit, a unit defining equivalent manure production of a piggery
TS	Total solids, a measure of dry matter content ($TS_{corrected}$ is TS corrected for the loss of VFAs during the TS measurement)
VS	Volatile Solids, a measure of organic matter content ($VS_{corrected}$ is VS corrected for the loss of VFAs during the preceding TS measurement step)
VFAs	Volatile fatty acids
USQ	University of Southern Queensland
USD	American dollars

1. Background to Research

1.1 Introduction

Biogas is a gas mixture produced naturally when manure-organic matter decomposes biologically in the absence of oxygen (i.e. anaerobically). This occurs in effluent treatment systems, such as in uncovered effluent ponds. This natural biological process by which biogas is produced is commonly termed anaerobic digestion. Because of the methane content in biogas, it is a flammable gas that can be used for energy to heat, cool or generate electricity, or biogas can be transformed into compressed natural gas or vehicle fuel (Skerman, Pech et al. 2015). For these use purposes, piggery biogas must be captured, such as by covered effluent ponds or engineered biodigesters, and the biogas must be pre-treated to a suitable quality prior to use for the above purposes.

Over the period 2011 – 2018, the Cooperative Research Centres for High Integrity Australian Pork (Pork CRC) funded a national research and extension program called the Bioenergy Support Program. This program aimed to facilitate the use of on-farm biogas energy in the Australian and New Zealand pork sectors. The program was successful in enabling over the period 2011-2018 a rapid increase in the proportion of the national pig herd for which biogas was being captured (i.e. increased from 20,000 Standard Pig Units (SPU) to 427,000 (SPU); (Skerman and Tait 2018)).

1.2 The need

1.2.1 Cost-feasibility of piggery biogas used at small to medium-sized piggeries

Whilst some smaller piggeries have trialled biogas use (e.g. 1,400 SPU piggery in Grantham; (Skerman and Collman 2012)), it has typically not been as economically attractive as at larger piggeries (Skerman and Collman 2012). As a result, to date, most of the Australian piggeries that are capturing biogas are at 1000+ sows farrow-to-finish (10,000+ SPU), where economies of scale with larger installations improves profitability (Skerman and Tait 2018).

However, early feasibility studies indicated that conventional piggeries with notable on-farm energy demand and at or above a nominal cut-off of around 5,000+ SPU (500+ sows farrow-to-finish), would be able to use biogas in a profitable manner (e.g. 5,399 SPUs, farrow-to-finish conventional, 4.7 years estimated payback period (McGahan, Valentine et al. 2013)). Nevertheless, to date there have not been any real case studies in Australia to confirm economic feasibility of biogas at or near this piggery size. Such a case study is therefore carried out in the current project, uniquely considering regulatory compliance costs that have previously been shown to adversely affect the cost feasibility of biogas use at other Australian piggeries (Skerman and Collman 2012).

1.2.2 Options for piggeries with low levels of biogas

An estimated 20% of the national Australian pig herd is farrowed in conventional housing but grown to market weight on deep litter. In such cases, piggery effluent is only produced by breeding pigs housed in conventional sheds, equivalent to between 20% and 40% (Tucker 2018)[1] of the total manure output of an equal-sized farrow-to-finish piggery with all conventional sheds. This is important because the amount of biogas produced from effluent in a covered pond is directly proportional to the amount of effluent (specifically manure organic matter) entering the covered pond. This means that a piggery with progeny on deep litter could produce 60-80% less biogas energy than an equal-sized all-conventional farrow-to-finish piggery and would likely have insufficient biogas to meet onsite energy demand.

To meet the shortfall in biogas energy at the above piggeries, two options could be explored:

- other sources of organic matter could be imported to the piggery and added to the piggery effluent sent to an onsite covered effluent pond. This is commonly called anaerobic co-digestion, and increases the organic loading on the covered effluent pond and can thereby increase biogas production; or
- additional anaerobic digestion systems can be installed at the piggery to also convert spent litter organic matter into biogas.

To clarify the feasibility of these options for Australian piggeries, the project provided:

- for anaerobic co-digestion, a review of materials handling and biosecurity considerations, expected impacts of organic matter sources on covered effluent pond operation, expected increases in biogas production, and an overview of anticipated additional financial benefits. For example, by importing other organic matter sources onto a piggery, additional gate fee income could be earnt by the piggery if the organic matter would have otherwise gone to landfill; and
- for spent litter digestion, a scenario analysis of a hypothetical piggery application to explore practicality and cost-feasibility.

1.2.3 Options for piggeries with excess biogas

Pig manure is generally a good organic matter source to produce biogas in covered effluent ponds. In fact, several Australian piggeries have previously reported that they were producing more biogas energy than was needed at the piggery (Skerman, Pech et al. 2015). The excess biogas is then either burnt in a flare, which can earn carbon credits and reduce odour, but does not recover energy, or can be used instead to generate excess electricity to export and sell to the electricity supply grid, but for a relatively low financial value (Tait 2016). To identify more profitable options for excess biogas at piggeries, Skerman et al. (2015) conducted a review and analysis of several existing and potential future uses of biogas. Two emerging options that were noted as potentially profitable were:

- using biogas energy to produce chilled drinking water for sows to alleviate heat stress and thereby improve production (incremental Return on Investment of 62%); and
- heating of a tallow tank for the preparation of feed mixtures with tallow (incremental Return on Investment of 110%).

Providing chilled drinking water for sows appeared to be a more widely applicable option, because tallow is not used at the majority of piggeries in Australia.

[1] This is estimated based on the proportion of total SPU numbers contributed by breeding sows, suckers and boars, with and without weaners, for a typical farrow-to-finish piggery.

In addition, biogas can instead be further treated to remove carbon dioxide (CO_2) and then be compressed or liquified to be used as a vehicle fuel for cars and trucks. This treatment of biogas is commonly called biogas upgrading. Whilst Skerman et al. (2015) concluded that "The cost and level of technology required for upgrading biogas produced by individual piggeries to the required standard is likely to be prohibitive", a subsequent APL funded study (Tait 2018) found that biogas upgrading systems could be available out of Europe at a suitable scale, cost and level of complexity acceptable for larger Australian piggeries.

To clarify options for Australian piggeries with excess biogas, the project provided:

- for producing chilled drinking water for sows, a cost-feasibility assessment of using absorption chiller units that run directly on biogas, rather than electrical chillers that require biogas to be first converted to electricity. The aim was to reduce cost and complexity of this biogas-use option for smaller piggeries; and
- for biogas upgrading to biomethane, a scenario analysis of a hypothetical piggery application to explore practicality and cost-feasibility. The project also assesses compliance aspects for use of European technologies at Australian piggeries.

2. Objectives of the Research Project

To address the above-mentioned opportunities and knowledge-gaps, this project sets out to:

- document a real biogas case study for a 500-sow farrow to finish piggery;
- identify small scale biogas system options for deep litter and alternative biogas uses at piggeries.
- clarify hidden costs of compliance and approvals, including for novel technology options.
- clarify cost-benefit of biogas to biomethane technology via feasibility analysis for a showcase Australian piggery project.

3. Research Methodology

3.1 Small-scale piggery biogas case study

3.1.1 Data collation and analysis

A biogas case study was conducted on a 550-sow farrow-to-finish piggery in Victoria with a biogas system that has been operating since 2017. Information was collated to assess cost-benefit of biogas use at this piggery. The study included a site visit to the piggery. Information collated and used in case study analysis included:

- quantitative data on the amount of biogas energy produced, the amount of biogas energy used and details about the biogas use-purposes;
- itemised actual capital and operating expenditure of biogas systems at the piggery;
- details about approvals and compliance costs included in the total biogas project cost;
- quantitative data on the actual financial benefits to the piggery from using biogas; and
- information on the non-financial benefits to the piggery from using biogas.

This information was subsequently written up in a case study with a cost-benefit analysis (CBA) as per the method in Section 3.4 below.

3.1.2 Effluent sampling and analysis

To confirm that the case study piggery was achieving a reasonable biogas yield from its piggery effluent, an effluent sample was sourced from the piggery and tested in the laboratory to quantify a maximum achievable methane (CH_4) production under ideal anaerobic digestion conditions.

For this, the producer collected piggery effluent samples from an agitated 90 kL in-ground pit at the piggery, into which effluent from all the pig sheds usually drained by gravity. This consisted of two samples collected over two days with a sampling bucket, each after effluent from several sheds had been drained into the pit. In this way, the two samples consisted of effluent from dry sow sheds, grower-finisher sheds or weaner sheds. The samples were refrigerated (not frozen) and posted cooled on ice-bricks via express post to a laboratory in Toowoomba for analysis.

Once received at the laboratory, the two samples were combined into a single aggregate sample for analysis, thereby being representative of "typical" effluent produced at the case study piggery. The aggregate sample was analysed for volatile solids (VS), volatile fatty acids (VFAs) and biochemical methane potential (BMP) as described directly below. VS was measured by Standard Method 2540 (APHA 2012) and was corrected for the loss of VFAs during the oven drying step, by adding the measured VFA to the measured VS measurement in accordance with Vahlberg et al. (2013). VFAs (as equivalent acetic acid) were measured using a Merck test kit (Cat. No. 101809) and a Spectroquant Pharo 100 spectrophotometer.

The BMP tests were conducted using an Automated Methane Potential Test System II (AMPTS II; Bioprocess Control, Lund, Sweden) at the University of Southern Queensland (USQ) laboratories in Toowoomba. For the test, an inoculum was added together with the piggery effluent sample to a 500 mL glass test bottle. The total liquid volume of the mixture in the test bottle was 400 mL and the relative amounts of inoculum and piggery effluent that were added were selected to ensure that twice as much VS was added as inoculum as compared to VS added as piggery effluent sample. This was to prevent organic overloading of the tests. The glass test bottles were sealed with rubber stoppers and screw-on lids with mixers, immersed in a heated water bath at 37 ± 1 °C, and without delay connected to caustic soda CO_2 traps of the AMPTS II system. The whole system was flushed with high purity nitrogen gas to remove any oxygen, before finally connecting it up to a gas volume meter. The AMPTS II system works by measuring the amount of methane produced over time from the anaerobic digestion of the organic matter in the sample bottle and corrects the measured value back to nominal standard gas conditions of 1 atm and 0°C. The AMPTS II intermittently stirs the contents of each test bottle using overhead stirrer units mounted on the lid of each test bottle.

Being a batch test, methane production progressively declines as biodegradable organic matter in each test bottle progressively runs out. The test is terminated when the amount of methane produced in one day is less than 1% of the total amount of methane produced up to that day (Verein Deutscher Ingenieure (VDI) 2016). At this point, the tests are deemed complete. pH of the final liquid contents in each bottle was measured to confirm that the tests had operated uninhibited.

Duplicate test bottles were set up with piggery effluent sample and inoculum, and triplicate test bottles were set up with only inoculum (no piggery effluent sample). The tests without piggery effluent sample measures the amount of methane produced from residual organic matter present in the inoculum and is therefore subtracted from the results of the test bottles with piggery effluent sample, to quantify the net amount of methane produced from only the organic matter in added piggery effluent sample. The net amount of methane produced is then divided by the amount of corrected VS in the added piggery effluent sample in the test bottle, to give the maximum biochemical methane potential or BMP of the effluent sample.

