Low Carbon Emission Roadmap for the Australian Pork Industry

Manual

Final Report
APL Project 2020/0086

October 2021

Integrity Ag and Environment

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Acknowledgements

This project is supported by funding from Australian Pork Limited and the Department of Agriculture and Water Resources.

Glossary

Business emissions	Scope 1 and Scope 2 emissions that are the most relevant emission sources to piggery operators, as these sources are within operational control of the farm
Carbon accounting	The process used to quantify greenhouse gas (GHG) emissions from an enterprise.
Carbon footprint	The process of quantifying GHG emissions emitted directly or indirectly by an individual, company or product (i.e. the sum of scope one, two and three emissions). A carbon footprint is more commonly used for products (i.e. dressed weight) than enterprises, but it can be applied at either scale. Several standards exist to define a carbon footprint, such as ISO 14067.
Crediting period	The period of time for which net GHG emissions reductions or removals will be verified.
Emission intensity	Emissions relative to output (i.e. CO_2-e per kg of LW sold or CO_2-e per kg of LWG). Emission intensity values allow for comparison and benchmarking between farms of different sizes. They are the standard unit for a product carbon footprint.
Organisation carbon footprint	Examines the impact of only emissions produced from an organisation
Product carbon footprint	Examines the impact of only emissions produced for a product
Scope 1 emissions	Direct GHG emissions occur from sources that are owned or controlled by a company
Scope 2 emissions	GHG emissions from the generation of purchased electricity consumed by a company
Scope 3 emissions	GHG emissions that are the consequence of the activities of the company but occur from sources not owned or controlled by the company. Some examples of Scope 3 activities are emissions from purchased breeders or grain, and use of services. These emissions can relate to the supply chain prior to the business (i.e. purchased gilts) or after the business in the supply chain (i.e. meat processing).

ACCU	Australian Carbon Credit Unit
AD	Anaerobic digestion
ANREU	Australian National Registry of Emissions Units
APL	Australian Pork Limited
BSFL	Black soldier fly larvae
C	Carbon
CER	Clean Energy Regulator
CFI	Carbon Farming Initiative
CH_4	Methane
CHP	Combined heat and power
CN	Carbon neutral
CO_2	Carbon dioxide
DEEDI	Department of Employment, Economic Development and Innovation
DISER	Australian Government Department of Industry, Science, Energy and Resources
dLUC	Direct land use change
ERF	Emission Reduction Fund
ESG	Environmental, Social and Governance
FAO	United Nations Food and Agriculture Organization

FCR	Feed conversion ratio
GE	Gross energy
GHG	Greenhouse gas
GWP	Global warming potential
HCL	Hydrochloride
HRT	Hydraulic retention time
ISO	International Standard
LCA	Life cycle assessment
LEAP	Livestock Environmental Assessment and Performance Partnership
LPG	Liquefied petroleum gas
LU	Land use
LW	Liveweight
MCF	Methane conversion factor
MJ	Megajoules
MMS	Manure management system
N	Nitrogen
N_2O	Nitrous oxide
NGGI	National Greenhouse Gas Inventory
NIR	National Inventory Report
PAS	Publicly available specification
PDS	Public disclosure statement
PIC	Property identification code
SF_6	Sulphur hexafluoride
SLL	Sustainability-linked loans
SOC	Soil organic carbon
SPU	Standard pig units
TKN	Total Kjedahl nitrogen
TS	Total solids
VERs	Verified emissions reductions
VS	Volatile solids

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1. Introduction

There is growing pressure in Australia on industries to reduce Greenhouse gas (GHG) emissions from livestock production to maintain community and consumer trust. The Australian Government has a target to reduce emissions towards a net-zero goal, and retailers have already moved to benchmark and reduce emissions from pork supply chains. The Australian pork industry has responded by developing a low carbon target by 2025, and while there is prior research available, it is difficult for producers to make progress with no "roadmap" to get there. This guide provides that roadmap.

The pork industry was among Australia's first to initiate GHG research, commissioning their first carbon footprint in 2008, and has steadily built the knowledge base over the past decade. This roadmap document takes the research completed in the last decade and consolidates it in a step-by-step guide to reducing emissions.

This document is a roadmap that will:

- Provide knowledge and confidence for pork producers to quantify their GHG emissions.
- Identify what is required to reduce emissions, store carbon and achieve low carbon or carbon neutral pork.
- Outline how to access funding and support to achieve the goal of low carbon pork.

This document is a key reference for producers of all scales and production methods as the industry moves towards a low GHG emissions future. The roadmap is focused most strongly on pig production at the farm level, but includes some reference to meat processing, post processing and retailing. Each of these stages contributes to the carbon footprint of pork, but of these stages, production at the farm is greatest, and also differs the most depending on the specifics of the production system. For this reason, the focus of this roadmap is on-farm production.

2. Understanding Greenhouse Gas Emissions

2.1 Greenhouse Gas Emissions

Greenhouse gases are defined as atmospheric gases responsible for causing global warming and climate change (UN Climate change glossary - UNFCC, 2021). GHGs in the atmosphere increase the retention of the Earth's outgoing energy, thus holding heat in the atmosphere. This heat trapping causes changes in the radiative balance of the Earth; the balance between energy received from the sun and emitted from Earth, and as a result alters the climate and weather patterns at global and regional scales.

GHGs are reported in the Australian Government's National Inventory Report (Commonwealth of Australia, 2019), also known as the National GHG Inventory or NGGI) and include:

- Carbon dioxide (CO_2),
- Methane (CH_4),
- Nitrous oxide (N_2O),
- Sulphur hexafluoride (SF_6).
- Other hydrofluorocarbons and perfluorocarbons.

All GHGs are not equal, methane and nitrous oxide have much higher warming effects than carbon dioxide. Global warming effects are typically measured in terms of radiative forcing that measures the immediate impact that incremental increases of GHGs have on the balance of incoming and outgoing radiation in the atmosphere (World Meteorological Organization, 1985). A positive radiation force indicates that the incoming energy is greater than the outgoing energy (Figure 1), whereas a negative radiation force indicates that outgoing energy is greater than incoming energy. To allow for a comparison between the quantity and potency of each gas, GHG emissions are standardised using the Global Warming Potential (GWP) system, which aims to determine the average warming impact of each gas over a 100-year time period (reported as GWP_{100}). The reporting unit is a carbon dioxide equivalent (CO_2-e). Using this system, the GWP_{100} value for methane used in Australia as of July 2020 is 28 (i.e. 28 times more warming potential than carbon dioxide), and the GWP_{100} value for nitrous oxide is 265. There are other metrics for determining the relative impacts of different GHGs, but GWP_{100} is most used in global GHG accounting.

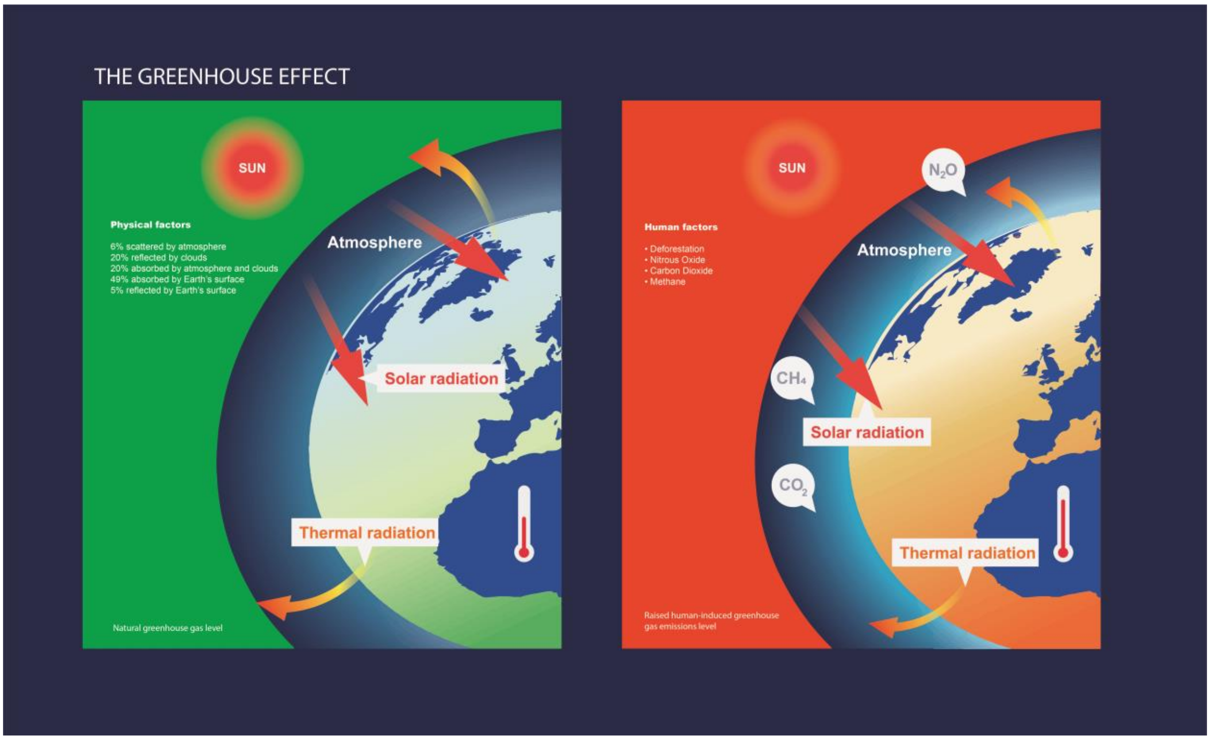


Figure 1. The global warming effect

2.2 The Carbon Cycle

The carbon cycle refers to the flows of carbon between different reservoirs on Earth. Reservoirs include carbon life forms such as plants and animals, oceans, rocks, soil, minerals and gases in the atmosphere. Carbon is transferred between these reservoirs through processes such as respiration, decomposition, photosynthesis, livestock emissions (including manure) and the combustion of fossil fuels and biosolids. The amount of carbon on the planet does not change because earth is a closed system. A balanced system occurs when the carbon naturally released from reservoirs is equal to the amount of carbon that is naturally absorbed by reservoirs.

However, the distribution of carbon between reservoirs can change and has been accelerated due to human impact. Particularly, the use of fossil fuels (fossil reservoirs of carbon), deforestation and soil carbon loss has created an imbalance in the carbon cycle through the increase of carbon in the atmosphere, leading to global warming. While the carbon cycle involves enormous amounts of carbon, the global warming is influenced by 'net' emissions, and carbon accounts only focus on these net changes. It's important to note that while there is a strong link between the carbon cycle and global warming impacts, there are other processes that also contribute to global warming. Some gases from agricultural systems, such as nitrous oxide (N_2O) are not part of the carbon cycle, but contribute to global warming. Some gases such as methane (CH_4) are part of the carbon cycle, and have a much larger impact on warming than may be assumed by the mass of carbon being released. Even though many terms refer to "carbon" when calculating global warming impacts, they generally include all relevant GHGs, as explained in the next section.

The main GHG emissions from pig production are carbon dioxide, methane and nitrous oxide, with the key contributing major sources being feed production, manure management, enteric emission, energy and purchased inputs (Figure 2).

Any process, activity or mechanism which removes GHG, or a precursor of a GHG from the atmosphere is termed a sink. Trees and other vegetation are considered sinks because they remove carbon dioxide through photosynthesis, and well as soil which can store organic carbon through cultivation of certain crops or the addition of soil amendments, such as manure or compost.