The inoculum used in the tests was sourced from an in-house culture produced in a 35 L continuously stirred tank anaerobic digester at the USQ laboratories, operating at mesophilic conditions (38 °C) and fed with a mixture of paunch contents (50% of mixture), pen manure (30% of mixture), and sludge from a covered pond (20% of mixture), all from a nearby meat processing facility. Three further test bottles were also set up with inoculum and cellulose instead of effluent sample. Cellulose is a well-known model substrate for anaerobic digestion and allows testing of the efficacy of the inoculum.

3.2 Options for piggeries with low levels of biogas

3.2.1 Anaerobic co-digestion of piggery effluent with other organic matter sources

A desktop literature review was carried out, searching for past research on the use of alternative organic matter sources to boost biogas energy production from covered ponds. Important technical aspects were explored, including anticipated increases in biogas potential by anaerobic co-digestion of various different organic matter sources together with piggery effluent, materials handling considerations for solid vs. liquid organic matter sources and the potential biosecurity issues associated with importing of external organic matter sources onto a piggery premises for co-digestion.

3.2.2 Anaerobic digestion of spent piggery litter

A desktop literature review was carried out, searching for pertinent investigations on anaerobic digestion of crop residue manure mixtures (i.e. resembling spent piggery litter). Using the information available in the literature, a desktop investigation explored a hypothetical scenario piggery where spent litter from grower-finisher pigs sheds is used as additional organic matter source for biogas production. The hypothetical scenario piggery was assumed to already have an existing covered pond with which biogas was being produced from effluent of conventional sheds wherein the breeding pigs were housed. In this way, the hypothetical scenario piggery would be producing biogas in a covered effluent pond whilst simultaneously producing additional biogas from spent litter in a separate dedicated anaerobic digester onsite at the piggery.

The herd size of the hypothetical scenario piggery was elected to be the same as that of the small case study piggery (Section 3.1), so that the PigBal model and capital and operating cost data of the small case study piggery could be reused for the analysis of the hypothetical scenario piggery. Wheat straw piggery litter was assumed as the deep litter type because it has been shown to provide the highest biogas production (Tait, Tamis et al. 2009). Alternative bedding types such as rice husks and saw dust do not provide enough biogas, which would negatively impact energy production and subsequent payback periods (Tait, Tamis et al. 2009).

Hence, these alternative bedding types were excluded from further consideration in the current work. Based on the literature review findings, a solid-state batch anaerobic digester was selected as suitable technology type for the spent litter digestion system (See Section 4.3 for further details). For the PigBal model, housing type of growers and finishers were changed to deep litter, wheat straw, with a bedding addition rate of 0.8 kg^{-1}.SPU.day^{-1} based on Kruger et al. (2006).

The original PigBal model of the small case study piggery had used a batch time of 5 weeks for grower pigs and 3.5 weeks for finisher pigs, which accorded with the growth of pigs at the case study piggery. It is noted that other piggeries typically have different batch times to these. However, the PigBal model showed that the corresponding average daily gain of the herd at the small case study piggery was "good". The growth rate was assumed to be unchanged when grower and finisher pigs were instead housed on deep litter, and so the batch times of the original case study were retained for the scenario analyses.

In a deep litter system, the operation of the grower-finisher stage, would be batch all-in all-out, meaning that the spent litter would be generated in a single large quantity when a batch of pigs leave the shed. The default in-shed loss factors were retained in PigBal, and the model assumed that the spent litter had a moisture content of 40%. The model provided estimates of the amount of spent piggery litter produced and the corresponding amount of VS.

A reputable supplier-constructor of covered effluent ponds in Australia, namely Waterlogic, was then contacted to seek assistance in scoping out and costing up a spent litter anaerobic digestion concept. Waterlogic assisted with the detailed definition of how they would construct an in-ground solid-state anaerobic digestion system, closely resembling the covered effluent ponds used by Australian piggeries to produce biogas from conventional shed effluent.

Waterlogic also provided a high-level cost estimate for the in-ground digester concept, which was then combined with capital and operating costs and biogas benefits data of the small case study piggery (Section 3.1), to conduct a CBA for the hypothetical scenario piggery that simultaneously produces biogas from spent litter in an in-ground digester and biogas from piggery effluent in a covered effluent pond, operating in parallel.

3.3 Options for piggeries with excess biogas

3.3.1 Using biogas to produce chilled drinking water for sows to alleviate heat stress

An Australian research study and South Korean research studies (Jeon, Yeon et al. 2006, Jeon and Kim 2014) suggested production benefits from chilled drinking water given to lactating sows under heat stress conditions, included: (1) exhibiting increased feed and water intake (Jeon, Yeon et al. 2006, Willis and Collman 2007); and (2) showing higher estimated milk production (Jeon, Yeon et al. 2006) resulting in piglets with a higher average daily gain and higher average weaning weight (Jeon, Yeon et al. 2006, Willis and Collman 2007). The Australian study quantified a 0.7 kg increase in weaning weight (Willis and Collman 2007) which was then estimated to be worth $61 per sow per year or $7,625 per summer for a 500-sow farrow-to-finish piggery (Willis and Collman 2007). Note that the Korean study (Jeon, Yeon et al. (2006), Jeon and Kim (2014)) observed a marginally smaller increase in weaning weight as a result of supplying chilled drinking water to sows (0.55-0.6 kg).

Prospective suppliers of gas-fired absorption chillers were contacted to source information and high-level costings. These are distinct from electrically driven chillers. The aim was to understand whether the direct conversion of biogas into chilled water using an absorption chiller would be more profitable than having to first use biogas to produce electricity with an engine generator to operate the electric chiller to generate chilled water.

Using the information sourced, a desktop investigation explored a hypothetical scenario piggery where biogas was also being used in an absorption chiller to produce chilled drinking water for sows during summer months. The hypothetical scenario piggery was assumed to already have an existing covered pond producing biogas. The herd size of the hypothetical scenario piggery was elected to be the same as that of the small case study piggery (Section 3.1), so that some of the capital and operating cost data collected for the small case study piggery could be reused for analysis of the hypothetical scenario piggery.

The cooling energy requirement for an appropriate absorption chiller unit was determined using a nominal chilled drinking water requirement of 38 L per lactating sow per day, cooled from a nominal 35°C down to 18°C. This is based on the conditions of the Australian study of Willis and Collman (2007). The Korean study of Jeon et al. (2006) utilised chilled water at 15°C and 10°C.

A CBA was performed using capital costs, operating costs and biogas benefits data from the small piggery biogas case study (Section 4.1), but adding the cost of an absorption chiller unit to the capital costs.

3.3.2 Converting biogas into biomethane and bio-CO_2

The main function of biogas upgrading equipment is to remove CO_2 so that methane concentration in the product gas (called biomethane) is increased to a level that resembles commercial natural gas. The quality of commercial natural gas in Australia is specified in the National Gas Rules (Australian Standard AS 4564-2011 – "Specification for general purpose natural gas" and Gas Safety (Gas Quality) Regulations 2007 (VIC), Version No. 003. Version as at 1 May 2017) and the Australian Energy Market Operator's (AEMO) Gas Quality Standard and Monitoring Guidelines (Declared Transmission System). In addition, the AEMO's Gas Quality Guidelines clarifies requirements with respect to the energy content, burning properties, odorising to enable leak detection, and purity of product natural gas. If the quality of a biomethane product meets these specifications, it could become saleable to third-party users of natural gas in commercial, industrial, or domestic markets.

There are several biogas upgrading technology types, all of which could meet natural gas quality requirements in Australia. However, only some of these technologies allow the simultaneous recovery of a saleable high-grade CO_2 by-product. These can be summarised as follows (Wilken, Strippel et al. 2017):

- Membrane-based: This technology separates CO_2 from biogas with a membrane that allows only CO_2 to pass through but not methane, so that a methane-rich product gas is retained, and a CO_2-rich by-product gas stream passes through, including to subsequent processing to produce a high-grade CO_2 by-product. A case study example in the Netherlands is available at the following website: https://foodandbeverage.pentair.com/~/media/websites/food-and-beverage/downloads/haffmans/biogas-upgrading/biogas_upgrading_haffmans_case-study_ecofuels.pdf. Last accessed 20/03/2020.

- Pressure swing adsorption (PSA): This technology forces CO_2 under pressure into a bed of highly porous solid media, leaving the methane behind to up-concentrate into a biomethane product. When the pressure is relieved, the CO_2 is released from the media and can be passed through to subsequent processing to produce a high-grade CO_2 by-product. See for example: https://www.sysadvance.com/#!/categoria/?id=biogas-upgrading. Last accessed 24/03/2020.
- Cryogenic treatment: Cryogenic treatment uses a phase change of CO_2 and methane at high pressure or low temperature into a liquid (or solid in the case of CO_2 only), to separate the CO_2 from the methane, thereby producing both a high-purity biomethane product as well as a high purity gas, liquid or solid dry ice CO_2 product. See for example: http://www.cryopur.com/en/technology/. Last accessed 24/03/2020.

The project aimed to conduct a desktop evaluation of a hypothetical large Australian piggery scenario with biogas upgrading to biomethane, to assess technical and commercial feasibility. For this, a large Australian piggery was selected and contacted to request voluntarily participation. The piggery that agreed to participate is in New South Wales and was already using biogas from effluent to generate electricity onsite at the piggery. The piggery was also located near a significant user of high-grade CO_2 and a significant user of commercial natural gas.

Information requested from the piggery for analysis were:

- confirmation that biogas was available at an excess of 250+ $Nm^3.h^{-1}$ for at least periods of an operational day to supply the raw biogas for a typical off-the-shelf biogas upgrading system;
- tonnages/volumes, form/grade and cost of CO_2 used at nearby facilities (<20 km away); and
- tonnages/volumes and cost of natural gas used at nearby facilities (<20 km away).

Prospective suppliers of biogas upgrading technology were contacted to source information and high-level costings to use in the desktop evaluation. These included:

1. Pentair Haffmans, Venlo, The Netherlands - Provides fully containerised membrane biogas upgrading systems coupled with containerised CO_2 cryogenic liquefaction facilities.
2. SysAdvance, Povoa de varzim, Portugal – Provides package vacuum PSA upgrading systems coupled with vacuum PSA CO_2 recovery systems.
3. CryoPur, Massy, France via Mr. Tony Siddons from Siddons Renewables, Melbourne, Australia – Supplies package cryogenic biogas upgrading systems; and
4. BioGTS, Jyväskylä, Finland (Formerly providing PSA upgrading systems, https://finland.mfa.gov.ua/storage/app/sites/28/imported_content/5e304b780c388.pdf - Formerly featured in APL study (Tait 2018) - **Now permanently closed, reason unknown**).

These technology providers had: an international reputation; had real showcase projects of a similar size and scope as would be expected of a biogas system at an Australian piggery; and had a technology that appeared to be reasonably mobile ("plug and play"), and would be reasonably practical for piggery staff to operate. They also offered reasonable after-installation service arrangements, such as remote diagnostics and support to remote installations.

CryoPur (via Siddons Renewables) and Pentair Haffmans responded with costing information. In addition, the scenario piggery had been previously approached in 2014 by Xebec Adsorption USA, Inc. with a budgetary quotation for a membrane-based biogas upgrading plant without CO_2 recovery, which at the time was not further pursued. Xebec Adsorption Québec Canada also offers PSA plants. This budgetary quotation was made available in-confidence for the project evaluation.

Based on the initial data collated, the project team conducted a preliminary feasibility check which showed that the biogas to biomethane concept was feasible at a high-level, sensitive to the sale of bio-CO_2. Based on this, the project proceeded to further stages of investigation (project Stop-go 1).

The project team visited the piggery to observe existing biogas systems and to discuss biogas use options and a biogas to biomethane concept.

No further responses were received from the above-listed biogas upgrading suppliers. Hence a decision was made not to proceed with an additional site visit to the piggery together with a technology provider (project Stop-go 2).

A proposed project concept was defined, assuming the future involvement of a third-party commercial supplier, for the reasons given above, and a CBA was performed based on historic costs of biogas equipment at the scenario piggery and based on available literature and information that could be sourced, including from Xebec Adsorption USA and CryoPur.

Bio-CO_2 was priced at what a near-by meat processing facility was currently paying for food-grade CO_2 (\$620.tonne^{-1}) and biomethane was priced at what a nearby feed mill was currently paying for natural gas (\$12.65.GJ^{-1}, total energy content). Note that, whilst the energy value of liquefied biomethane used as vehicle fuel could be considerably higher, the piggery did not foresee a reasonable medium-term demand for liquified biomethane as a vehicle fuel in the region.

3.4 Cost-Benefit Analysis (CBA) methods

To evaluate cost benefit, the present work calculated Net Present Value (NPV), which is the difference between the present value of cash inflows and the present value of cash outflows over a period of time, accounting for the depreciation in the value of money over time. In this work, a nominal 20-year project life, which aligned with the typical expected life of biogas equipment. A 5% annual discount rate was used for future cash flows (*d*). NPV was calculated using Equation 1:

$$NPV\ [AUD] = \sum_{n-1}^{20} \frac{C_n}{(1+d)^n} - C_0 \qquad \text{(Equation 1)}$$

where C_n is the net revenue during year n and C_0 is initial capital investment.

Payback period was also calculated, as the time taken to recoup the initial capital investment using the annual net revenue (annual total gross revenue – annual total operating expenses). All currency values given are in Australian dollars (AUD, 2019) and currency conversions between Euros and Australian dollars used a nominal exchange rate of 1.7 Euros.AUD^{-1}.

Cost-benefit calculations were calculated for two cases:

- a case where the biogas project infrastructure was financed with a loan (termed "with debt finance"), with an assumed interest rate applied to the loan principal of 5% per annum; and
- a case where the project owner had cash available to fully finance the biogas project infrastructure without needing to incur a loan, and therefore interest payments did not apply (termed "without debt finance").

4. Results/Findings

4.1 Small-scale piggery biogas case study

4.1.1 Description of piggery and onsite biogas systems

The case study piggery is a 535-sow farrow-to-finish piggery in Victoria, with all pigs housed in conventional sheds on a single site (Figure 1). The pig herd is equivalent to an estimated 6,154 SPUs with an average turnoff live weight of 99 kg. The piggery uses a liquid feeding system with a predominantly grain-based diet. Feed ingredients (April-May 2019 data) and feed usage data (2017-2018) were made available and were entered into Pigbal 4 (Skerman, Willis et al. 2018) to estimate equivalent SPUs and estimate biogas energy potential.

Manure handling practices differed between different sheds at the piggery. Specifically, the nursery, farrowing and dry sow sheds all had pull plug systems, with manure discharged at different frequencies. The weaner shed had a trench gate system with manure discharged twice weekly and flushed with additional water on one of these occasions. The grower/finisher shed had an open trench at the back of the pig pens, flushed twice daily with water. These differences would likely affect in-shed organic matter losses and accordingly would influence biogas production potential.

The piggery used bore water. Effluent was not screened onsite. Effluent volume produced by the piggery is estimated at 14-16L.SPU.d^{-1} averaged over an operational week. All effluent is gravity drained into an agitated 90kL in-ground pit with a laser level switch to pump effluent from there into a 6ML covered anaerobic pond (Figure 2).

The covered anaerobic pond was purpose-built during 2017-2018 to be long, narrow and deep to reduce the cost of the biogas cover and to facilitate desludging. The cover consisted of 2.5mm thick impermeable high-density polyethylene (HDPE). A safety vent was available, mounted through the pond bank (not through the cover), to safely vent biogas if the flare or generator was not operational and biogas was building up under the cover to unsafe pressure levels (e.g. 70Pa). The producer noted that the covered pond was built with spare capacity to cater for potential future expansions in piggery production capacity.

Figure 1 Aerial photograph of biogas case study piggery, showing shed layout. The covered pond and biogas equipment are visible in the top right-hand corner.

Figure 2 Photograph of onsite covered anaerobic pond at the biogas case study piggery. The pond is approximately 25m wide, 100m long and 5m deep with an internal batter slope 1:2 (vertical:horizontal). Liquid treatment volume is approximately 5.5ML including sludge storage. Total pond volume is approximately 6.5ML. Typical operating freeboard is approximately 0.5m. The pond cover can provide additional gas storage for an estimated 2,300m^3@ 50Pa.

Once biogas exits from under the cover, it passed through an external scrubber tank (Figure 3) fabricated from an old milk vat to remove hydrogen sulphide (H_2S). Internal spray nozzles were installed through the lid of the tank to spray treated effluent from an onsite effluent irrigation pond over the top of a bed of plastic Pall rings. The biogas flowed in from the base of the vessel and moved upwards through the packing in a counter-current direction to effluent flowing down the packing. A small quantity of air was continuously injected into the scrubber vessel near the base. Microorganisms that grew on the Pall rings inside the vessel used the oxygen in this added air to convert H_2S in the biogas into elemental sulphur and/or calcium sulphate (calcium is present in the added effluent). The producer did note that since implementing this method of H_2S removal, significant maintenance had been required not previously anticipated, such as having to manually remove and clean the packing on an approximate half-yearly basis. Similar reports have been received from other piggeries, including the scenario piggery of the biomethane study (Section 4.3.2). This led the case study piggery to instead implement an alternative simpler H_2S removal method described by Skerman and Tait (2018).

After the scrubber tank, the treated biogas passed through a shell and tube heat exchanger, wherein the biogas (tube side of the heat exchanger) was cooled with chilled water (shell side of the heat exchanger), to condense out and remove any moisture from the biogas. The chilled water was supplied by an electrical chiller unit (not an absorption chiller in this case). A knockout pot and wire mesh demister after the heat exchanger captured the condensate. This set-up is visible in Figure 4. The treated and dried biogas was then pumped by variable-speed centrifugal blowers to either a 42kWe combined heat and power engine generator (CHP) unit or to a safety flare (See below), with a pressure transducer used to regulate the blower speeds to maintain the gas supply pressure to the CHP unit or flare at about 8kPa. Flow meters were installed to record biogas flow rates to the flare and CHP unit. The producer noted that the flow meters were relatively expensive, with one installed for the CHP unit and one installed for the flare, in anticipation of registering under the Emissions Reduction Fund (ERF). However, since the piggery did not end up registering an ERF project (See Section 4.1.6), the producer thought that less costly meters could probably have been appropriate.

Figure 3 External scrubber tank used for removal of H_2S. Effluent is pumped to the top of the tank via the pipeline with in-line strainer visible on the right side of the tank. A small quantity of air is continuously injected into the scrubber tank by the air blower visible to the right of the tank. The covered pond and biogas inlet pipe are visible at the back and base of the tank. Note how the electrical supply for the air pump is set-back at a nominal distance away from the biogas piping and scrubber tank, to exclude viable ignition source from where elevated methane concentrations may exist due to potentially leakages. This was by expert design of an external consultant.

Figure 4 Electrical chiller (not absorption chiller) and shell and tube heat exchanger used to condense and remove moisture from the biogas prior to use at the case study piggery.

The CHP unit was purchased as a second-hand unit (albeit thought to have never been used) from a machine sales and service company based in Queensland (Figure 5a). It is likely it was originally built to operate with natural gas from a coal seam gas well in the Surat Basin. The generator engine required significant retrofitting, both to bring it back into service after a substantial period of disuse wear (Figure 5a), as well as to de-rate and certify it as a Type B appliance to run on biogas. The original rating of the CHP unit was 60kVa (42kWe) and was de-rated to 32kWe to run on biogas, due to the fact that piggery biogas has vapours that is said to burn much hotter than cleaner coal seam gas and biogas is expected would have a significantly lower methane concentration than coal seam methane. Since commissioning and following the case study site visit, the producer paid for the CHP unit to be fitted with water jacketed exhaust manifolds from the marine industry, which has since allowed the electricity output of the generator to be increased to 37KWe without substantially increasing the operating temperature. The generator engine ran 24/7, except during routine maintenance, formerly with a 32 kWe output and now with a 37kWe output. The CHP unit generated electricity used onsite at the piggery and the excess was exported to the electricity supply grid. Hot water was also produced by recovering heat from the engine cooling circuit and was circulated through underfloor heating systems in the farrowing sheds. Prior to the installation of the biogas system, the shed heating system was originally designed to operate in a closed loop, with hot water produced by a Rheem Raypak Liquid Petroleum Gas (LPG) heater.

Figure 5 Photos of the biogas-fuelled combined heat and power engine generator (A, B, C) and the emergency flare (D). The respective photos show (A) the generator unit when originally purchased second-hand with wear and tear due to disuse and (B) after retrofitting and installation at the case study piggery, (C) the control system screen, and (D) the solar-spark partially shrouded emergency flare. The flare has a thermocouple to confirm whether the flare is operational by measuring the presence of a hot flame.

The new hot water supply was plumbed into the existing hot water loop via a water mixer to achieve the desired set-point temperature, whilst retaining the old liquefied petroleum gas (LPG) service capability in case the biogas generator was not operational. The CHP unit used about $20m^3 \cdot hr^{-1}$ of biogas at a methane concentration of approximately 60-70% by volume. The nursery sheds had evaporative cooling and overhead gas tube radiant heating. At the time of the site visit, the producer was in the process of installing a new hot water system to use biogas energy in the nursery sheds. The cost of the additional hot water system was included in the capital costs below, but the producer did not know whether the existing onsite generator would be able to supply enough heat to displace all LPG usage onsite.

The CHP unit distributed power via an underground cable to the piggery or to export via a monitoring and protection relay. The CHP unit only ever operated when there was a connection to the supply grid, because the system was not set up to run in island mode separated from the grid. The CHP unit tripped automatically if the grid was disconnected and the generator engine did not start unless the grid connection was available and operational.

4.1.2 Biogas production potential from effluent at the case study piggery

Total solids ($TS_{corrected}$), volatile solids ($VS_{corrected}$) and VFA concentrations measured for the piggery effluent sample (Section 3.1.2), were observed to be 23.6 $g.L^{-1}$, 18.2 $g.L^{-1}$ and 3.9 $g.L^{-1}$, respectively. These concentrations are within the range reported for piggery effluent from Australian piggeries (Gopalan, Jensen et al. 2013, Astals, Musenze et al. 2015, Skerman, Willis et al. 2016), specifically 15-69 $g.L^{-1}$ for $TS_{measured}$, 11-50 $g.L^{-1}$ for $VS_{measured}$ and 0.2-7.5 $g.L^{-1}$ for VFAs.