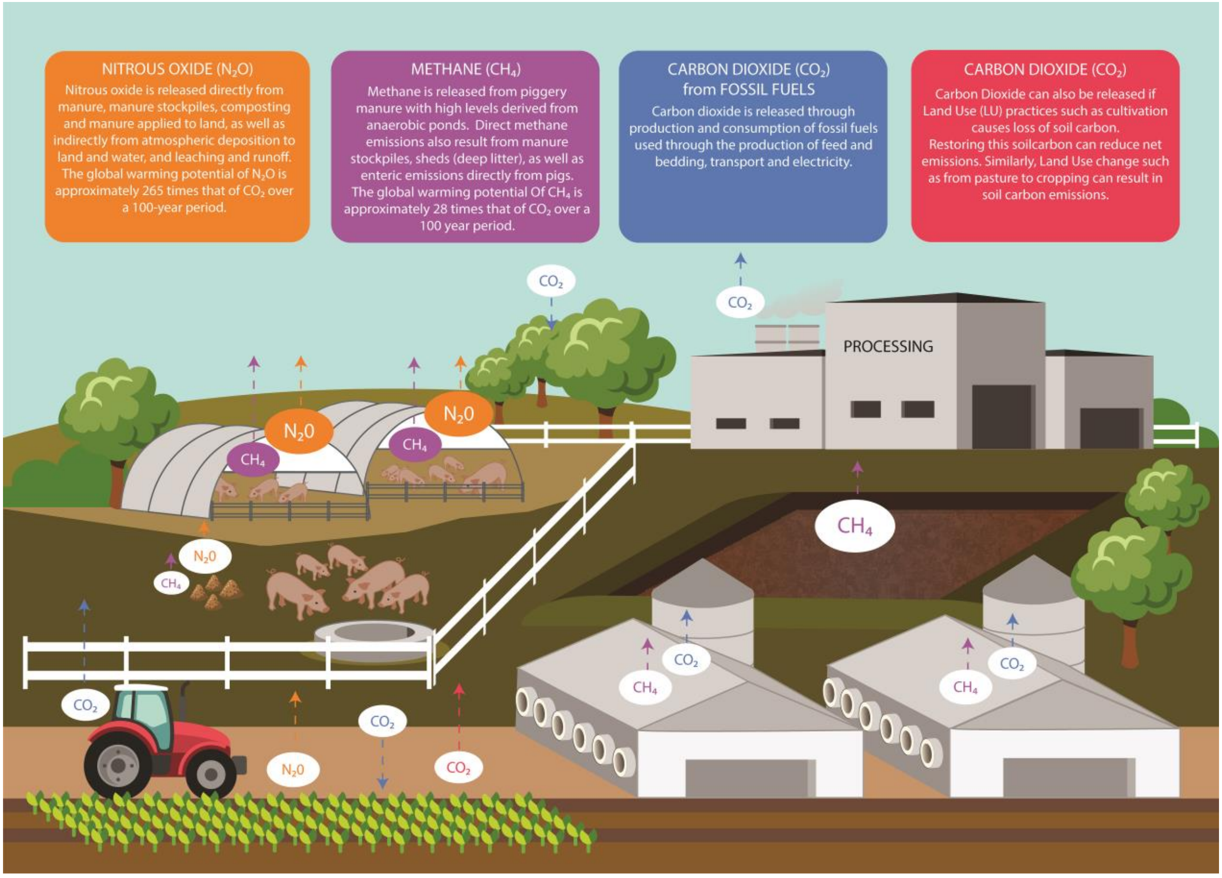


Figure 2. Sources and sinks of major greenhouse gas emissions on a pig farm

2.3 Carbon Account and Carbon Footprint – What's the Difference?

The GHG emissions generated by a piggery operation and other farm-related activities can be estimated by developing a 'carbon account'. A carbon account allows producers to calculate their current GHG emissions and helps them to understand the main drivers of emissions.

It is both difficult and expensive to measure the quantity of GHG emissions or the carbon storage on a piggery. For this reason, carbon accounting is done through calculations, to produce an estimate of emissions and carbon storage. While it is called 'carbon accounting' for simplicity, the full natural cycle of carbon moving through the system is typically not included; only the changes caused by fossil fuel burning, or long-term changes in carbon storage in soil or vegetation is included. Carbon accounting also includes other GHG emissions (e.g. nitrous oxide) and may be better termed "GHG accounting". In this document, the two terms are considered synonymous. Creating a carbon account allows producers to understand how GHGs interact with the productivity of the enterprise.

Standard practice is to report emissions using different classification depending on where the emissions arise and how they relate to the business. The framework of the GHG Protocol has been adopted here, which is common in business GHG accounting.

According to the GHG Protocol (Ranganathan *et al.*, 2004), emissions are defined into three scopes:

- **Scope 1**: "Direct GHG emissions occur from sources that are owned or controlled by the company".
- **Scope 2**: "Accounts for GHG emissions from the generation of purchased electricity consumed by the company."
- **Scope 3**: "Are a consequence of the activities of the company but occur from sources not owned or controlled by the company. Some examples of Scope 3 activities are extraction and production of purchased materials, transportation of purchased fuels, and use of sold products and services." These can be further broken down into two sources:
    - **Upstream emissions:** from sources such as the production of purchased feed, and manufacture of chemicals.
    - **Downstream emissions:** from sources such as those associated with the transportation and processing of pigs.

The key sources of emissions for a piggery (pre-farm, on-farm and post-farm), separated by scope, are outlined in Figure 3.

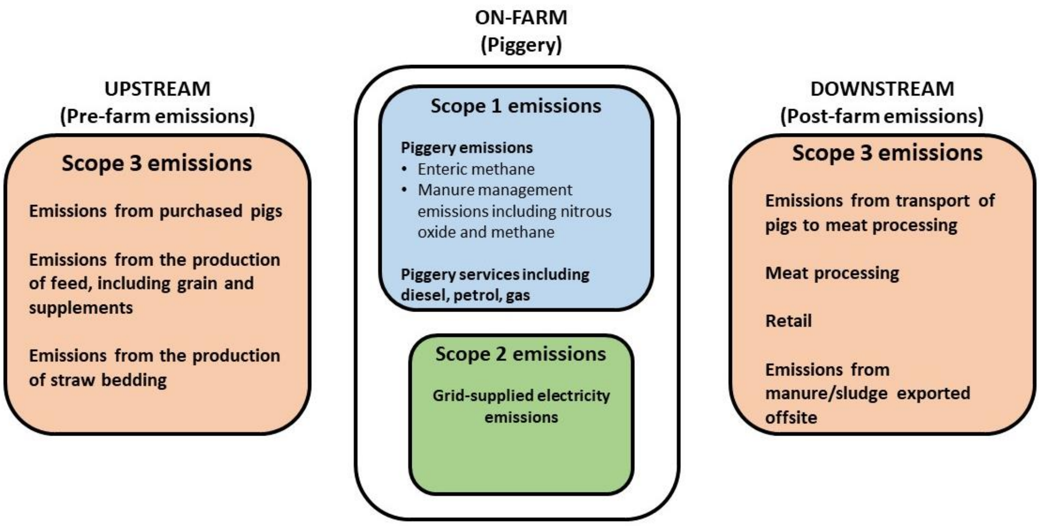


Figure 3. The breakdown of greenhouse gas emissions from a piggery into Scope 1, 2 and 3 emissions

The terms **carbon accounting** and **carbon footprint** are often used interchangeably; however, there are some clear differences. **Carbon accounting** is typically focused on business emissions and carbon storage and may be limited to Scope 1 and Scope 2 sources only. Inclusion of Scope 3 emissions is optional. Scope 1 and Scope 2 emissions are the most relevant emission sources to piggery operators, as these sources are within operational control of the farm and are also referred to as **business emissions**. The important difference between this and a **carbon**

footprint is that inclusion of Scope 1, Scope 2 and Scope 3 emission sources is mandatory for a carbon footprint assessment. It should be noted that the further a business is up the supply chain (i.e. retail supermarket), the larger their upstream Scope 3 emissions. When all businesses account for their Scope 1 and 2 emissions, the result is the total global GHG emissions, as such, undertaking a business level assessment avoids 'double-accounting' emissions.

A carbon footprint examines the combined impact of all emissions produced from an organisation or for a product (i.e. an *organisation* carbon footprint, and a *product* carbon footprint), and is most commonly reported for a product (e.g. kilograms of CO_2-e per kilogram of liveweight - LW, carcass weight or retail meat). The product carbon footprint estimated in kilograms of CO_2-e per unit of product is commonly referred to as the **emission intensity**. One benefit of including all emission scopes within a carbon footprint is that it allows 'like for like' comparison between different production systems and even different products altogether, provided they provide the same function. For this reason, it is commonly used for benchmarking and comparisons. A carbon footprint is important when you compare one product against another or you wish to market a products' low carbon credentials.

A carbon footprint is defined by the International Standard ISO 14067 (ISO, 2013), and sector specific guidance has been provided by the United Nations Food and Agriculture Organization (UN FAO), Livestock Environmental Assessment and Performance Partnership (LEAP) guidelines for the environmental performance of pig supply chains (FAO, 2018) and animal feed supply chains (FAO, 2016).

Emissions from agri-food supply chains also differentiate the contribution from land use (LU) and direct land use change (dLUC). Emissions or carbon storage associated with LU relate to soil carbon losses from cultivation for crop production which leads to CO_2 emissions from soil, or in some cases better management practices could result in carbon storage, in which case this would represent a "negative" emission dLUC (for example, conversion of forest to cropland, resulting in the loss of carbon stored in trees and potentially soil, or planting trees, which changes LU from a pasture or crop back to a forest). These sources are often reported separately from a carbon footprint because there is an acknowledged higher level of uncertainty in these emission sources.

2.4 GHG Emission System Boundary

To calculate the GHG emissions, a system boundary must be established to formalise what emissions to include in the assessment. The boundary definition will vary depending on the goals of the carbon assessment, with different boundaries required for an assessment of a product to retail shelf, compared with to farm gate.

This roadmap defines the system boundary for the assessment of GHG emissions as including all Scope 1 and 2 emissions (i.e. on-farm), all upstream Scope 3 emissions (i.e. feed production, purchases) and downstream Scope 3 emissions to the point of delivery to meat processing. The assessment will include Scope 3 impacts from LU change associated with feed production. Based on the proposed boundary, emission will be reported in kilograms of CO_2-e per kilogram of LW delivered to the point of processing.

2.5 Carbon Neutrality

There are multiple definitions of carbon neutral, and multiple standards that are required for making claims in the market. However, each build upon the basic concept of zero net release of GHG emissions into the atmosphere.

Importantly, the leading carbon neutral certifications require determining the **carbon footprint**, then reducing emissions and then offsetting the remainder of emissions, either by generating carbon credits through carbon storage on the site (i.e. vegetation or soil carbon sequestration) or purchasing carbon credits available in the carbon market.

Climate Active, managed by the Australian Government Department of Industry, Science, Energy and Resources (DISER) certifies businesses and products that have credibly reached carbon neutrality by calculating, reducing and offsetting their carbon emissions. Certification is available for business operations, products and services, events, buildings and precincts. To be certified, a business or production system must meet the requirements of the Climate Active Carbon Neutral Standard. Certification requires an independent third party to verify the **carbon footprint** and offsets. Operators must meet ongoing certification and reporting requirements (e.g. annual reporting) to use the Climate Active trademark on their products. Other global accreditations such as PAS 2060 also exist.

2.6 What is Low Carbon Pork?

All Australian states have a goal of reducing emissions on the pathway to net-zero emissions by 2050 or sooner (Table 1). The Australian pork industry has established a goal of being low carbon by 2025 in line with this approach.

Table 1. Federal and state emission reduction target summary for Australia

Jurisdiction	**Relevant targets**	**Reference**
Federal	26 – 28% below 2005 by 2030	Australia's 2030 Emissions Reduction Target (Australian Government, 2020)
New South Wales	50% below 2005 levels by 2030 Net-zero emissions by 2050	Net Zero Plan, Stage 1: 2020-2030. (Department of Planning Industry and Environment, 2020)
Queensland	Net-zero emissions by 2050	Queensland's 2019 Greenhouse Gas Emissions and Targets, Queensland Climate Active (Queensland Government, 2021)
Victoria	Projected to be 18% below 2005 levels in 2020 32-39% below 2005 levels in 2025 45-60% below 2005 levels in 2030 Net-zero emissions by 2050	Interim Emissions Reduction Targets for Victoria (2021-2030) Independent Expert Panel on Interim Emissions Reduction Targets for Victoria, 2019 Climate Change Act 2017 (State Government of Victoria, 2021)

South Australia	50% below 2005 levels by 2030 Net-zero emissions by 2050	Climate Change and Greenhouse Emissions Reduction Act 200, (Government of South Australia, 2007)
Western Australia	Net-zero emissions by 2040	Western Australian Climate Change Policy (The Government of Western Australia, 2020)
Tasmania	60% below 1990 levels by 2050 (legislated)	Tasmania's Climate Change Action Plan 2017-2021 (Tasmanian Government, 2021)

Australian Pork Limited (APL) and the pork industry have developed goals relating to carbon, with this document providing the roadmap to achieve industry 'low carbon emission' pork by 2025. This definition includes the aspiration that the industry becomes carbon neutral in the future.

The trends in total emissions and emissions intensity from the Australian pork industry over the last forty years is shown in Figure 4. A 69% reduction in emissions intensity was achieved from 1980 to 2020, with a 44% reduction in total emissions (Watson *et al.*, 2018). The 1990 data shows that the total emission for the industry as a whole may increase, even if the emissions intensity decreases. This is a result of an increase in the size of the national herd. In the last decade, a relatively low reduction in emissions has been achieved, and there will need to be substantial effort to lower emissions from all sectors of the industry to reach the low emission target.