Figure 6 presents measured methane production data from the BMP test (Section 3.1.2). The cellulose positive control test showed that the inoculum used in the tests was functional. The BMP of the effluent sample was observed to be 319 Nm^3 CH_4 $tonne^{-1}$ VS fed for one test bottle and 291 Nm^3 CH_4 $tonne^{-1}$ VS fed for the other test bottle (Figure 6). These methane yields were within the range reported for piggery effluent from Australian piggeries (Gopalan, Jensen et al. 2013, Astals, Musenze et al. 2015, Skerman, Willis et al. 2016), specifically 150-640 Nm^3 CH_4 $tonne^{-1}$ VS fed. Accordingly, the test results suggested that methane yield at the case study piggery could be typical and moderate, and that the extent of feed wastage at the case study piggery was also typical (Skerman, Willis et al. 2016).

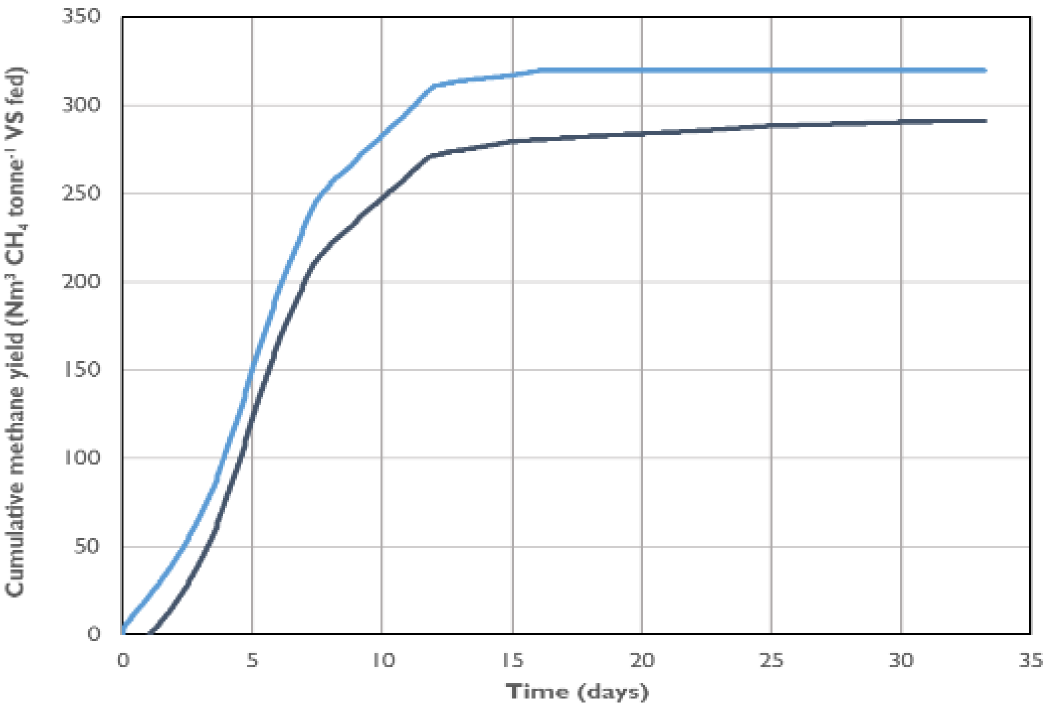

Figure 6 Duplicate biochemical methane yield measured for the effluent sample from the case study piggery

The PigBal 4 model predictions estimated that on average 1.71 $tonnes.day^{-1}$ of VS would enter the covered effluent pond at the case study piggery. Based on the BMP test results above, this could produce up to 21-23 Nm^3 $CH_4.hr^{-1}$ or 32-35 Nm^3 $biogas.hr^{-1}$ at a nominal CH_4 concentration of 65%. Because the CHP unit at the case study piggery was said to typically consume 20 Nm^3 $biogas.hr^{-1}$ 24/7, and because excess biogas was routinely being flared onsite (the flare was operational when the site was visited), the covered pond appeared to be achieving a manure to methane conversion efficiency of 62% of the BMP or better. This indicated that the covered pond was probably operating as well as expected (Craggs and Heubeck 2008).

4.1.3 Biogas system costs

Table 2 lists actual complete capital costs of the biogas installation at the case study piggery, including significant items relating to regulatory approvals (e.g. gas permit/certification). The biogas project was delivered in a piecemeal manner (not turn-key), so that the producer and producer staff's involvement in the development of the biogas project would also have represented a significant lost opportunity cost. The producer estimated this lost opportunity cost at approximately $50,000, also included in Table 2.

Table 2 Actual capital, installation and commissioning costs of the case study biogas project.

Item		Price exc. GST	Comments
Dam construction/sludge extraction		$ 85,486	Over-specified sludge extraction systems/piping meant that pond construction costs was somewhat higher and possibly excessive.
Dam cover		$131,097	
Effluent piping, tanks etc.		$6,363	
Flare		$17,200	
Concreting		$4,434	
Generator	Second-hand unit	$8,000	
	Pick up and modification	$27,054	Fit heat exchange, gas train, control system
	parts	$6,460	
	Transport from QLD to piggery	$3,406	
Manufacture gas skid		$80,066	Blowers, valves, flow meters chiller
Water jacketed exhaust manifolds from the marine industry		$1,500	
Gas Permit/certification		$3,272	
Electrical chiller Unit (not absorption chiller) and commission		$11,550	
Hand-held detector		$1,309	Safety when working
Personal gas detector		$7,513	To do daily quality checks
Hydrogen sulphide scrubber vessel	Lid	$2,388	
	Pal rings	$5,805	
Commissioning	living expenses	$7,238	
	labour	$27,475	
Electrical Engineering		$15,577	
Control systems and circuit boards		$16,500	
Local electricians		$40,221	
Electrical network provider services		$4,000	
Farm labour		$20,406	
Computers/Internet connection		$800	
Hot water system into farrowing shed		$14,800	
Hot water system in weaner sheds		$14,800	
Lost opportunity costs due to producer involvement in biogas project		$50,000	
Total		$ 614,720	

The producer noted that the level of automation on the CHP unit was significantly more sophisticated (and thus more costly) than perhaps could be expected for future piggery installations. However, the producer wanted the added flexibility and versatility that this automation would provide. The producer also noted that the design of the sludge extraction system on the covered pond was likely more sophisticated than could be expected for future piggery installations, but again, wanted the certainty that sludge would be effectively extractable from under the pond cover. This was because of the inherent value of the nutrient fertiliser content that sludge provided to the producer when seasonally land-applied to reduce chemical fertiliser needs and because other reference projects in Victoria had reported problems with sludge extraction.

Table 3 lists estimated actual maintenance costs of the biogas system onsite. The costs of desludging the covered pond were not included, because prior to installation of the covered pond, the producer was already desludging uncovered anaerobic ponds and spreading sludge on agricultural land onsite. The biogas system did not require additional intervention or supervision on a regular basis. Note that the costs in Table 3 were actuals whilst the generator was new with relatively low technical issues and may increase with ageing in the future.

Table 3 Summary of annual operating costs for biogas systems at the case study piggery.

Item	Annual cost
Generator oil replacement \$4.50 L^{-1} x $35L.service^{-1}$	\$ 2,730
Generator labour motor servicing	\$ 2,418
Generator spark plugs	\$ 1,196
Generator oil filter	\$ 520
Repairs maintenance labour	\$ 6,500
Repairs maintenance parts	\$ 2,600
Testing	\$ 1,040
Total	\$ 17,004

4.1.4 Energy demand and biogas energy use at the case study piggery

Table 4 summarises actual historic monthly electricity consumption at the case study piggery before biogas systems were installed in 2017/2018, as well as estimated maximum and average power loads of the site. For comparison, the amount of electricity that a 32kWe generator can generate when operating 24/7 for one month is 23,000-23,808 kWhe. It was apparent that the onsite CHP unit could displace most of the onsite electricity demand, but only during average load periods. This is because the maximum load of electricity needed at the site (Table 4) exceeded the rated output capacity of the CHP unit, and therefore still required the importing of significant quantities of electricity from the supply grid.

4.1.5 Cost-benefit

In the CBA, it was assumed that operating costs and anticipated savings/revenues remained constant with time. Depreciation on assets and tax paid on additional revenue were not considered. The producer had finance available and did not require debt finance to install the biogas system. However, for comparison, the CBA considered an additional scenario where debt finance was secured and utilised at a nominal 5% interest rate. Future cash flow calculations assumed a nominal 5% discount rate. A 6-months lag was assumed to apply, from when the initial capital investment occurred to when the biogas systems were fully operational and incurred savings. Accordingly, half of the annual benefits were applied within the 1st year of the project.

Table 4 Summary of actual historic metered electricity use at the case study piggery.

Month	Maximum kWe load	Average kWe load	kWh.e total usage	kWh.e Peak usage	kWh.e Off-Peak usage
January	52	22	16,200	7,700	8,500
February	55	22	14,900	8,200	6,800
March	54	22	16,200	8,200	8,000
April	55	20	14,300	7,000	7,300
May	51	19	13,900	7,900	6,000
June	50	18	13,000	7,100	5,900
July	49	18	13,400	7,300	6,200
August	52	19	14,400	8,500	5,900
September	53	20	14,700	8,000	6,600
October	46	20	14,600	7,400	7,200
November	50	20	14,400	7,700	6,700
December	53	21	15,700	7,800	7,900
Yearly totals			175,700	92,800	83,000

Electricity costs at the case study piggery historically were about \$38,000.annum^{-1}. The site's electricity contract finished at about the same time as when the biogas project was completed, so electricity costs increased in the subsequent contract pricing period. For the CBA, the producer provided electricity tax invoices for the 3 months prior to start-up of the biogas system (July 2018 = \$4,448 charge; August 2018= \$4,512; September 2018= \$4,648) and a tax invoices for the months following successful start-up and subsequent to installation and commissioning of the water jacketed exhaust manifold (January 2020 = \$29; February 2020 = -\$152). The difference between the before and after electricity costs was then assumed to represent the typical benefit to the case study piggery (i.e. = \$4,536 per month (average) – (-\$61 per month = \$4,598 per month, or \$55,170.annum^{-1}).

Historically, LPG cost onsite was about \$35,000 per annum, based on an approximate 60-70 c.L^{-1} price. The majority proportion of this LPG was now being displaced with hot water produced from biogas, so the historic annual cost was scaled to a nominal price of \$1.L^{-1} LPG to give an estimated benefit of \$50,000.annum^{-1}. Accordingly, total annual energy savings amounted to \$55,170+\$50,000 = \$105,170).

Operating costs of the biogas system (Table 3) were largely paid for by the sale of Large-Scale Renewable Energy Credits (LGCs), estimated to be about \$10,000 per annum at a market price of \$41.LGC^{-1}.