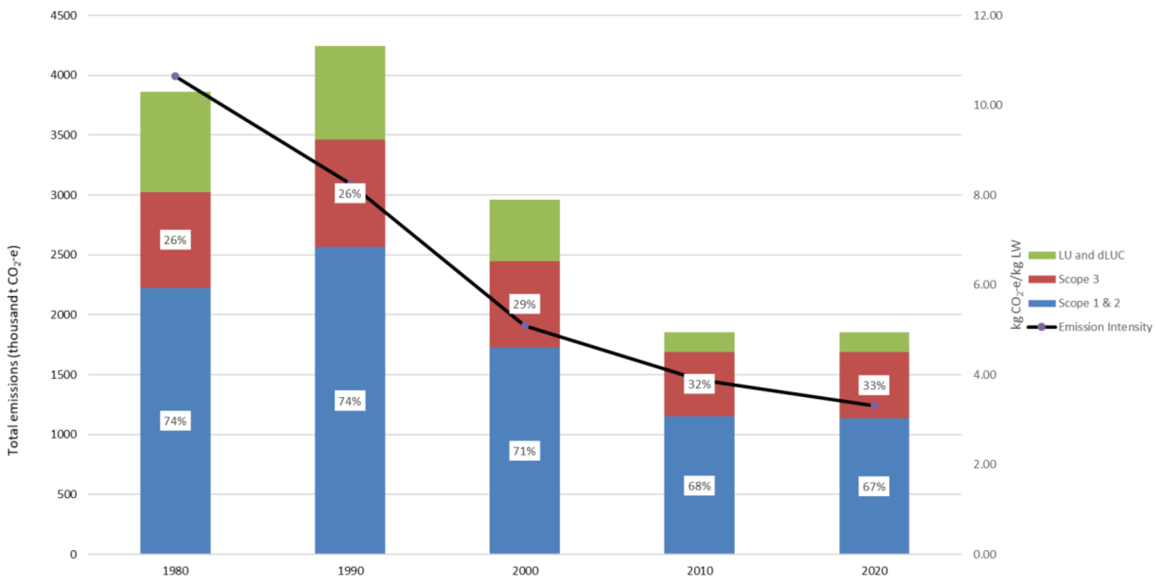


Figure 4. Changes in Scope 1, 2 & 3 total emissions and emission intensity over the period 1980 to 2020 for Australian pork production (adapted from Watson *et al.*, 2018)

2.7 Current Position of Australian Pork

Results of research into the relative GHG emissions associated with the four principal meat proteins consumed in Australia are presented in Figure 5. Pork has a relatively lower GHG emission intensity compared with the major red meats. Chicken, which has the lowest emission intensity of the major meat products, is approximately 35% lower than pork. It should be noted that the emissions intensities shown in Figure 5 are for a “retail ready” product, which includes emissions from meat processing, and accounts for mass losses and co-product production during processing. The focus of this roadmap is primary production, so results are presented here as emissions per kilogram LW delivered to point of processing.

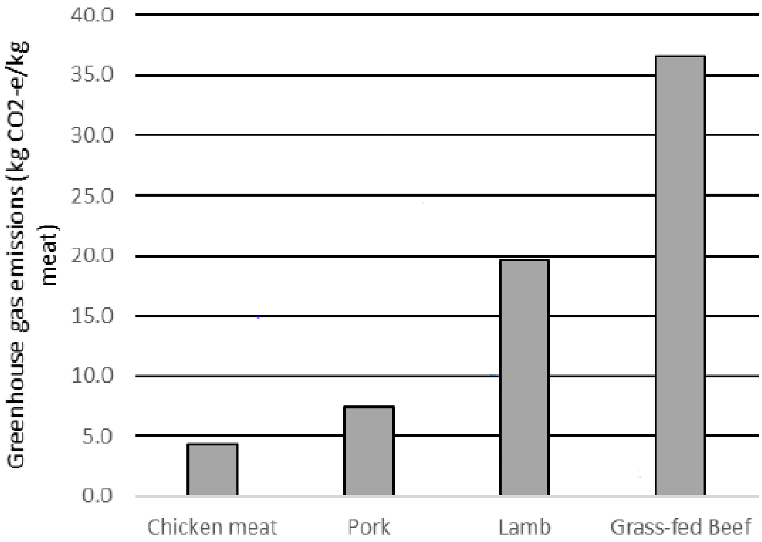


Figure 5. Comparison of greenhouse gas emissions for meat produced in four different Australian livestock systems (Wiedemann, 2018)

Notes: GHG emissions include meat processing and LU and dLUC emissions

3. Carbon - Emissions, Baseline and Benchmarking

3.1 Emission Benchmarks

GHG emission benchmarks are important as they provide a basis to compare different production systems, as well as to assess the efficacy of different emission mitigation strategies. The four benchmark production systems for this roadmap include:

- Conventional farrow to finish.
- Conventional breeding and deep litter grower/finisher.
- Outdoor breeding and deep litter grower/finishers.
- Outdoor breeding and grower/finisher.

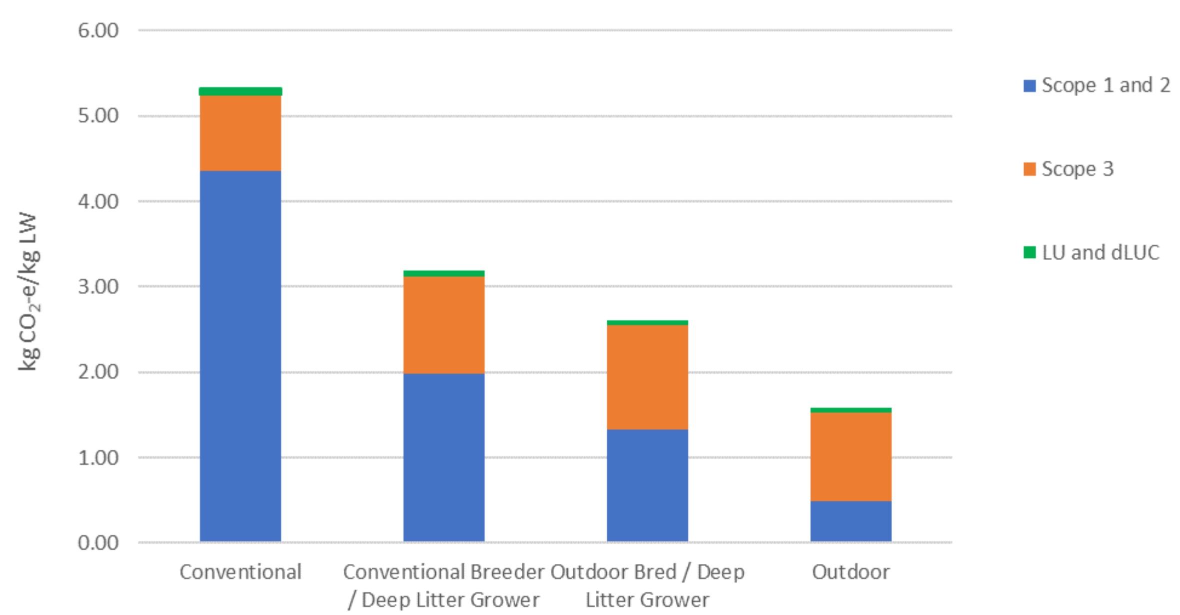
Data and assumptions for the key input parameters of the benchmark production systems are provided in Table 2.

Table 2. Key activity data for benchmark scenarios

Key Parameters	Conventional	Conventional breeding and deep litter grower/finisher	Outdoor breeding and deep litter grower/finishers	Outdoor
Location	New South Wales			
Herd Composition	1000 sow farrow to finish			
Pigs weaned/sow.year	23.2	23.2	18.3	18.2
FCR (whole herd)	3.3	3.3	3.7	4.0
Finisher pig weight	100 kg			
Feed	Australian wheat/barley dominant (2% imported soybean meal)*			
Feed Milling	onsite			
Electricity	grid supplied			
Transport distance for feed	100 km			
Transport distance for fuel	100 km			
Transport distance to processing	200 km			
Manure Management System	Anaerobic Pond	Anaerobic Pond and Stockpiled Litter	Direct to Land and Stockpiled Litter	Direct to Land

*Reference: PigBal v4

Benchmark emissions are shown in Figure 6, with the contribution of Scope 1 and 2 emissions, and Scope 3 emissions to the total emissions intensity (kg CO_2-e / kg of LW) providing a baseline for the different types of production. The LU and dLUC emissions associated with feed production are reported separately for each benchmark case.



	Conventional	Conventional Breeder / Deep Litter Grower	Outdoor Bred / Deep Litter Grower	Outdoor
Scope 1 and 2	4.35	1.98	1.32	0.49
Scope 3	0.90	1.15	1.23	1.03
LU and dLUC	0.06	0.06	0.06	0.06
Total	**5.32**	**3.19**	**2.61**	**1.58**

Figure 6. Emission intensity benchmarks for four Australian pork production systems

Notes: LU = Land Use. dLUC = direct Land Use Change. These refer to losses or sequestration associated with using or changing land management.

Conventional production has a significantly higher GHG intensity than other methods of production. This is largely due to the methane emissions associated with effluent treatment ponds from uncovered anaerobic ponds. The relative contribution from LU and dLUC are small for the benchmark scenarios due to the selection of an Australian wheat/barley based diet and low imported soybean meal inclusion. Figure 7 provides a breakdown of the total emission intensity by source. Based on 74% of pigs being produced in conventional systems in Australia (Wastson et al. 2018), the high contribution from conventional MMS to the total emissions across the industry is clear.

The benchmark scenarios assumes that feed milling occurs onsite, and consequently the energy used for milling is included as a Scope 2 emission. If a piggery purchases feed from offsite, these emissions would be classified as Scope 3.

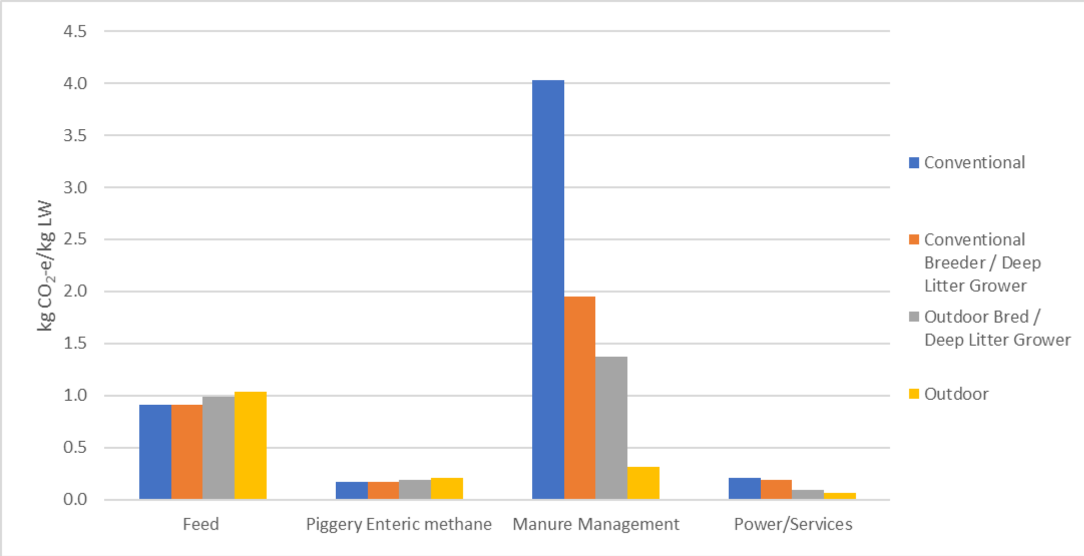


Figure 7. Sources of greenhouse gas emissions for four Australian pig production systems

3.2 Embodied Emissions in Feed

Emissions generated during the production and manufacture of feed ingredients can contribute between 15-35% of total GHG emissions for conventional systems and up to 65% in outdoor systems. Embodied emissions in feed are driven by three main factors:

1. Emissions associated with growing crops (e.g. diesel and nitrogen fertiliser) and field emissions from crop production.
2. Emissions associated with imported commodities, additives, and pharmaceuticals.
3. Grain milling/transport distance.

If feed is purchased form offsite than all emissions are categorised as Scope 3 emissions (pre-farm, or from upstream processes). If feed is milled onsite then some of the emissions associated with supplying power to the milling process will be classified as Scope 2. Also included are emissions associated with LU for cropping, which may include both emissions or carbon sequestration (storage), and dLUC where, for example, land has been converted from pasture to cropland, which can result in soil carbon losses. In terms of GHG contribution, feed production is typically the second largest source after manure management.

3.2.1 Emissions from the production of feed ingredients

Australian pig diets are formulated using locally grown cereal grains and some imported products. The source of the dietary component has a significant impact on the GHG emissions. Each dietary component has associated emissions dependant on the local environment (e.g. soil and climate) and production system (dry land or irrigated). GHG emissions are also inclusive of emissions from the manufacture of fertilisers, diesel use and field emissions of nitrous oxide. The efficiency of grain production is important: less inputs relative to yield results in lower emission intensity grain.