NPV for a nominal 20-year project life was estimated at \$485,000 with debt finance, or at \$621,000 without debt finance. This equates to a payback period of 7.7 years with debt finance and 6.3 years without debt finance. These results indicated that the economic feasibility was moderate. The producer commented that they considered this payback as good based on pure economics, but if management time and cost was to become significant in the future they would probably have wanted a better return. The payback and NPV were heavily influenced by high capital costs not anticipated when the project was initiated, despite the use of a second-hand natural gas generator. This highlights the potential for significant costs for retrofits, gas certification and electricals not anticipated prior to initiating a biogas project. Such ancillary costs are often not well understood in feasibility studies and yet can clearly be very influential to the feasibility of a piggery biogas project.

4.1.6 *Other benefits from a biogas project*

The producer noted how because the case study piggery was in a populated area, there were originally significant concerns over on-going relationships with neighbours because of manure-related odour, and how installing the biogas system greatly reduced odour at the piggery. The producer recalled how at a public opening of the biogas system, neighbours who attended commented on the odour reduction benefits of the biogas system. Into the future, it is likely that biogas systems will likely become increasingly important to mitigate manure-related odour at piggeries.

The case study piggery was not producing and selling carbon credits under the Emissions Reduction Fund (ERF). It was estimated that the piggery would be abating 1,613 t CO_2-e annum^{-1} with the biogas project, equating to 1,613 Australian Carbon Credit Units (ACCUs), and $20,969.annum^{-1} of earnings at a nominal sale value of $13.ACCU^{-1}. However, with auditing and mandatory regulatory compliance costs of the ERF at $10,000-$15,000.annum^{-1}, the cost-benefit of the ERF would be marginal for the case study piggery. To date, ERF benefits of biogas projects have been attractive for larger piggeries (1,000+ sow farrow-to-finish), but in the future the ERF may also become attractive for smaller piggeries if the sale price of carbon credits could again increase to historic levels of $20-$23.ACCU^{-1}.

4.2 Options for piggeries with low levels of biogas

4.2.1 *Anaerobic co-digestion of piggery effluent with other organic matter sources*

Considerations

Ideally, an organic matter source being imported to a piggery for anaerobic co-digestion would substantially increase overall biogas production without compromising the health of a covered effluent pond (Tait, Astals et al. 2017). Additional organic matter sources should be strongly avoided if they would increase the organic loading rate to the covered effluent pond to unsafe levels, or if they would introduce toxins or inhibitors of the anaerobic microorganisms in the pond (Tait, Astals et al. 2018). Some very concentrated (e.g. glycerol and fatty wastewaters) or complex organic matter sources (e.g. chicken manure) would be particularly risky in this regard (Tait, Astals et al. 2017). An overloaded or inhibited effluent pond would likely produce an odorous outflow (Tucker 2018) or excessive sludge or scum that can reduce treatment capacity. Any organic matter source that may pose a significant biosecurity risk should also be strongly avoided (e.g. municipal solid waste, slaughterhouse house) or otherwise would require significant and costly pre-treatment to mitigate the biosecurity risk (Al Seadi, Rutz et al. 2013). In addition, the importing of other organic matter sources can introduce additional nutrients, which then need to be considered in the overall nutrient balance and environmental practices of the piggery.

The form of alternative organic matter source is also very important (e.g. particulate or soluble). For example, conventional shed effluent is a pumpable water suspension, whereas other residues, such as from crop production, are particulate and would likely accumulate as a float layer under a pond cover (Tait, Astals et al. 2017). Other organic matter sources rich in oils and fats can take a lot longer to be converted into biogas and may also accumulate in a covered pond or even cause inhibition of anaerobic microbiology in the pond (Tait, Astals et al. 2018). Some organic matter sources may become septic and odorous onsite at the piggery if stored for excessive periods (Bochmann and Montgomery 2013).

Some materials are transported and received as liquids or slurries in tankers, others are received pre-packaged and require depackaging, and others are received as stackable solids requiring machinery to move, bunker storage and potentially leachate collection if uncovered and exposed to wet weather (Tait, Astals et al. 2017). Solid-liquid separation may be required to remove sand and grit from slurries, or mixing to homogenise and keep heavier organic solids in suspension (Tait, Astals et al. 2017).

Benefits

There are several possible organic matter sources that could significantly increase biogas production from covered effluent ponds. For example, Table 5 lists some previously reported values of BMP for various organic matter sources. In addition, gate fees received by the piggery producer can provide substantial added financial benefits from a piggery biogas installation and could be negotiated at a set price just below the landfill levy in the respective Australian state. This could be potentially inclusive of transportation costs to the piggery. Some piggeries already use by-products in their feed formulations and send any excess to onsite covered effluent ponds. This then provides added benefits by significantly increasing organic loading and thus biogas production potential, provided that the effluent pond is not being overloaded.

4.2.2 Anaerobic digestion of spent piggery litter

An alternative to importing organic matter sources from offsite is to instead use the spent piggery litter produced onsite at a piggery as an organic matter source for producing additional biogas. However, spent litter is unsuitable or use in covered effluent ponds, being a particulate residue that can cause blockages or can accumulate as a floating matt under the pond cover. For this reason, a different anaerobic digester technology is required for spent piggery litter.

There are currently no anaerobic digesters in Australia operating with spent piggery litter. However, Australian laboratory and pilot-scale studies (Tait, Tamis et al. 2009, Yap, Astals et al. 2016) have explored solid-state batch digestion concepts previously used in Europe for crop residues plus piggery wastewater (Mussoline, Esposito et al. 2014).

In this work, the cost-benefit of biogas from spent litter was evaluated for a hypothetical farrow-to-finish piggery with grower-finisher pigs housed on wheat straw deep litter (Section 3.2.2). The piggery size was selected to be the same as the small piggery case study (Section 4.1), so that capital and operating costs and the PigBal model could be reused for the scenario CBA. Section 3.2.2 details the adjustments that were made to the PigBal model for the purposes of the scenario analysis.

Table 6 summarises PigBal model outputs for the scenario analysis and shows that organic matter (VS) available in grower-finisher spent litter would be 2.5 times as much as would be available in effluent if the grower-finisher pigs were instead housed in conventional sheds. Therefore, to make the deep litter concept comparable to the covered pond scenario at the case study piggery, only the grower spent litter produced by this scenario piggery was used for biogas production in the scenario analysis, thereby keeping the VS amounts being subjected to anaerobic digestion comparable between the case study piggery and the deep litter scenario piggery. The PigBal model estimated that the VS output in grower spent litter (after in-shed losses) would be 382 dry tonnes per year, which is near equivalent to the VS output if all the grower-finisher pigs were instead housed in conventional sheds.

Table 5 Methane potential and other relevant characteristics of organic matter sources for co-digestion (Adapted from Tait et al. (2017)).

Residue type	**Dry matter content (%)**	**Volatile solids content (% of dry matter)**	**BMP, Biochemical Methane potential (m^3 CH_4 / tonne VS fed)**	**Known inhibition or other risk#**	**Reference**
Piggery shed effluent	1.7-6	64-84	150-640		(a), (c), (d)
Apple pulp, apple residues			306, 317		(a), (b)
Asparagus peels			219		(a)
Alcohol*	40	95	400		(c)
Banana peels			289		(a)
Brewers spent grains	20	90	330	Potentially unsuitable for covered pond	(c)
Confectionary			320		(b)
Carrot peels			388		(a)
Citrus			473		(a)
Chocolate			370		(b)
Fruit and vegetable residues	15-20	75	470		(c), (b)
Fish oil*	90	90	500	Oil inhibition	(c)
Fish residue			390		(b)
Gelatin			100-150	Ammonia inhibition	(b)
Kitchen waste			370-450		(b)
Leachate of food waste			478		(b)
Mango peels			370-523		(a), (b)
Mixed food waste			472		(a)
Potato peels			267		(b)
Poultry droppings	5	80	300	Ammonia inhibition	(c)
Concentrated whey (20-25% protein)	5	90	330		(c)

(a) (Lesteur, Bellon-Maurel et al. 2010); (b) (Raposo, Fernandez-Cegri et al. 2011); (c) (Al Seadi, Rutz et al. 2013); (d) (Gopalan, Jensen et al. 2013); #Organic loading limits apply to most substrates; Biosecurity risk may be important to various; *Strong methane boosters, however, at significant organic overloading risk.

Table 6 *PigBal 4 model outputs for an equivalent piggery to the small piggery biogas case study, but with grower and finisher pigs on straw-based litter added at a rate of 0.8kg.SPU^{-1}.day^{-1}.*

Modelled characteristic	Value
Total Standard Pig Units (SPUs)	6,154
Total SPUs housed in deep litter sheds	3,419
Wet mass = Manure + waste feed + litter removed from all deep litter sheds, following in-shed losses and at 40% moisture	1,775 wet tonnes per year
Total solids (TS) = Manure dry matter + waste feed dry matter + litter dry matter removed from all deep litter sheds, after in-shed losses	1,065 dry tonnes per year
Volatile solids (VS) = Manure VS + waste feed VS + litter VS removed from all deep litter sheds, after in-shed losses	909 dry tonnes per year*
* VS if the grower-finisher pigs were instead housed in conventional sheds	370 dry tonnes per year

The batch solid-state digestion concept adopted for the scenario analysis would involve contacting a stacked heap of straw-based spent litter with a water medium (termed leachate) to initiate biological conversion into biogas. This is commonly called a "leachbed" and in the case of commercially available systems occurs in an enclosed space that looks like a garage (e.g. BEKON, https://www.bekon.eu/en/technology/).

In the current work, to minimise use of concrete and steel and construction costs, an in-ground digester was instead conceptualised, which would have some similarities to a covered effluent pond, except for the impermeable plastic cover being retractable to allow periodic loading of spent litter at the start of a digestion batch or unloading of digested residue at the end of a digestion batch. A similar approach was previously adopted by Mussoline et al. (2014) to convert rice straw and piggery wastewater into biogas.

In short, the operation of the in-ground digester concept would involve:

1. filling an in-ground lined dam with spent piggery litter using a front-end loader (via an access ramp) or excavator;
2. covering the dam with the retractable impermeable plastic cover to capture the biogas that will be produced;
3. pump leachate from the onsite effluent dams into the in-ground digester to fully flood the bed of spent litter inside with the leachate. This initiates and sustains its biological conversion into biogas;
4. periodically pumping the leachate out via a sump in the base of the digester (See further below) and sending this leachate to the existing onsite covered effluent pond, and then repeating step 3 above; and
5. when biogas production had declined (because biodegradable organic matter in the batch of spent litter has been converted into biogas), the impermeable plastic cover is retracted and the digested residue emptied out with an excavator and front-end loader (via an access ramp); and
6. repeating from step 1.

Importantly, when the in-ground digester is opened up to remove digested litter, flammable methane gas or toxic hydrogen sulphide gas might be released in significant amounts, creating a safety hazard for people nearby. To prevent unsafe conditions, the digestion would typically be continued until biogas production had drastically declined to a minimum, the digester would be carefully opened, isolating people from hazardous exposure, and the digester would be left open and well-ventilated for a significant time period before removing the digested residue.

Two batch digesters running in parallel would allow more consistent biogas production and would reduce the need for onsite storage of spent litter prior to digestion. In general, it is important to link the design of the in-ground digester to the on-farm frequency of batch clean out. To size the in-ground digester, a total digestion time for each batch of spent litter was nominally assumed to be 25 weeks (175 days), because the digestion of spent piggery litter with crop residues can take a long time to complete (Tait, Tamis et al. 2009, Mussoline, Esposito et al. 2014). This would mean that each digester would operate with 12.5-weeks' worth of grower-pig spent litter, equivalent to 180 wet tonnes, or with an assumed density of 0.7 $kg.m^{-3}$ would equate to $270m^3$ ($=440m^3$ with a 0.5 m freeboard allowance).

A potential supplier, Waterlogic, proposed how the in-ground digester might be constructed. It was to be lined with an impermeable plastic liner (2 mm HDPE) to protect surrounding groundwater, and the liner covered with a 50 mm sand layer with a 140GSM geotextile separation layer on top and a 100 mm x 50 mm crushed rock/recycled concrete aggregate top layer with a further 140GSM geotextile layer on top of that to prevent clogging and to potentially act as a sacrificial layer when the digested residue is removed by excavation. Waterlogic had used similar approaches with municipal landfills in Australia (Figure 7).

Figure 7 Example in-ground dam lining performed by Waterlogic, showing liner on the left and geotextile protective layers (Source: Waterlogic).

For the biogas cover, Waterlogic proposed 1 mm Flexible Polyethylene (FPE), with 3 welded inspection ports of an inner diameter of 160mm. The cover was to be manually pulled across the in-ground digester and anchored around the perimeter under a 160 mm layflat hose to be filled with water after positioning in a shallow trench, acting as a temporary ballast for the cover. The edge of the cover was to be wrapped around the layflat hose and secured along the inside edge with sandbags. When the digestion was complete, the water in the layflat hose could then be simply drained and the layflat hose pulled off the cover to allow it to be retracted to remove the digested residue. The geotextile layer on the crest bank would provide a protective underlay for the cover. Waterlogic proposed that leachate be pumped via an excavated pit at the base of the digester, also lined or fitted with a PE wet well welded into the liner. Waterlogic proposed a sump access line ~100mm to allow the suction line of an external pump to access the sump inside the digester. Leachate was to be pumped back into the digester via a 32mm metric poly pipe running inside the biogas extraction piping to reduce the amount of base liner penetrations. The concept is depicted in Figure 8.

Waterlogic provided a high-level cost estimate for supply and installation of the in-ground digester, including lining and base layer, the cover and biogas collection system, and the leachate distribution system. To this, nominal excavation and pond construction costs were added at $15.m^{-3} (for 880 m^3). Because grower-finisher pigs at the scenario piggery are on deep litter, the VS output from conventional sheds at the scenario piggery would be reduced to 30% of that at the small case study piggery (Section 4.1). Accordingly, covered effluent pond capital costs for the scenario piggery was set at 30% of that given for the small piggery case study in Table 2. The rest of the capital costs of the small piggery case study were assumed to apply for the scenario piggery. Lastly, a nominal cost for an excavator was added. The capital costs are summarised in Table 7.

Table 7 High-level concept cost-benefit - Spent litter in-ground digestion concept.

Item	Price exc. GST
Estimated capital costs	
Small piggery case study – Total capital costs (in Table 2)	$ 614,720
Discount for smaller covered effluent pond	- $130,000
Plus in-ground digester costs (by Waterlogic)	$ 52,000
Plus in-ground digester excavation costs (880m^3 @ $10.m^{-3})	$ 8,800
Plus excavator purchase costs (nominal)	$ 80,000*
Total capital costs	*$ 625,520*
Estimated annual operating costs	
Small piggery case study – Total operating costs (in Table 2)	$ 17,004
Deep litter loading and unloading costs	$ 10,000
Total operating costs	*$ 27,004*
Total annualised benefit	
Small piggery case study – Total benefits	*$105,170*

**May already be on-farm for manual handling of spent deep litter*

The operating costs and biogas energy benefits were assumed to be identical to that of the small piggery case study (Section 4.1). Whilst the loading and unloading of the digester is likely to incur additional labour costs, materials handling of spent litter would be of operations at a deep litter piggery, and so may not substantially escalate the normal operational costs of the overall piggery. Regardless, an additional operating cost was allowed for digester loading and unloading, at a nominal $10,000 per annum. This is also included in Table 7.

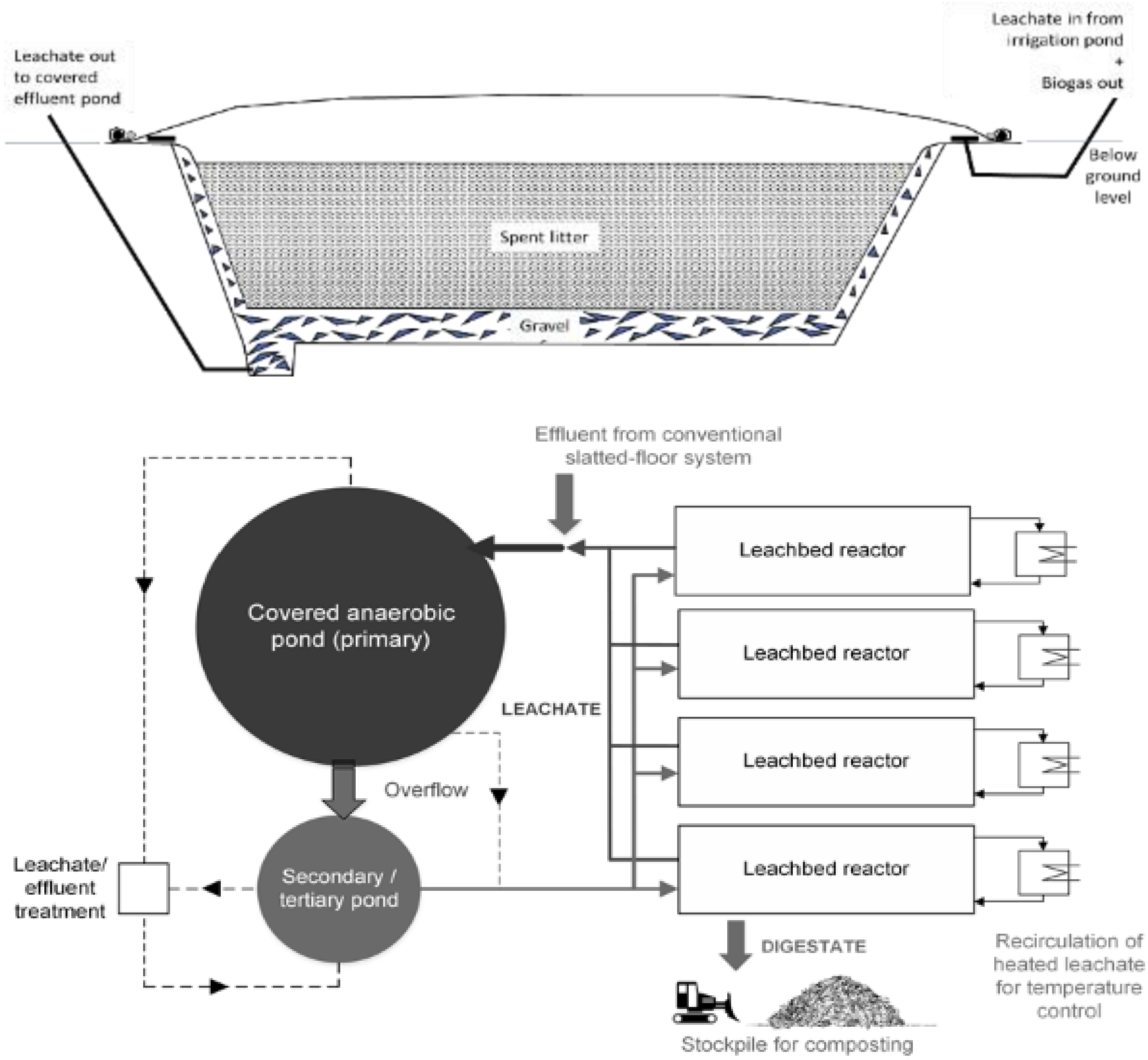

Figure 8 Depiction of in-ground digester concept (Adapted from(Yap 2017)).

Based on these costs and benefits, the NPV of the scenario project concept across a 20-year nominal life was estimated at $330,000 with debt finance (at nominal 5% interest on finance), and $485,000 without debt finance. The estimated payback period was 10 years with debt finance and 7.1 years without debt finance. This showed that the business case of this scenario project concept was weaker than the business case of biogas-use in the small piggery case study (Section 4.1). The main reasons for this were higher overall capital costs and higher annual operating costs for the scenario piggery, albeit that these were highly approximate and should be refined via future investigations.

The anaerobic digestion of spent piggery litter may also provide other benefits, such as mobilising and/or up-concentrating nutrients into digested residue (Yap 2017) to facilitate land-application for beneficial reuse of nutrients in spent litter. The value of these benefits should be costed on a site by site basis, to further evaluate economic benefits.

4.3 Options for piggeries with excess biogas

4.3.1 Using biogas to produce chilled drinking water for sows to alleviate heat stress

The search for commercially available absorption chillers revealed that some natural gas fuelled chiller units were able to both heat and cool, simultaneously. This might allow for farrowing sheds and nurseries to be heated with hot water from the absorption chiller unit whilst simultaneously producing chilled drinking water for sows from the same absorption chiller unit. Moreover, excess chilled water could be usable for shed cooling, thereby reducing overall shed cooling energy consumption (e.g. by reducing the demand for forced fan ventilation).

A retrofit would be required before biogas could be used to fuel an absorption chiller unit designed to run on natural gas. However, an Australian study has already showed such retrofits to be possible for a hot water system designed to operate on natural gas (Skerman and Collman 2012).

Table 8 summarises the heating and chilling requirements for a conventional piggery at the same size as the small case study piggery. To estimate a hypothetical demand for hot water in the farrowing sheds of this piggery, the historic LPG usage data reported by Skerman and Collman (2012) for a 700-sow specialised breeder unit, were proportionally scaled with total sow numbers (Table 8).

Table 8 Summary of heating and chilling demands for a hypothetical piggery scenario using an absorption chiller fuelled by biogas.

Basis	**Quantity**
Total number of sows	546
Lactating sows	119
Chilling duty	
Chilled drinking water[1]	4600 $L.d^{-1}$
Total cooling capacity[2]	3.8 kW
Heating duty	
Hot water production – Total energy demand for farrowing shed at 546 sow piggery[3]	30 kW

[1]based on 38 L per day of chilled per lactating sow per day (Willis and Collman 2007)
[2]based on cooling chilled water from nominal 35°C down to 18°C (Willis and Collman 2007)
[3]based on 1200 $GJ.annum^{-1}$ LPG usage at 700 sow specialised breeding unit (Skerman and Collman 2012)

Information was sourced on a absorption chiller unit that provides the chilling and heating demand given in Table 8, and such a chiller unit was being sold by Robur S.p.A., Zingonia, Italy, www.robur.com. For illustration purposes, a standard set-up marketed by Robur is depicted in Figure 9, albeit that a solar hot water system, an additional natural gas fired hot water boiler and an additional chiller unit shown in this figure would not be required in a proposed piggery installation.