Emissions, and carbon storage, can also result from land use in cropping. Practices that promote soil carbon loss, such as continuous cultivation, will lead to carbon dioxide being released from the soil from the loss of soil carbon. These are termed "Land Use" carbon dioxide emissions. If improved practices such as zero tillage is used it may be possible to slow carbon losses or build very small amounts of soil carbon, but this is generally difficult in Australian cropping zones (Grain Growers, 2021).

Direct Land Use Change is the term given to the situation where changing land use, from pasture to cropping for example, results in a loss of carbon. Reversing this change can also build carbon, resulting in a 'negative' emission similarly to LU sources. These are usually reported together. The most important source of emissions in pig feed production is from imported soybean meal. Soybean meal can be used as a source of protein in pig diets, imported from Brazil, Argentina or the USA. Soybean meal imported from countries such as Argentina and Brazil has a higher emissions intensity compared to locally sourced crops, driven by dLUC (conversion of forest or pasture to cropland) to increase crop production. One strategy to reduce dLUC emissions from imported soybean meal would be to increase local production of alternative protein crops, though this would need to be achieved without expanding crop land in Australia, in a way that leads to dLUC emissions. The use of ingredients with lower cultivation impacts and cultivated in regions close to the location of pig production can reduce the environmental burdens of pig feed production (de Quelen *et al.*, 2021). However, there lies a balancing act for nutritionists to formulate diets according to raw material availability, nutritional composition and cost as well as considering the GHG emissions. For example, soybean meal is preferably formulated into diets because of its amino acid profile and improved digestibility compared to alternative protein sources (e.g. canola meal, cottonseed meal, peanut meal and sunflower meal) and using a different protein source may require more synthetic amino acids in the diet.

3.2.2 Energy and transport emissions

Energy associated with resource use for the milling and transportation of feed components is dependent on distance travelled to the mill and the truck type used (e.g. B-double, road-train, truck-and-dog). Emissions associated with the transport of feed ingredients can be reduced by using the most efficient trucks and sourcing locally. Feed milling and grain transport contribute less than 20% of the energy associated with feed production (Wiedemann, McGahan and Murphy, 2012) so this also needs to be balanced with selecting grain supplies that are naturally low in emissions. If local grain is produced inefficiently with high emissions, it may be better to transport grain from further afield that is grown in more efficient production regions.

3.3 Enteric Emissions from Digestive Processes

In Australian piggeries, enteric methane is a minor source of emissions contributing between 3% to 8% of total emissions (Wiedemann *et al.*, 2016) depending on production system. Enteric methane production in pigs is a by-product of the digestive process from anaerobic fermentation of microbial populations. The gut microbiota includes anaerobic microorganisms which ferment dietary organic matter components (starch and plant cell wall polysaccharides, proteins and other materials). The end-products released include volatile fatty acids, carbon dioxide, hydrogen gas and methane. The process of methanogenesis allows the absorption of volatile fatty acids and releases the gases as by-products through eructation. While this isn't a big emission source as it is with ruminants, there are still small amounts emitted. The biochemical pathway to produce methane uses dietary energy. In Australia a methane conversion rate of 0.7% of gross energy intake is used to estimate enteric GHG emissions (Commonwealth of Australia, 2019) for pigs. The amount of methane is influenced by the dietary composition and feed intake. The National Inventory Report (Commonwealth of Australia, 2019) provides the following formula for calculating enteric methane emissions:

$$\textit{Enteric methane emissions (kg)} = \textit{feed intake (kg)} * 18.6 * 0.007/F$$

Where:

8.6	= energy content of a typical diet in MJ GE/kg;
0.007	= methane conversion rate of gross energy;
F	= 55.22 MJ/kg of methane

3.4 Manure Management Emissions

The Australian pork industry is comprised of production systems that could be classified conventional, deep litter or outdoor. Based on the 2020 industry projections (Watson *et al.*, 2018), the breakdown of the national herd by production system is:

- 74% conventional production.
- 20% deep litter.
- 6% outdoor (free range).

The GHG emissions associated with an individual operation will vary significantly depending on the production system, feed composition and efficiency, and most importantly, the manure management system (MMS). Manure management is a major source of GHG emissions for all production types, contributing 40% to 75% for conventional and deep litter systems and around 20% for outdoor systems.

The primary GHGs that arise from a piggery MMS are methane and nitrous oxide. Methane emissions are primarily emitted from handling manure anaerobically (in the absence of oxygen), such as using anaerobic effluent ponds in conventional piggery systems. Nitrous oxide is also emitted directly from manure (in deep litter and outdoor housing), and from manure stockpiles or composting. Conditions favourable to nitrous oxide are the opposite to methane: it is generated in aerobic conditions where there is sufficient nitrogen, moisture and oxygen. Nitrous oxide is also emitted from soils, following the addition of manure or effluent. Further nitrous oxide emissions also occur from indirect sources. In this situation, losses of nitrogen in other forms, such as ammonia released to the atmosphere or nitrate leached in soils can result in secondary (or indirect) losses of nitrous oxide.

It is not possible to directly measure GHG emissions from a MMS, so to quantify emissions, estimates are made for methane and nitrous oxide generated from each GHG source. The National Inventory Report (2019) provides methods specific to Australian conditions and operations. To quantify GHG emissions, it is necessary to first estimate both the volatile solids (VS) and nitrogen (N) generated in a piggery waste stream (manure, urine, waste feed and bedding). The methodology for estimating methane production from a piggery MMS is based on the VS produced. VS is a measure of the biodegradable or organic matter content of the piggery waste stream, and directly contributes to the production of methane. The Nitrogen (N) component of the waste stream is precursor to nitrous oxide emissions.

The best available tool for estimating VS and N is the PigBal 4 model. PigBal 4 is a Microsoft Excel® spreadsheet, mass balance model for intensive piggeries in Australia. By entering typical animal characteristics, feed intakes, diet compositions and feed waste rates, the model calculates the VS and N in the animal manure and waste feed. Published values are also available in the National Environmental Guidelines for Indoor Piggeries (Tucker, 2018).

The following generalised formula is used for estimating methane emissions from piggery operations:

$$E_M = VS \ x \ B_o \ x \ MCF \ x \ \rho$$

Where:

E_M = methane emissions (kg/year)

VS = volatile solids (kg/year) (PigBal 4 or Appendix 5.E.3 in NIR 2019 (Commonwealth of Australia, 2021))

B_o = methane emission potential, (0.45m^3 CH_4 /kg VS) (IPCC, 2019)

MCF = methane conversion factor (Table 26 in Appendix A)

ρ = specific density of methane (0.6784 kg/m^3) *(National Greenhouse and Energy Reporting (Measurement) Determination 2008 (Commonwealth))*

The methane emission potential (B_o) is a measure of the degradation extent or degradability of the volatile solids. Methane potential is dependent on class of pig, feed composition, feed wastage and effluent management, with growing pigs typically producing manure with higher B_o than breeder pigs (Gopalan et al, 2013). The NIR provides a default value of 0.45m^3 CH_4/kg VS which is used in methane emission calculations.

The methane conversion factor (MCF) varies depending on the manure management and climatic conditions and can theoretically range from 0 to 100%. Both temperature and retention time play an important role in the calculation of the MCF, and as such different MCFs apply to different MMS for each state of Australia as shown in Table 26.

The relatively high MCF values for uncovered anaerobic ponds demonstrate the methane generation potential compared with all other MMS. Studies by Wiedemann et al. (2016), showed that the GHG footprint from conventional Australian pork production is dominated by methane production from anaerobic ponds with a contribution of 62-64% of total emissions. The installation of a methane capture system on an anerobic pond reduces the MCF from 0.75 to 0.1 (86% reduction) as the methane is reused or destroyed rather than released to the atmosphere. Due to a small volume of emissions generated from secondary ponds and losses through the covered pond system or digester, the MCF for these systems does not reduce to zero.

Nitrous oxide emissions from piggeries are generated from a portion of the nitrogen content in pig manure volatilising, either directly from the manure or when applied to soil and undergoing chemical transformation to form nitrous oxide. Pigs are fed high quality diets with high levels of crude protein, and as a result, pigs may excrete between 45 and 65% of the nitrogen consumed in feed. Feed waste also contributes nitrogen to the MMS and is included in the estimation of emissions for completeness. There are two types of nitrous oxide emissions that must be calculated to determine the emissions from an operation. They are:

- Direct Emissions - emissions generated directly from manure, manure stockpiles, composting and manure applied to land.
- Indirect emissions – emissions resulting from atmospheric deposition of ammonia nitrogen to land and water, and leaching and runoff from outdoor piggery operations.

While the absolute nitrous oxide emissions are relatively small, the high global warming potential makes them a significant component of the GHG calculation, particularly for deep litter and outdoor piggeries. To determine direct nitrous oxide emissions from a single operation, the emissions from each component of the MMS are calculated as follows:

$$E_{direct} = AE\ x\ NOF\ x\ C_g$$

Where:

E_{direct} = nitrous oxide emissions (kg)

AE = total nitrogen (kg/year) (PigBal 4 or Appendix 5.E.3 in NIR 2019 (Commonwealth of Australia, 2021)

NOF = nitrous oxide emission factor for pigs in each state (in Table 27 in Appendix A)

C_g = factor to convert elemental mass of N_2O to molecular mass (44/28)

Further details and methodology for calculating indirect nitrous oxide emissions is included in Appendix A.

When a piggery has multiple nitrous oxide sources onsite, such as deep litter shelters and spent litter stockpiles, consideration must be given to the total nitrogen balance. Nitrogen lost through direct emission must be removed from the indirect nitrous oxide calculations to avoid it being double counted.

Emissions from manure applied to land are attributed to crop or pasture production – i.e. the system where the nutrients contained within the manure are used. If manure or effluent is disposed of without any beneficial use, the emissions should be calculated and attributed to the piggery.

3.4.1 Conventional piggeries

Conventional MMS have the following GHG emission sources:

- Emissions from the anaerobic treatment ponds.
- Emissions from secondary/facultative treatment ponds.
- Emissions from separated solids/stockpiles (if present).
- Indirect emissions from ammonia volatilisation.

The main GHG emissions associated with different stages of conventional piggery production are shown in Figure 8 with the methane emissions from the treatment ponds being the major contributor.

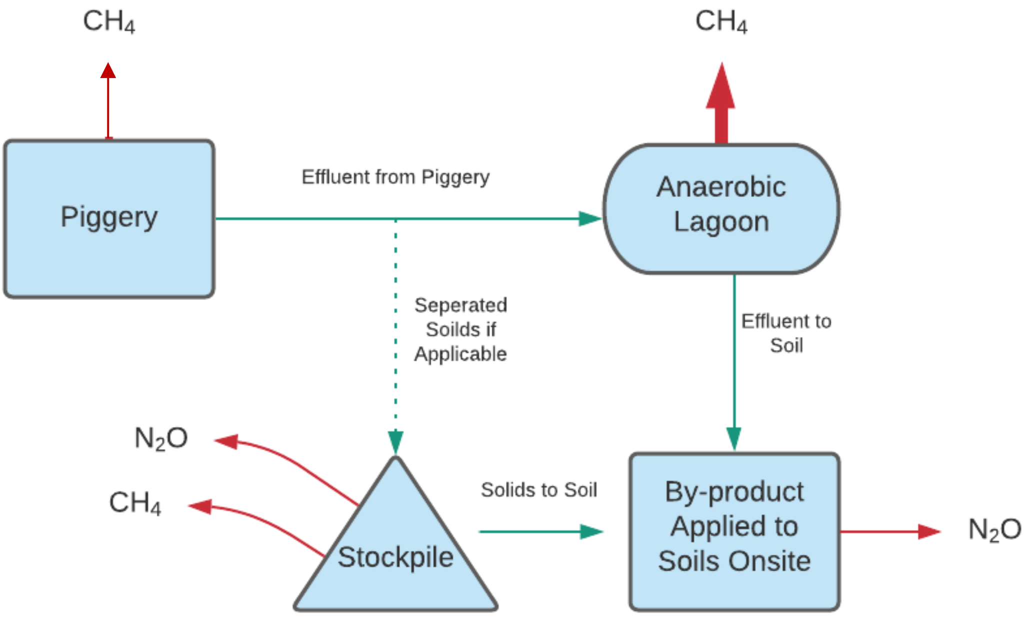


Figure 8. Conventional piggeries - mass flow method of estimating manure management emissions (adapted from Commonwealth of Australia, 2021)

The characteristics of effluent discharged from a conventional piggery operation depends on the feed utilised, management practices, piggery design and water quality and quantity used in the cleaning of the individual facility. The composition of effluent produced can vary widely. The total solids (TS) content in conventional piggery effluent varies between 0.5% to 3.5% TS (Tucker, 2018). Exiting the piggery, effluent may undergo solids screening, and is then typically discharged to anaerobic ponds for primary treatment prior to entering facultative ponds for further treatment and/or storage prior to reuse through irrigation or evaporation.