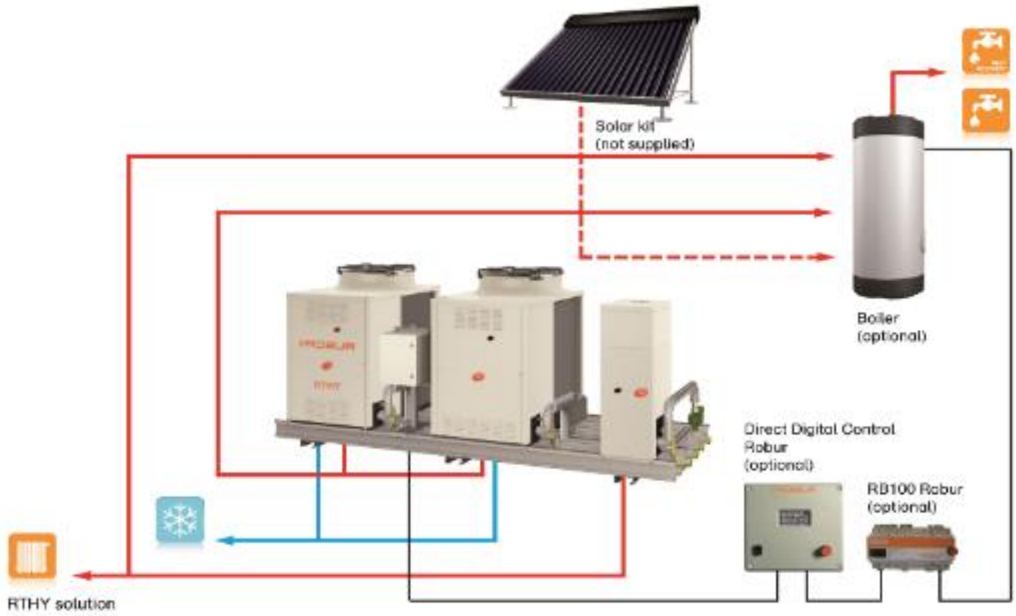

Figure 9 Illustrated absorption chiller/heater set-up by Robur S.p.A., Zingonia, Italy, www.robur.com, showing hot water (red lines) and chilled water (blue lines) produced by the same chiller units.

Robur provided catalogue purchase costs for a range of chiller units, the smallest of which was the GA ACF-HR (5 TR module) with chilling capacity of 17.9 kW, able to chill water down to a temperature of 3°C and able to receive water at a maximum temperature of 45°C. The same chiller unit had a hot water production capacity of up to 32 kW, being able to heat the hot water up to 75°C, which is expected to be suitable for underfloor heating applications. This meets the heating requirements in Table 8 and exceeds the cooling requirements in Table 8, potentially providing excess chilled water that may facilitate shed cooling, and thereby save on existing energy consumption for shed cooling (e.g. mechanical ventilation fans).

The chiller unit is said to consume 2.65 $m^3.h^{-1}$ of pure natural gas, which would be equivalent to the methane in 4 $m^3.h^{-1}$ of raw biogas at 65% methane. This biogas demand is moderate compared to the biogas available at the small case study piggery (Section 4.1.2) and thus may already be available as excess biogas at such a piggery, then being used by a chiller unit instead of being burnt in a flare with no energy recovery.

A CBA was performed. For this, the cost provided by Robur for a new absorption chiller unit was converted from Euros into AUD and to this were added nominal costs for freight and installation, and the result was added to the capital costs reported for the small piggery case study (Section 4.1). A further nominal allowance was included for an insulated milk vat to store chilled water, assumed to be the same as the total cost quoted in Willis and Collman (2007) scaled with time at a nominal annual inflation rate of 2.5%. Operating costs of the small piggery case study (Section 4.1) were assumed to apply, adding a nominal annual allowance of $3,000 for operating and maintenance of the new absorption chiller unit and chilled water supply lines. Biogas benefits were assumed identical to that of the small piggery case study (Section 4.1), except that part of the previous LPG usage would now be displaced by biogas in the new absorption chiller unit instead of by hot water produced by the generator at the small case study piggery (Section 4.1). Also, the estimated annual production benefit of chilled drinking water for sows during summer months was estimated by Willis and Collman (2007) at $7,625 for a 500 sow piggery. This was then scaled proportionally to 546 sows to estimate the benefit for a piggery of a size equal to the small piggery case study. The CBA is summarised in Table 9 below.

Table 9 High-level concept cost-benefit – Chilled drinking water for sows.

Item	Price exc. GST
Estimated capital costs	
Small piggery case study – Total capital costs (Section 4.1)	$ 614,700
Plus purchase price of natural-gas fuelled absorption chiller (10,240 Euros)	$17,400
Plus nominal freight and installation costs for chiller	$20,000
Milk vat and chilled water piping – Nominal allowance	$5,600
Total capital costs	*$ 657,700*
Estimated annual operating costs	
Operating costs for biogas infrastructure (nominal allowance)	$ 20,000
Total annualised benefits	
LPG and electricity savings (from Section 4.1)	$105,170
Production benefit from chilled water supply to 546 sows during summer months only	$ 8,200

Based on these costs and benefits, the NPV of the scenario project concept across a 20-year nominal life was estimated at $496,000 with debt finance (at nominal 5% interest on finance), and $644,000 without debt finance. The estimated payback period was 7.9 years with debt finance and 6.4 years without debt finance. A comparison between the CBA results of the smaller piggery case study (Section 4.1) and the biogas business case of the current piggery scenario, shows that the business case is marginally improved by adding an absorption chiller unit to supply chilled drinking water for sows under heat stress during summer months.

4.3.2 Converting biogas into biomethane and bio-CO_2

The large Australian piggery that agreed to voluntarily participate in the biomethane study was already capturing biogas from conventional effluent with two covered ponds and using it to generate electricity. This electricity was being used onsite at the piggery and by a nearby meat processing facility owned by the piggery company (Figure 10), with the electricity produced from biogas supplying the bulk of the electricity demand onsite and at the nearby meat processing facility. The demand for additional biogas electricity was minimal and the production of additional biogas electricity would be economically unattractive. As a result, the conventional effluent from the two smallest production units onsite ("Module 1" and "Module 2") currently flow into uncovered anaerobic ponds, and biogas from these units is not currently being harnessed.

The piggery has registered ERF projects for the site and has been generating and selling carbon credits economically under the ERF for several years. The value of these credits over time paid for a considerable proportion of the existing biogas infrastructure onsite at the piggery. With the generation of electricity from biogas, the piggery produces and sells LGCs, as with the small piggery case study (Section 4.1). The revenue from these LGCs were expected to largely cover the operating and maintenance costs of the generators.

Specific biogas infrastructure at the piggery included two large covered anaerobic ponds (Figure 11), which received conventional shed effluent from the three largest production units at the piggery (named "Module 3", "Module 4" and "Module 5"). The biogas being captured were treated by micro-aeration to remove hydrogen sulphide and chilled to remove moisture (similarly to the small piggery case study) and passed through a bed of activated carbon to polish the biogas prior to use. The clean biogas was then fed to three 500 kWe Evo 2G generators (1.5 MWe total) at a central location onsite at the piggery (Figure 11).

Figure 10 Aerial Photograph of large Australian piggery that voluntarily participated in the biomethane study, showing various biogas components onsite at the piggery

Figure 11 Photographs of biogas infrastructure, taken during the project site visit. The infrastructure includes two covered anaerobic ponds (top) and three 500 kWe Evo 2G generators (bottom left corner), producing electricity with biogas containing about 65% methane (bottom right corner).

During the piggery site visits, investigations and discussions with the piggery Environmental Manager clarified that the involvement of a third-party entity (a commercial-industrial gas producer supplier) would be preferred for the development of a biogas to biomethane concept, because:

- The piggery preferred not to be responsible for operation of sophisticated specialist upgrading equipment that was not directly related to their core business of pig production, but would be able to readily produce and sell their biogas to a third-party commercial gas supplier to be upgraded; and
- suppliers of commercial gases already had established business in the region where the piggery was located, and therefore would likely be able to harness an existing demand from an established customer base, reducing overall project risk; and
- significant compliance and regulatory requirements associated with biogas upgrading equipment and distribution of commercial gas products could be more readily addressed by an experienced producer-supplier of commercial gases.

To produce the biogas to be upgraded to biomethane and bio-CO_2, the piggery would extend and cover an existing uncovered anaerobic pond located between Module 1 and Module 2 (Figure 12). This new covered anaerobic pond would then receive, treat and capture biogas from the pigs housed in Module 1 and Module 2, equivalent to an estimated 57,400 SPUs. The extension of an existing pond was preferred over purpose-building a new pond, because conventional effluent could be by-passed into other effluent ponds onsite, whilst this pond was being reconstructed, the space appeared to be available and the soil conditions were known and expected to be reasonable.

Figure 12 Aerial photograph showing existing uncovered "Mod 1 Anaerobic Pond", which is proposed to be extended to form a new covered anaerobic pond that captures biogas from Module 1 and Module 2 onsite at the large piggery.

The piggery environmental manager estimated costs for the new covered pond installation to be approximately $2M, based on scaling of historic costs of their existing biogas installations down to the number of pigs/conventional manure output of Module 1 and Module 2. This capital cost estimate included: excavation and enlarging of the current Module 1 anerobic pond (~$450K); upgrade of effluent handling systems (sumps, pumps, macerators and instrumentation) because Module 2 effluent will need to be pumped to the new pond (~$400K); HDPE cover with ballasts and drainage (~$400K); biogas collection system (manifolds, blowers, emergency flares) (~$100K); sludge recirculation and extraction system (~$300K); electricals/controls (~$150K); overheads, planning, engineering, fencing, contingency (~$200K). The biogas is then to be relayed to a feed mill approximately 8km away from the piggery (pipeline travel path along main public roads) (Figure 13), which was the selected site for a third-party biogas upgrading facility. This would require installation of biogas piping along main public roads, expected to be met with significant but not insurmountable approvals challenges. A nominal amount of $350k was added for buried biogas piping up to the feed mill (costed at $35k per 800m, for 8km, based on historic costs incurred by the piggery).

Figure 13 Aerial photograph of piggery, and nearby feed mill and meat processing facility.

Accordingly, the total capital costs to be incurred by the large piggery amounted to \$2.35M for installation of the covered pond and biogas piping up to the feed mill, and based on this cost, a nominal sale price was set at \$0.16 per Nm^3 of raw biogas produced, supplied and sold to the commercial gas company operating the upgrading facility at the feed mill. These earnings by the large piggery from the sale of raw biogas would then pay for the capital invested by the piggery and would provide a reasonable internal rate of return to the piggery.

The third-party entity would lease a parcel of land at the feed mill from the same piggery (who also owns the feed mill) and on this land the third-party entity would install and operate a containerised biogas upgrading facility. The expected footprint of the biogas upgrading facility would be approximately two 40-foot containers, one 20-foot container and a 50-tonne liquid CO_2 gas storage tank (Figure 14). The biogas upgrading system could either use a membrane-based technology, PSA technology or cryogenic upgrading technology (Section 3.3.2), albeit that cryogenic upgrading technology is generally recognised to be most expensive, and there is currently minimal local demand for liquified biomethane, a primary target product of cryogenic biogas upgrading. Hence, membrane-based upgrading was selected as a more cost-effective option to produce biomethane gas, readily usable at the feed mill. For this though, it is assumed that the piggery would be able to register an ERF project and earn and sell carbon credits for the destruction of this biomethane at the feed mill.

The feed mill had an existing annual natural gas demand of about 50,000GJ, priced at approximately \$12.5.GJ^{-1}, and this energy demand was approximately equal to what would could be provided by biomethane produced by a biogas upgrading unit sized to receive 250$m^3.hr^{-1}$ (on average) raw biogas flow. This was then selected as the basis for costing of a biogas upgrading facility to conduct a CBA. A PigBal model provided by the piggery environmental manager indicated that approximately 350$m^3.hr^{-1}$ of biogas potential (65% methane concentration) would be available from Module 1 and Module 2.

Figure 14 Example membrane-based biogas upgrading infrastructure in the Netherlands, by Pentair Haffmans. The infrastructure is fully containerised inside pre-assembled 40-foot containers, making it modular and readily transportable. Photos also show infrastructure inside the containers, including a compressor and membrane units for separation of methane from CO_2 (left), heat exchangers (middle), and refrigeration units able to produce liquid CO_2. This example system is identical in size to what would be suitable for the large piggery concept, i.e. 250 $m3.hr^{-1}$ raw biogas flow. Source: Tait (2018).

The third-party entity operating the biogas upgrading facility would need to install a 100kWe biogas fuelled electricity generator to generate enough electricity for the biogas upgrading facility to operate on. For this, the entity would also be generating LGCs as an important revenue stream. This 100kWe generator would consume approximately 50-60$m^3.hr^{-1}$ of additional biogas, which the piggery is to supply and sell to the upgrading facility at the price set above.

The biogas upgrading facility will receive and polish the raw biogas of any remaining hydrogen sulphide, moisture, and other impurities, typically involving treatment with an activated carbon filter and a chiller unit. The polished biogas is then compressed and fed to a set of membrane modules to separate CO_2 from methane, with the CO_2 passing through to subsequent compressor stage and being fed to a series of activated carbon filter/dryer modules and then onto a cryogenic liquefaction system, which produces high-grade liquid bio-CO_2 that is stored in a storage tank onsite until it is distributed to existing customers in the region. From details provided by Pentair Haffmans, a potential supplier of membrane-based upgrading systems, an estimated 1,247 tonnes of CO_2 would be produced per year. Of this, the nearby meat processing facility owned by the pig producing company could only purchase and use 185 tonnes per annum of food grade CO_2 at a typical purchase price of around $620 per tonne ($114,000.annum^{-1}). The remainder of the CO_2 would need to be distributed to the existing customer base in the region, via truck, as is typically done by companies such as BOC or Air Liquide.

A CBA was performed, looking at the project proposition from the perspective of the third-party entity owning and operating the biogas upgrading facility. For this, approximate capital costings sourced from Pentair Haffmans were used and to this nominal costs for freight ($40k) and installation (80% of base capital costs) were added. Lastly, a nominal allowance was included for the turn-key cost of the 100kWe biogas electricity generator. The resulting capital costs are summarised in Table 10.

Operating and maintenance costs sourced from Pentair Haffmans were used, converted from Euros into Australian dollars using a nominal exchange rate of 1.7 (noting the current much weaker position of the Australian dollar) and to this a nominal operating and maintenance cost of $30k per year was added for the 100kWe biogas electricity generator. The cost of raw biogas paid to the piggery was also added. These are summarised in Table 10.

Income/revenue streams from operating the biogas upgrading facility included 50,000 GJ per annum of biomethane sold at the current price of $12.5.GJ^{-1}($625,000.annum^{-1}), 1,247 tonnes of CO_2 sold at the current price of $620 per tonne, and the value of LGCs generated and sold from the operation of the 100kWe generator running on biogas at the feed mill. The CBA assumed that costs are incurred in year 1, but that, due to construction and commissioning in year 1, revenue/benefits are only sourced from year 2 onwards. These are summarised in Table 10.

Table 10 High-level concept cost-benefit – Biogas to Biomethane from the third-party biogas upgrading facility operator's perspective

Item	Price exc. GST
Estimated capital costs	
Membrane biogas upgrading system (250m^3.hr^{-1} raw biogas flow) plus liquid CO_2 recovery system*	$ 3,060,000
Freight (nominal allowance)	$40,000
100kWe generator module (all inclusive, turn-key)	$200,000
Total capital costs	*$ 3,300,000*
Estimated annual operating costs	
Operating costs for upgrading facility (nominal allowance)#	$ 204,000
Full-time operator staff	$ 100,000
Operating and maintenance of 100kWe generator module	$ 30,000
Total annual operating costs	*$ 334,000*
Total annualised benefits	
Biomethane sales (50,000 GJ per annum at $12.5.GJ^{-1})$	$ 592,500
Bio-CO2 sales (1,247 tonnes per annum at $620.tonne^{-1})	$ 773,000
Large-Scale Renewable Energy Credits (LGCs) (at $48.MWh^{-1})	$ 42,000
Total annual benefits	*$ 1,407,500*

* Based on cost of €1M, converted to Australian dollars with an exchange rate of 1.7, and then multiplied by 1.8 to allow for contingencies and installation/integration costs

\# Based on cost of €70k per annum for lease, €50k per annum for maintenance, converted to Australian dollars with an exchange rate of 1.7

$ Assumes a nominal up-time of 95% and 5% methane losses

Based on these costs and benefits, the NPV of the scenario project concept to the third-party biogas upgrading facility operator across a 20-year nominal project life was estimated at $5.3M with debt finance (at nominal 5% interest on finance), and $5.8M without debt finance (Internal Rate of Return of 20-22%). The estimated payback period was 5.2 years with debt finance and 4.5 years without debt finance. This shows a strong business case for the biogas to biomethane concept, worthy of further exploration.

It is estimated that, based on the biogas sale price of $0.16 per Nm^3 of raw biogas and the sale of carbon credits under the ERF, the large piggery will have similar returns on investment from the biogas to biomethane project.

5. Implications & Recommendations

The project carried out cost benefit analyses on several biogas production and use options for Australian piggeries. These analyses included a real biogas case study for a medium-sized 535-sow farrow-to-finish piggery in Victoria, Australia. Also, scenarios were developed and explored with options for piggeries with minimal biogas production negatively impacting on techno-economic feasibility, as well as options for piggeries with excess biogas that cannot be profitably utilised.

The real piggery case study results showed moderate economic feasibility for biogas at the 535-sow farrow-to-finish size, with a 6.3-year simple payback period. The producer at this case study site also gained significant social-license benefits from the biogas system, with notable improvements in community relations due to odour reduction achieved by the on-farm biogas system. Alternative renewable energy sources (e.g. solar and wind) do not provide such benefits. These results showed that biogas may be feasible at the medium piggery size, and that similar biogas opportunities therefore existed for other Australian piggeries at or above this piggery size.

Some piggeries would produce low levels of biogas because all or part of their herd is on deep litter, thereby providing less piggery effluent (or none) for biogas production in covered anaerobic ponds. These piggeries could consider importing and use of other safe organic matter sources from external industry for biogas production in existing covered ponds. Whilst this may provide additional revenue streams from gate fees received for diverting the organic matter away from landfills, any organic matter source that may pose a significant biosecurity risk should be strongly avoided (e.g. municipal solid waste, slaughterhouse house).

Spent piggery litter is also an organic matter source and can therefore be converted into biogas. However, spent piggery litter is unsuitable for covered anaerobic pond treatment. A different dedicated anaerobic digestion system would be required that can handle high solids materials such as spent piggery litter. A cost benefit analysis for an in-ground litter digestion concept showed marginally less profitability than in the base case piggery case study, specifically with an estimated 7.1-year simple payback period. The batch-wise operation of a litter digester would require periodic mechanical emptying and reloading with an excavator/front-end loader, which would increase manual handling and labour requirements above what is typical for a deep litter piggery. There are currently no biogas systems in Australia operating on deep litter but based on the moderate economic feasibility a future trial is recommended to clarify true cost-benefit. This could make use of the in-ground digester concept described in this report.

For piggeries that produce excess biogas unable to be profitably utilised, an option could be to use the biogas directly in an absorption chiller unit to supply chilled drinking water for sows under heat stress or for shed cooling applications. This may be particularly important into the future, with a likelihood of more extreme climates. Because such absorption chillers run directly on the fuel gas, without the need for an intermediate electricity generation step, this may also provide future options for piggeries that are unable to afford or install an electrical generator. Commercially available absorption chiller units can simultaneously produce chilled water and hot water, and this would also provide versatile energy options for a piggery, having need of both heating and cooling. However, the cost-benefit analysis suggested that the generation of onsite electricity provided a greater benefit than only producing hot water or chilled water for heating and chilling applications.

Future investigations should trial the use of an absorption chiller running on biogas, to clarity true-cost benefit for Australian piggeries. It may be possible to source a much more cost-effective absorption chiller than assessed in the current work, and also to reduce the size of covered pond infrastructure onsite to only provide biogas necessary for operating the absorption chiller, thereby saving on capital costs and improve profitability.

Large piggeries with excess biogas (>250$m^3.hr^{-1}$) could consider selling this biogas to a third-party commercial gas manufacturer-supplier to be purified and converted into saleable biomethane and bio-CO_2. These products can be sold instead of natural gas and commercial gaseous CO_2 to existing customers. The analysis showed that current market prices would provide favourable economic benefits for both the producer who has to invest some funds to build a covered pond and connected pipework, as well as the third-party entity who has to pay for the infrastructure required to produce the biomethane and bio-CO_2. Estimated payback period was 4.5 years for both. The economic feasibility was highly sensitive to the sale of liquid CO_2 at the current market price, so the feasibility of distributing and selling CO_2 should be further explored in future studies.

The involvement of a third-party gas manufacturer-supplier would complicate arrangements, but would also significantly de-risk the project for the producer. Contract negotiations between the producer and the third-party entity would be key here, including careful consideration of the amount and quality of raw biogas, the length of the contract and options to renegotiate at regular intervals, financial gains vs. risks (e.g. arrangements for when biogas supply is interrupted because of upset in the covered pond operation).

Overall, the report has identified potential technologies, provided a real biogas case study, conducted feasibilities of real-life scenario projects, and provided a good evidence-based justification of various biogas concepts for Australian piggeries. Based on the observed cost benefits being moderately to highly feasible, future investigations and research are recommended to trial and pilot the spent litter digestion concept, the use of an absorption chiller unit for chilled and hot water production and a biogas to biomethane concept. Such work would help clarify real cost-benefit and practical opportunities and constraints for Australian piggeries.

6. Intellectual Property

The scenario analyses developed and documented in this report represent potential future commercial projects, and as such have imbedded commercial value for researchers and Australian pig producers. The intention is to publish (with Australian Pork Limited's prior written approval), components of the work in public domain outlets to broadly promote biogas benefits for piggeries and thereby encourage future projects.

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8. Publications Arising

An international peer reviewed journal manuscript is in preparation, covering the case study components and the options analysis components of this project. Written approval to publish will be sought from APL prior to submission of this journal manuscript. Mr. Alan Skerman and key staff from the large piggery that participated in the biomethane study have tentatively agreed to participate as co-authors of this journal manuscript.