Anaerobic digestion (AD) is a key part of the treatment process and consists of a series of biological processes by which biodegradable organic matter is decomposed by microorganisms in the absence of oxygen, producing methane, carbon dioxide and other gases. This process occurs naturally in many anoxic environments.

3.4.2 Deep litter

Deep litter MMS have the following GHG emission sources:

- Emissions from the litter surface within the shed.
- Emissions from stockpiles.
- Indirect emissions from ammonia volatilisation.

GHG sources and emissions from deep litter piggeries are shown in Figure 9.

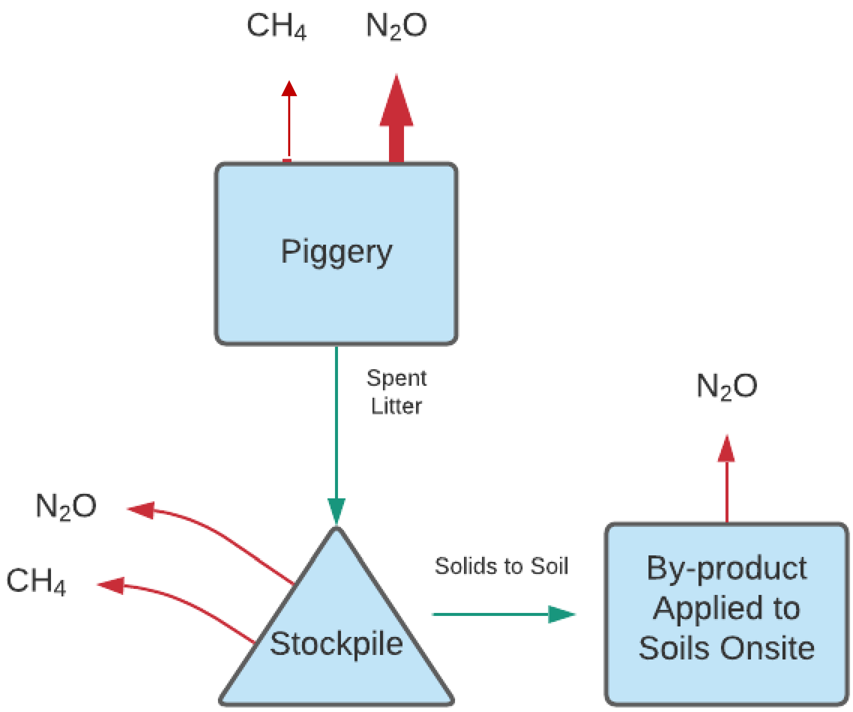


Figure 9. Deep litter piggeries - mass flow method of estimating manure management emissions (adapted from Commonwealth of Australia, 2021)

Deep litter piggeries house pigs on litter (straw, sawdust, rice hulls or similar). The use of litter eliminates the need to use water for removing manure, because moisture from excreta and spilt water is absorbed and evaporated from the litter material, which is then removed and replaced when the batch of animals is removed. Consequently, deep litter sheds do not require effluent ponds, resulting in lower emissions. Manure is contained in a solid, predominantly aerobic form that is not conducive to significant methane production, though small amounts of methane are still generated. Once litter is removed from the shed it is typically stockpiled or composted and then used as a replacement fertiliser by being spread on cropping land or pastures. Stockpiling and composting are predominantly aerobic manure treatment systems, limiting GHG emissions. Because of the predominantly aerobic MMS, nitrous oxide is a more important emission source here.

Manure is generally stockpiled at deep litter piggeries to allow for litter to be applied at the ideal time of the year for crop production, which is typically in autumn or spring, prior to winter or summer crop planting. Stockpiling is therefore a management tool rather than an essential process, though some benefits may arise from stockpiling (reduced bulk, reduced moisture content) if the material partially composts.

Composting of spent litter is a common method of treatment and has the effect of reducing total mass. moisture, and volatile nutrients. Aerobic conditions within the composting piles generate carbon dioxide and nitrogen which can increase the GHG emissions from an operation compared with minimum stockpiling and reuse.

3.4.3 Outdoor piggeries

Outdoor piggery MMS have the following emission sources:

- Emissions from the manure deposited in paddocks.
- Indirect emissions from ammonia volatilisation.
- Indirect emissions from leaching and runoff.

Outdoor piggeries in Australia generally employ a rotational system, where the pigs are kept in small paddocks with basic housing. The paddocks are rotated with a pasture or cropping phase. During the stocked phase, the pigs are supplied with prepared feed, but can also forage. During the non-pig phase, the area grows pastures or crops that are harvested to remove the nutrients deposited from pig manure during the stocked phased. As Figure 10 shows, the manure in a rotational system is spread by the pigs directly to the soil and is the key source of GHG emissions from this production system.

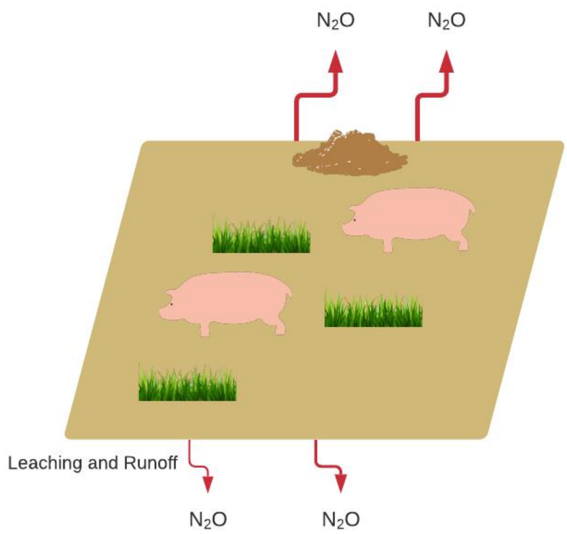


Figure 10. Outdoor piggery emission sources

3.5 Energy and Other Purchased Inputs

Of the direct energy sources required on-farm, electricity is the major energy used, followed by diesel. The Australian Pork industry is heavily reliant on reliable and affordable energy supplies. The type of piggery has an influence on direct energy requirements. For farrow to finish piggeries, 40-66% of the total energy is required for the breeder unit (McGahan, Warren and Davis, 2014). Within the breeder units, 77% of direct energy is attributed to piglet heating requirements through intensive heat lamps (Tucker & McGahan, 2015). Some piggeries also include on-site feed milling, which is another source of energy demand. Piggery housing has an impact on direct energy consumption. Indoor housing methods such as conventional sheds require climatic control to provide thermal comfort. Modern tunnel ventilation systems can achieve this, however, these can contribute to a large portion of energy demand at piggeries. Climate also has an influence on piggery energy usage. Warmer climates have a higher demand for summer cooling through evaporative cooling pads and fans, whereas energy demand in cooler climates is driven by winter heating loads. Deep litter and outdoor systems use natural ventilation and therefore electrical consumption is lower.

4. Emission Mitigation

4.1 Emission Reduction Strategies

Delivering lower emissions or carbon neutrality over time requires a plan. This section details a range of targeted emission mitigation strategies, primarily aimed at the two main GHG sources in piggery production: feed and manure management (Figure 11). Each emission mitigation strategy is applied to the relevant benchmark cases to demonstrate the total emission reduction that could be expected.

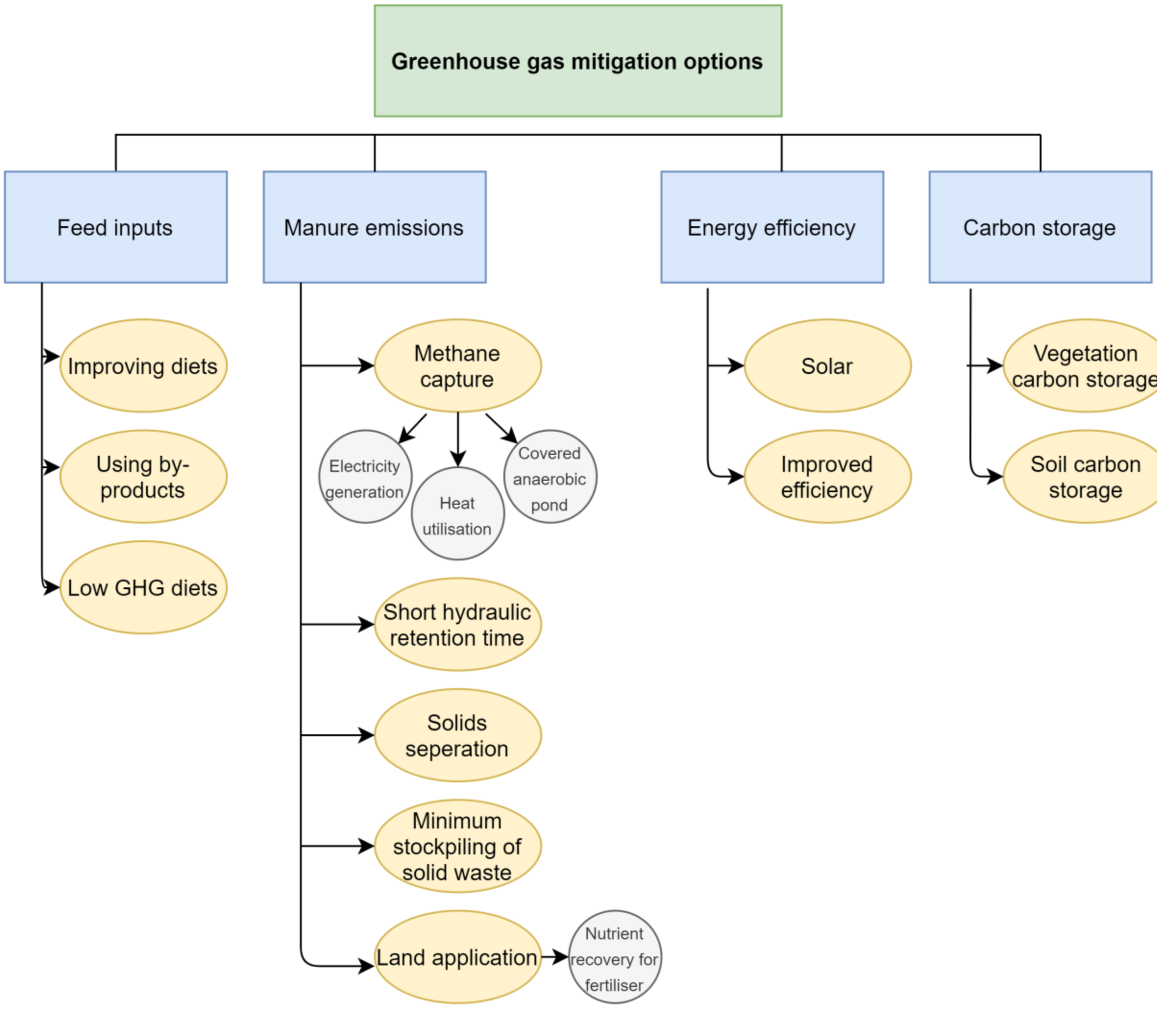


Figure 11. Greenhouse gas emission mitigation options for Australian piggeries

4.2 Production Efficiency

For business carbon accounting (Scope 1 and 2 sources only) it is not possible to develop meaningful emission intensity benchmarks, because different piggery configurations will substantially alter the basis for comparison, in much the same way as FCR differs between farrow to finish and grower-finisher piggeries. Until separate benchmarks have been established that account for different piggery configurations (for example, reporting emissions relative to LWG in grower / finisher piggeries) the only suitable benchmark is to use Scope 1, 2, upstream Scope 3 emissions and emissions to the point of delivery to meat processing are reported in kg CO_2-e per kg of LW sold to account for the emissions across the full life of the animal (i.e. the full carbon footprint).

Efficiency may be improved by reducing FCR via improved growth rates, improved breeding rates or lower feed waste, contributing to a lower emissions intensity.

4.2.1 Minimising feed wastage and improving feed conversion ratios

FCR is a key indicator that influences many aspects of environmental management, including feed requirements (and therefore environmental impacts associated with feed requirements) and manure emissions. Increases in pig productivity have been demonstrated to significantly reduce GHG emissions. Wiedemann et al. (2018) showed that production efficiency, and specifically whole herd FCR, explained 88% of the variation in GHG emissions from conventional Australian piggeries because of the dual impact on feed requirements and upstream impacts, and manure production, leading to lower MMS emissions. Improvements may be achieved at some piggeries via management practices that reduce FCR, provided other factors such as diet composition, shed type or shed energy inputs are not affected.

Calculation of FCR will usually incorporate the amount of feed wasted by pigs. Wasted feed will either drop on the slats/flooring and be flushed through the effluent treatment system with the manure, remain in the litter of deep litter sheds or remain on the range area for outdoor production. McGahan et al. (2010) showed that a 5% variation from the standard 10% allowance for feed wastage can result in ± 30% variations in the effluent VS for an average-sized grower pig (25 – 40 kg LW). Because VS loading is the primary determinant of methane generation from effluent treatment, a reduction in feed wastage will lead to lower GHG emissions. However, it should be noted, that if a piggery has the capacity to cover its ponds, then the importance of feed wastage on GHG emissions is diminished, as the methane is captured. Nevertheless, lower feed wastage improves overall system efficiency, reduces costs and embedded emissions in feed production, milling and transport.

A 25% improvement in whole herd FCR for a 1000 sow farrow to finish conventional system, via achievable reductions in feed wastage and production improvement, can decrease GHG emissions (

Table 3 and Table 4). For a conventional piggery operation (

Table 3) the expected reduction in emission intensity is 25%, while for a conventional breeder/deep litter grower operation (Table 4) the expected reduction in emission intensity is 22%.

Table 3. Comparison of greenhouse gas emissions (GHG) from a conventional piggery operation with and without improved feed conversion ratio (FCR)

Emission Source	Conventional GHG emissions intensity (kg CO_2-e/kg LW)	Low FCR - GHG emissions intensity (kg CO_2-e/kg LW)	% Reduction
Scope 1			
Piggery Enteric methane	0.175	0.136	23%
Piggery Manure methane	3.850	2.774	28%
Piggery Manure Direct nitrous oxide	0.000	0.000	
Piggery services	0.030	0.030	0%
Feedmilling & Feed production	0.048	0.036	24%
Scope 2			
Piggery services	0.163	0.163	0%
Feedmilling & Feed production	0.054	0.041	24%
Business GHG emissions intensity - Scope 1 & 2	**4.32**	**3.18**	26%
Scope 3			
Manure Indirect nitrous oxide	0.032	0.022	32%
Piggery services	0.020	0.020	0%
Feedmilling & Feed production	0.848	0.661	22%
Transport	0.027	0.023	15%
GHG Emissions - Scope 3	**0.93**	**0.73**	22%
LU and dLUC Emissions	0.063	0.058	9%
Carbon footprint GHG emissions intensity - Scope 1, 2 & 3	**5.31**	**3.96**	25%

Note: improved FCR achieved through better herd management, diet formulation and reduced feed waste.

Because FCR is such an important production and environmental indicator, special care is needed to calculate and report this. Recording errors can lead to a substantial miscalculation: for example, a 5% error in recorded inventory on-hand translates to a 5.3% inherent error in calculated FCR. It is recommended to implement a data management plan to provide transparency and accuracy when calculating the carbon account. The Australian Pork Industry Quality Assurance Program (APIQ, 2021) recommends the on-farm Piggery Management Manual should include a system for document control of pig movements and transport. However, these standards only refer to movements where ownership changes or pigs are moved to a different Property Identification Code (PIC). Improved inventory management systems which record internal stock movements can reduce error associated with inventory on-hand and calculated FCR, which translates to improving the accuracy of the carbon account.

Table 4. Comparison of greenhouse gas emissions (GHG) from a conventional breeder/deep litter grower piggery operation with and without improved feed conversion ratio (FCR)

Emission Source	Conventional Breeder/ Deep Litter Grower - GHG emissions intensity (kg CO_2-e/kg LW)	Low FCR - GHG emissions intensity (kg CO_2-e/kg LW)	% Reduction
Scope 1			
Piggery Enteric methane	0.175	0.135	23%
Piggery Manure methane	1.054	0.857	19%
Piggery Manure Direct nitrous oxide	0.280	0.188	
Piggery services	0.012	0.012	0%
Feedmilling & Feed production	0.048	0.027	43%
Scope 2			
Piggery services	0.136	0.136	0%
Feedmilling & Feed production	0.054	0.000	100%
Business GHG emissions intensity - Scope 1 & 2	1.76	1.36	23%
Scope 3			
Manure Indirect nitrous oxide	0.026	0.018	31%
Piggery services	0.016	0.016	0%
Feedmilling & Feed production	0.848	0.653	23%
Transport	0.027	0.022	15%
GHG Emissions - Scope 3	0.92	0.71	23%
LU and dLUC Emissions	0.063	0.058	9%
Carbon footprint GHG emissions intensity - Scope 1, 2 & 3	2.74	2.12	22%

4.3 Reducing GHG Emissions Associated with Ingredients and Feed Production

4.3.1 Optimising the diet to improve the manure management system

Commercial pig diets are formulated to meet the physiological status of the breeding or growing animal. Termed phase feeding, these feeding systems adjust dietary energy and protein content to the requirements of each stage of production. With adequate dietary protein and amino acids supplied according to physiological state, nitrogen excretion is minimised which is an effective strategy for reducing GHG emissions. Diet digestibility and pig nutrient utilisation also influences the excretion of nitrogen and volatile solids. Digestibility can be improved through strategies such as changes to diet composition, optimisation of diet particle sizes, use of pelleted diets (Chassé, Guay and Létourneau-Montminy, 2020) and use of enzymes (Park *et al.*, 2020). Improved digestibility contributes to the higher growth rates and improved feed efficiency (lower FCR) in herds and leads to lower manure excretion rates and subsequent lower GHG emissions from the MMS. In deep litter and outdoor piggeries where nitrous oxide is the main emission source, reducing dietary nitrogen to reduce excretion is also a useful option to reduce GHG emissions.

4.3.2 Using by-products and waste products as feed

Lowering the GHG emissions via the diet can be achieved by replacing high GHG intensity feed inputs with lower GHG intensity alternatives. There are four categories of feed products, based on the production system they are sourced from, to differentiate the level of associated environmental burdens:

1. Primary products (wheat, barley, sorghum).
2. Co-products (canola meal, soybean meal).
3. By-products (meat meal, tallow, whey, yeast products).
4. Residuals or waste products from food manufacturing.

Primary products are single products produced for the purpose of feed production. Co-products are generated from a production system where multiple products are produced from a system. These are high value products in their own right. Both primary products and co-products are attributed a proportion of the 'environmental burden' of the production system where they originated.

Some feed sources arise from low value by-products from other production systems. For example, meat-meal is a rendered product from bone and meat waste from meat processing. In this case, no environmental burden is allocated from the original production system, but processing required (i.e. rendering) is attributed to the product.

Residuals and wastes are products that have a negligible value and demand is low. Recovering residuals or waste sources from the human food manufacturing industry can also allow piggery owners to save money, as often by-products provide a less expensive source of nutrients than traditional feeds. Where transport is paid by the piggery to bring the product to the site, the impacts of transport are attributed to pork production. If the product is transported to the piggery free-of-charge, there is no need to attribute transport to pig feed, as this is part of the waste management from the originating system.

For a conventional operation (Table 5) the expected reduction in emission intensity for replacing a standard wheat/barley diet with approximately 35% by-products and waste products (carbohydrates, dairy and fish waste) is 10%. This reduction, however, is dependent on the digestibility and protein content of the by-products. Lower digestibility ingredients and ingredients with excessive protein will increase VS and nitrogen excretion rates and lead to higher MMS emissions.

Table 5. Comparison of greenhouse gas (GHG) emissions from a conventional piggery operation replacing a standard wheat/barley diet with 35% by-products and waste products

Emission Source	Conventional - GHG emissions intensity (kg CO_2-e/kg LW)	Low FCR - GHG emissions intensity (kg CO_2-e/kg LW)	% Reduction
Scope 1			
Piggery Enteric methane	0.175	0.176	0%
Piggery Manure methane	3.850	3.421	11%
Piggery Manure Direct nitrous oxide	0.000	0.000	
Piggery services	0.030	0.030	0%
Feedmilling & Feed production	0.048	0.048	0%
Scope 2			
Piggery services	0.163	0.163	0%
Feedmilling & Feed production	0.054	0.054	0%
Business GHG emissions intensity - Scope 1 & 2	4.32	3.89	10%
Scope 3			
Manure Indirect nitrous oxide	0.032	0.029	11%
Piggery services	0.020	0.020	0%
Feedmilling & Feed production	0.848	0.783	8%
Transport	0.027	0.020	23%
GHG Emissions - Scope 3	0.93	0.85	8%
LU and dLUC Emissions	0.063	0.057	10%
Carbon footprint GHG emissions intensity - Scope 1, 2 & 3	5.31	4.80	10%

Under current laws, swill (food that has been offered for human consumption) are not allowed to be fed to pigs. Waste meat products are not allowed to be fed to pigs unless they are rendered.

There are more opportunities to produce environmentally friendly feed products for pigs. For example, Japan converts around 50% of its food waste to livestock feed in licensed treatment plants to produce a product marketed as "Ecofeed" for piggeries. The Japan Food Ecology Center converts around 40 t/day of food waste into liquid feed.

Another approach to feed formulation is to consider availability, cost and the environmental burden of all ingredients, to formulate a cost-effective diet with lower GHG intensity. In France, environmentally-friendly feed formulation was used to develop diets for the growing and finishing phase by Quelen et al. (2021). Diets were formulated by considering both feed cost and environmental impacts represented by reducing cereals and oil meals and balancing with protein-rich crops and co-products. The use of the 'Eco-diet' reduced the total emissions at the farm gate by 10.6% compared to standard grower and finisher phase diets. There was no impact on growth performance, carcass and yield, lean meat percentage or carcass weight. Emission intensities of some commonly used ingredients in Australian pig diets are given in Table 6. Emission intensity for cereal grains varies between source regions. For example, barley sourced from southern regions of Australia has a lower emission intensity compared to barley sourced from central regions influenced by irrigation, fertiliser use, tillage, yield, and transport. Mitigation strategies for reducing GHG emissions through diet formulation needs to consider the source region, raw material availability, cost, amino acid balance, digestibility, and the emission intensity.

Table 6. Emission intensities, emissions from land use change and annual supply of typically used ingredients in diets

Ingredient	Emission intensity ($kg\ CO_2$-e/t)*	Emissions from direct Land Use Change ($kg\ CO_2$-e/t)	Typical annual supply for a 1000 sow farrow to finish conventional piggery (t)
Barley[1]	229-341	-	1100
Wheat[1]	156-252	-	5300
Canola meal	284	-	520
Soybean meal (sourced from Argentina)	633	2454	60
Blood meal	1900	-	100
Meat and bone meal	386	-	186
L-Lysine HCL	3450	-	26
Vitamin/mineral premix	1345	-	16

* (Ecoinvent, 2018)

[1]Emission intensity varies between source region.

4.3.3 Replacing high greenhouse gas intensity ingredients with lower intensity alternatives

Soybean meal imported from Brazil or Argentina is a high emission feed source because of dLUC emissions. Soybean meal content in Australian pig feed typically ranges from 2 – 9.5% depending on region, the class of pigs fed, and producer preferences. From a production perspective, the amino acid profile and digestibility of soybean meal makes it preferable to alternative protein sources (e.g. canola meal, cottonseed meal, peanut meal and sunflower meal) but high performance diets can none-the-less be developed with minimal soybean meal.

For the purpose of this roadmap, a low GHG diet is the conversion from a relatively high imported soybean meal content diet (~ 9%) to a reduced soybean meal diet. The soybean meal content in the low GHG diet is substituted for alternative protein sources. Reductions is total GHG emissions of up to 24% can be achieved through this change in feed composition. Care is needed when changing diet profiles to ensure that a reduction in impacts associated with changing a particular feed ingredient doesn't correspond to poorer FCR and higher manure emissions, which would counter the reduction in emission reduction achieved.

Alternative protein products can be used as a substitute for soybean meal content, which will result in a reduction in the LU and dLUC emissions. If alternatives are used, diets may require the use of synthetic lysine to balance the amino acid profile. Chemical synthesis of amino acids removes emissions associated with resource use, LU, feed, water and energy for cultivation of crops or meat meal sources. Manufactured synthetic amino acids have a high emissions intensity due to high energy use during production, but this is usually less than the reduction in emissions achieved by using less soybean products. The carbon footprint for manufactured lysine has been estimated to be 6.1 - 8.0t CO_2-e/t, varying according to source region (e.g. Germany, Denmark or France) (Marinussen and Kool, 2010).

4.3.4 New feed alternatives to reduce the use of high GHG ingredients: Algae and Black Soldier Fly Larvae

Feeding pigs alternative nutrient sources such as algae introduces the possibility of reducing GHG emissions associated with feed production. Cultivation systems suitable for algae derived feeds and fuel are called “high-rate ponds”, which are shallow, raceway type systems, with minimal mixing required. Some of the advantages that algae feeds have over conventional livestock feeds are the use of land unsuitable for food crops; reuse and recovery of waste nutrients; use of brackish or saline waters. A study commissioned by the Pork CRC determined that the inclusion of algal meal as a replacement for canola meal did not cause any significant reduction of pig performance if correctly formulated into the diet (Henman, 2012). However, despite the many positive reviews of algae as an alternative low GHG feed, Grant & Batten (2013) showed that the net GHG reduction was equivalent to just 0.01 kg CO_2-e/kg LW, after increased energy demand for manufacturing the algae was taken into account.

There are new technologies which look at alternate pathways to convert food waste into animal feed. The black soldier fly larvae (BSFL) can recover residual nutrients in manure and be used as a source of protein in livestock diets. The BSFL containing around 40% protein, can then be used in pig diets in place of high-protein feeds such as soybean and fish meal. Studies show an improved performance when added into the diets of grower pigs at an inclusion rate of 0.3 - 0.9% (Nekrasov *et al.*, 2018). There will be additional factors that need to be considered with BSFL, such as animal health and biosecurity implications. If these systems are developed in the future, protocols will need to be developed to reduce risks.

Whilst there is potential for reducing GHG emissions associated with feed production using new feed alternatives, the practicality remains largely unknown. There is a need for adequate research and development into nutrient sources such as algae and the BSFL which considers the viability of sourcing the required quantity for pig diets.

4.4 Manure Management System Emissions

Emissions associated with manure management is a key contributor to GHG emissions for all production systems. Significant research and investment over the last several decades have developed a range of viable methods for avoiding manure emissions or improving the utilisation of the resources (both methane and nitrogen) that are contained within livestock waste streams.

4.4.1 Methane capture

The use of methane capture systems to utilise biogas is a common practice in most parts of the world. Systems can range from simple covered pond designs, to advanced, in-ground or above ground digesters. The process for all systems works by capturing the biogas generated from the anerobic digestion of effluent which can be burnt to generate electricity and/or heat. An additional benefit from biogas capture systems is potential odour reduction.

Covered anaerobic ponds are designed in much the same way as uncovered anaerobic ponds, however a high-quality geo-membrane cover is used to capture the methane gas that is produced. Pre-treatment (solids separation) of the effluent stream is optional. Covered ponds are designed with a hydraulic retention time (HRT) of 40-50 days (less than uncovered anaerobic ponds) and a variable sludge accumulation period between 6 months and several years.

Engineered digestors are custom built inground ponds or above ground tanks that typically have heating and mixing to assist in maximising the biogas generation. Conditions within the digestor are managed to maximise biogas production.

The yield of biogas and the resulting methane composition produced from a covered anaerobic pond or digester is highly dependent on various factors such as the concentration of volatile solids, methane potential of feedstock (B_o), design of anaerobic system, inoculum, nature of substrate, pH, temperature, loading rate, HRT, carbon to nitrogen ratio, volatile fatty acids content, and other trace gases, which all influence the biogas production (Dhevagi, Ramasamy and Oblisami, 1992). Research has shown that the methane potential does vary depending on class of pig with effluent from finisher, grower and weaner degrading to a greater extent, and having almost twice the methane potential as that from dry sow and farrowing sheds (Gopalan et al, 2013). This factor needs to be considered when determining the viability of a methane capture system.

A number of options exist following the capture of biogas, with each described below.

- **Electricity Generation:** The methane gas captured in the covered anerobic pond can be combusted in a generator to produce electricity. The power generation units which are suitable for use in the Australian piggery industry are spark-type gas engines and micro-turbines (Murphy, McGahan and Wiedemann, 2012). Methane can be converted to electricity onsite using these engines, which operate with efficiencies of 25-40%.
- **Heat Utilisation:** Methane can be used in a boiler to produce heat and hot water for the piggery. A typical boiler has an efficiency of about 90%. The heat produced can be used to offset the annual gas usage of the site leading to reductions in the energy expenditure of the piggery. Because of the large volumes of gas, heat generation may be well beyond the requirements of the piggery.
- **Combined Heat and Power (CHP):** CHP generation is another energy recovery option. A variety of reciprocating engines can be used, including spark ignition and compression ignition engines. Methane is burnt in a reciprocating gas engine to drive an alternator to produce electrical energy. Simultaneously the heat energy exhausted by the engine and the coolant system is recovered, usually in the form of hot water (80 – 90°C). The conversion of methane gas into electrical energy is approximately 25-40%; while an additional 45-55% can be recovered as heat energy.

Table 7 provides the expected reduction in GHG emissions from including a covered anerobic pond (or anaerobic digestor) and CHP to a conventional farrow to finish piggery operation. It is assumed the power generated offsets 100% of the Scope 2 electricity requirements. The expected reduction in overall emission intensity is 53%.

Table 7. Comparison of greenhouse gas (GHG) emissions from a conventional piggery operation with and without anaerobic digestion and CHP energy recovery

Emission Source	Conventional - GHG emissions intensity (kg CO_2-e/kg LW)	Low FCR - GHG emissions intensity (kg CO_2-e/kg LW)	% Reduction
Scope 1			
Piggery Enteric methane	0.175	0.175	0%
Piggery Manure methane	3.850	1.283	67%
Piggery Manure Direct nitrous oxide	0.000	0.000	
Piggery services	0.030	0.026	12%
Feedmilling & Feed production	0.048	0.036	25%
Scope 2			
Piggery services	0.163	0.000	100%
Feedmilling & Feed production	0.054	0.000	100%
Business GHG emissions intensity - Scope 1 & 2	4.32	1.52	65%
Scope 3			
Manure Indirect nitrous oxide	0.032	0.032	0%
Piggery services	0.020	0.001	93%
Feedmilling & Feed production	0.848	0.841	1%
Transport	0.027	0.027	0%
GHG Emissions - Scope 3	0.93	0.90	3%
LU and dLUC Emissions	0.063	0.063	0%
Carbon footprint GHG emissions intensity - Scope 1, 2 & 3	5.31	2.48	53%

4.4.2 Short hydraulic retention time tanks

Short HRT ponds/tanks are an alternative manure management method for conventional piggery systems. Short HRT systems consist of a pond, or tank, sized and designed to retain liquid effluent onsite for less than 30 days. This short HRT reduces methane generation by decreasing the opportunity for the development of anaerobic conditions created by the traditional long HRT (often >100 days) ponds. Short HRT systems need to be operated with a batch system rather than continuous flow, so that anaerobic conditions are not established. Provided they are operated this way, methane emissions will be very low (McGahan *et al.*, 2016).

Short HRT systems can be combined or operated in tandem with solids separation systems, to improve the characteristics of effluent for irrigation. If a short HRT system is constructed as a sediment basin, solids removal can be facilitated by removing the supernatant and solids separately (the latter being the heavier and more dense particles that have settled by gravity or lighter material that floats). This type of approach utilises gravity to separate approximately 60-70% of the VS (Kruger, Taylor and Ferrier, 1995), including 20% of the nitrogen (N) and 40% of the phosphorus (P), and this can be increased with the addition of lime or coagulants to as much as 80% of VS, 30-35% of N and 70-90% of P.

The main advantages of short HRT systems compared to methane capture (covered ponds or engineered systems) are the lower construction and operation costs, and increased suitability for small to medium sized operations. Table 8 demonstrates a short HRT can reduce GHG emissions by 53% compared with the benchmark conventional piggery operation. This is a similar reduction to that achieved though the introduction of a covered anerobic pond. Modelling of the short HRT scenario assumed that 75% of effluent was directed to the short HRT system, while the remainder was treated though a conventional system pond system. This scenario is reflective of typical on-farm operational conditions where the year-round usage of effluent may not be viable, generally due to periods of wet weather limiting opportunities for irrigation. On conventional farms, it is common practice for effluent exiting anaerobic ponds or digestors to then enter secondary ponds. Secondary ponds provide some treatment, and additional storage time to allow for flexibility in the timing of irrigation. Short HRT systems in secondary ponds will have a positive effect on the overall GHG emissions from a system and could potentially be part of an overall GHG reduction strategy to minimise emissions.

It should be noted that there are some challenges with effectively operating a short HRT system. Enough storage needs to be maintained to ensure periods of wet weather can be managed to avoid irrigating when conditions are not favourable for best-practice nutrient management. Solid separation is needed to avoid applying high levels of nutrients, and specialist irrigation equipment may be needed to handle higher levels of organic matter in the effluent. Odour also needs to be monitored to ensure high-odour conditions are not created. These systems would be more suitable for smaller piggeries in lower-rainfall regions with good management.

Table 8. Comparison of greenhouse gas (GHG) emissions from a conventional and 75% short hydraulic retention time pond piggery operation

Emission Source	Conventional - GHG emissions intensity (kg CO_2-e/kg LW)	Low FCR - GHG emissions intensity (kg CO_2-e/kg LW)	% Reduction
Scope 1			
Piggery Enteric methane	0.175	0.175	0%
Piggery Manure methane	3.850	1.077	72%
Piggery Manure Direct nitrous oxide	0.000	0.037	
Piggery services	0.030	0.030	0%
Feedmilling & Feed production	0.048	0.048	0%
Scope 2			
Piggery services	0.163	0.163	0%
Feedmilling & Feed production	0.054	0.054	0%
Business GHG emissions intensity - Scope 1 & 2	**4.32**	**1.58**	63%
Scope 3			
Manure Indirect nitrous oxide	0.032	0.021	34%
Piggery services	0.020	0.020	0%
Feedmilling & Feed production	0.848	0.848	0%
Transport	0.027	0.027	0%
GHG Emissions - Scope 3	**0.93**	**0.92**	1%
LU and dLUC Emissions	0.063	0.063	0%
Carbon footprint GHG emissions intensity - Scope 1, 2 & 3	5.31	2.48	53%

4.4.3 *Solids separation*

Solid separation removes a portion of the TS contained in an effluent stream through settlement in sedimentation basins or static/mechanical screening. TS removal results in a reduction in the VS entering an anerobic pond. Different solid separation methods remove different proportions of solids, with reported values of:

- 70% VS removal using sedimentation basins.
- 37% VS removal using screw press separators.
- 25% VS removal using static rundown screens.

The reduction in VS content of the effluent entering a pond and may reduce the methane generation potential from the anerobic digestion processes. However, it should be noted that the material that is most readily removed, such as husks from barley, have lower methane potential compared to other components. This means emission reduction will generally be less than expected from the VS removal rate. Solid separator systems are relatively common and feasible to apply across conventional piggeries, as the technology is well-researched and proven. These systems may represent one of the easiest abatement opportunities for conventional piggery producers in Australia.

Although relatively easy to install, there are several technical requirements for using a solid separation system for emission abatement, including solids removal efficiency of the specific system and effluent and solid management after treatment that will impact on the total emission profile. Post treatment of effluent and solids must be managed to ensure the GHG emissions of the total system are reduced. Additionally, odour releases and reactivity of effluent and solids removed should be considered.

The inclusion of a solids separation process, such as a sedimentation basin or screen has the potential to reduce the GHG emissions.

Table 9 demonstrates a 25% reduction from the installation of a screw press separator (37% VS removal) into a conventional piggery treatment process.

Table 9. Comparison of greenhouse gas (GHG) emissions from a conventional and manure management system (MMS) with screw press solids removal piggery operation

Emission Source	Conventional - GHG emissions intensity (kg CO_2-e/kg LW)	Low FCR - GHG emissions intensity (kg CO_2-e/kg LW)	% Reduction
Scope 1			
Piggery Enteric methane	0.175	0.175	0%
Piggery Manure methane	3.850	2.463	36%
Piggery Manure Direct nitrous oxide	0.000	0.045	
Piggery services	0.030	0.030	0%
Feedmilling & Feed production	0.048	0.048	0%
Scope 2			
Piggery services	0.163	0.163	0%
Feedmilling & Feed production	0.054	0.054	0%
Business GHG emissions intensity - Scope 1 & 2	**4.32**	**2.98**	31%
Scope 3			
Manure Indirect nitrous oxide	0.032	0.026	20%
Piggery services	0.020	0.020	0%
Feedmilling & Feed production	0.848	0.848	0%
Transport	0.027	0.027	0%
GHG Emissions - Scope 3	**0.93**	**0.92**	1%
LU and dLUC Emissions	0.063	0.063	0%
Carbon footprint GHG emissions intensity - Scope 1, 2 & 3	**5.31**	**3.96**	25%

4.4.4 Minimum stockpiling of solid waste

Common practice for handling solid manure in the pig industry is to stockpile this material prior to land application or sale. Stockpiling allows enough material to accumulate to warrant land application or sale. However, stockpiling manure results in nitrous oxide emissions that may be mitigated by alternative management. Options to minimise GHG emissions from a stockpile is:

- **Avoid Stockpiling** – Spread immediately following removal from shelters, avoids stockpile emissions. The additional benefit of immediate spreading is that the nutrients in the manure are retained and can be utilised through the crops in the receiving paddocks to reduce fertiliser requirements. A disadvantage is that moisture levels are often higher, resulting in higher mass of the product being transported.
- **Litter off-farm** – If litter is immediately removed from the farm, for reuse by a third party, this reduces the total emissions at the piggery by avoiding the emissions from stockpiles. The use of manure on land then becomes part of the upstream emissions for the cropping enterprise and not considered within the system boundary for the piggery.
- **Covering Manure Piles** – The covering of manure piles can significantly reduce the nitrous oxide emissions (Naylor *et al.*, 2016). Covering can be undertaken with any impermeable material for example tarpaulins which are placed over the piles immediately following removal from shelters.

For a conventional breeder and deep litter grower operation, the contribution to the carbon footprint from both methane and nitrous oxide emissions from stockpiles is typically about 12% of Scope 1 and 2 emissions, and 8% of the total emissions. If a producer converts to a no stockpile or litter off farm system, it is expected that the total GHG emissions savings would be 8% of the total carbon footprint. While covering manure piles does not completely eliminate stockpile emissions, this may provide a practical alternative to reducing emissions while allowing some flexibility in the timing of spreading.

Composting of spent litter is a common method of treatment and has the effect of reducing total mass. moisture, and volatile nutrients. Aerobic conditions within the composting piles generate carbon dioxide and nitrogen which can increase the GHG emissions from an operation compared with minimum stockpiling and reuse. It is recommended that deep litter be managed through avoiding stockpiling, reuse off farm or covering of stockpiles.

4.4.5 Land application and fertiliser replacement

Manure, spent bedding and sludge from piggery production are a valuable resource, and are typically utilised through the application to agricultural land. Nutrients (nitrogen, phosphorus and potassium) as well as organic carbon contained within the material can be beneficial to soil health and the cultivation of commercial crops. The application of manure has the effect of reducing the demand for manufactured fertilisers in the cropping production cycle.

The production of fertiliser requires a significant amount of energy, resulting in high GHG emissions. Using manure will have the effect of reducing or avoiding the requirement for manufactured fertiliser products and their associated GHG emissions.

4.4.6 Other manure management options

Alternative manure management options that have showed potentially viable reductions in GHG emission are included below.

- **Biomethane production.**

Biomethane is produced from biogas by removing the carbon dioxide and any other contaminants to produce a high quality renewable methane gas and carbon dioxide. Options exist for piggeries with a methane capture system and excess biogas to either sell the biogas to a commercial processer to produce biomethane and bio-carbon dioxide, or to process onsite to produce biomethane. The sale of sale of biogas or biomethane would reduce the GHG emission from an anaerobic pond to a similar level as biogas reuse on site through a generator or CHP. Evaluation of biomethane production for large piggery operation by Tait et. al. (2020) indicate that the commercial value of biogas may make this a viable option for large scale producers.

- **Acidification of Effluent**

Acidification of effluent is based on the principle of reducing the pH of the effluent exiting the piggery to inhibit the growth of microbes and the production of GHG emissions from the anaerobic pond, including methane, nitrous oxide and ammonia, which are all influenced by effluent pH. Acidifying the effluent to less than pH 4.5 will achieve the maximum GHG emissions abatement, but this pH range may be impractical due to the cost of artificial acidification and the high mineral content of effluent after treatment. There is little experience in acidifying effluent in Australia and it may not be practical. There are also questions over the suitability of acidic effluent for land application.

4.5 Changing housing type

GHG emissions from conventional production are dominated by methane production from methane released from anaerobic ponds. Changes to production type has the potential to significantly impact on the GHG emission from an operation, and across the industry.

Changes to whole-system management by using alternative housing such as deep litter and litter stockpiling results in predominantly aerobic manure treatment, resulting in lower emission factors for methane, than with uncovered anaerobic ponds. An Australian study observed a 66% and 80% decrease in emissions from the manure excreted in litter-based housing with and without litter stockpiling respectively, compared with conventional housing with an uncovered anaerobic effluent-treatment pond (Phillips *et al.*, 2016).

While a transition from a conventional piggery operation to a deep litter system isn't practical in many cases, the significant GHG abatement for production based on this system may be an important consideration when establishing a new piggery operation, refurbishing an older piggery or planning an increase in production at an existing farm.

4.6 Energy Efficiency

Energy efficiency measures are also a viable option for reducing on-farm energy demand. To determine energy savings, pork producers must first monitor and benchmark their energy usage. Some energy reduction strategies include:

- Heat recovery from air ventilation to heat the piggery, reducing other supplementary heating demand (e.g., LPG).
- Ventilation rate changes with changing circumstances (pig weight, humidity, temperature). Control of the ventilation rate should work according to the micro-climate of the building.
- Energy-efficient lights and fans.
- Alternatives to heat lamps.
- Regular maintenance of tunnel ventilation systems, such as cleaning fan blades and shutters to maintain efficiency.
- Use of variable speed drive fans and hybrid ventilation where appropriate.

For example, if a small-medium deep litter piggery (with breeding in conventional sheds) was to convert from 100% grid electricity use to 100% solar energy the total GHG emissions for the enterprise could be reduced by up to 5%.

4.7 Mitigation Potential Summary

Different mitigation strategies are suitable for the three main production systems in Australia. Table 10 provides a summary and qualitative assessment of the GHG mitigation strategies applicable for each production type, including details in the total mitigation potential, commercial opportunities and applicability to different scales of operations.

Table 10. Qualitative assessment of greenhouse gas (GHG) mitigation strategies for Australian piggery operations

Mitigation Strategy	Mitigation Potential[1]	Capital Cost	Operating Cost	Ease of Applying Commercially	Applicable to Small and Medium Sized Operations[2]	Applicable to Large Sized Operations[2]
Conventional						
Improved FCR	Medium	Low	Low	High	Yes	Yes
Use of By-Products and Co-products as Feed	Low	Low	Medium	Medium	Yes	Yes
Low GHG Diet	Medium	Low	Medium	Yes	Yes	Yes
Covered Pond	Very High	High	Medium	Low	No	Yes
Short HRT	High	Medium	Medium	Medium	Yes	No
Solids Separation – screw press	Medium	Medium	Medium	High	Yes	Yes
Deep Litter						
Improved FCR	Medium	Low	Low	High	Yes	Yes
Low GHG Diet	Low	Low	Medium	Yes	Yes	Yes
Use of By-Products and Co-products as Feed	Medium	Low	Medium	Medium	Yes	Yes
Minimum Stockpile of	Low	Low	Medium	Medium	Yes	Yes
Covered Stockpiles	Low	Medium	Medium	Medium	Yes	No
Outdoor						
Improved FCR	Medium	Low	Low	High	Yes	Yes
Low GHG Diet	Medium	Low	Medium	Yes	Yes	Yes

[1] Very High = ≥ 50% mitigating effect; High = 50 to 30 percent mitigating effect; Medium = 10 to 30 percent mitigating effect; Low = ≤ 10 percent mitigating effect. [2] Small/Medium operation classified as less than – 1000 sow farrow to finish (approx. 11,000 SPU)

5. Carbon Storage

The storage of carbon, also known as carbon sequestration, is the process of removing carbon from the atmosphere and depositing it in a reservoir. The two key reservoirs that provide opportunities for the sequestration of carbon for a piggery operation are vegetation and soils. The following sections detail the main principles behind carbon sequestration and how they may play an important role in the carbon accounts for a piggery operation.

5.1 Vegetation Carbon

Trees can sequester large amounts of carbon dioxide from the atmosphere, which can reduce net emissions (Ramachandran Nair *et al.*, 2010; Doran-Browne *et al.*, 2016). The amount of carbon that can be stored in vegetation is largely dependent on:

- The availability of suitable land that can be dedicated to tree planting.
- Rainfall.
- Soil fertility.
- Tree species planted.

Tree planting projects usually consist of environmental tree plantings, which are a mixture of species suited to the region, or monoculture tree plantings of a single species. Environmental plantings are primarily aimed at improving environmental benefits through increased biodiversity, such as restoring habitat for native wildlife while also generating carbon credits. Monoculture plantings are typically fast-growing trees that are aimed solely at storing carbon and are less beneficial for improving biodiversity. The biodiversity and carbon benefit (carbon credits) of the two types of planting is shown graphically in Figure 12.

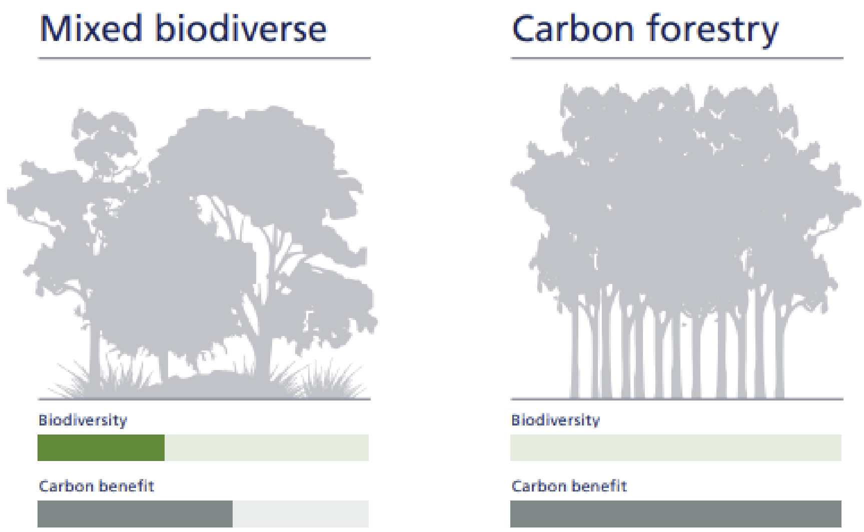


Figure 12. Graphical representation of biodiversity and carbon credit benefits of environmental and monoculture tree planting projects. (Government of South Australia, 2017)

Carbon sequestration through tree planting is a long-term strategy as it requires several years of establishment to receive carbon benefits. Other benefits of tree planting can include:

- Increased biodiversity.
- Erosion and salinity control.
- The provision of shelter for other livestock at the site.

The age of the tree, species, environmental conditions (soil type, rainfall) and management influences the rate of carbon sequestration. Although higher rates of carbon sequestration occur in new plantations, mature plantations will continue to sequester carbon over their lifetime at a slow rate as they reach maturity (Unwin and Kriedemann, 2000).

Two factors control total carbon storage in a tree planting: area available, and sequestration rate. Sequestration rates vary between a low of about 2.5 t CO_2-e /ha·yr and a maximum of 30 t CO_2-e /ha·yr for very high growth rate species in high rainfall regions. A mid-point level of 7-10 t CO_2-e/ha·yr is reasonable to help estimate carbon potential. Area available for tree planting is governed by the land available at the site. For many piggeries tree plantings for buffers and to line roads or fence lines is beneficial from an amenity point of view. However, this will rarely be more than 10ha. To increase this to a higher level often requires dedicated planning and reallocation of land from other purposes, and for most farms, 25-50 ha would be a large planting. Carbon storage with a 10 ha at 7.5 t CO_2-e/ha·yr will be 75 t CO_2-e/ha·yr , increasing to between 187-375 t CO_2-e/ha·yr for larger plantings. Of course, this can be increased with high growth rate species in high rainfall regions, or where irrigation can be used. Compared to the carbon account from a conventional 1000 sow farrow-finish piggery, this represents between <1-3% of emissions.

Table 11. Calculated area required for tree plantings to reduce emissions from a 1000 sow farrow to finish conventional system

Emissions reduction		Total area required (ha)
%	Total tonnes CO_2-e	Mixed environmental plantings
5	604	81
10	1209	161
25	3022	403
50	6044	806
75	9066	1209
100	12088	1612

Multiple factors need to be considered to maximise carbon sequestration in tree plantings and native regeneration. Whilst it is not possible to control long-term climate patterns, tree species, planting patterns and thinning activities should be considered by producers to help maximise carbon storage.

5.2 Soil Carbon

Soil carbon is vital to soil health, and to many physical and chemical processes that occur in soil. Higher carbon levels promote better soil structure, and can store large amounts of nutrients that are released slowly for plant growth. Improved soil structure aids infiltration and storage of water in the soil profile.

Soil carbon (C) storage results from the movement of carbon dioxide from the atmosphere into the soil via plant biomass processes (Ussiri and Lal, 2017). At any one time, the total carbon stored in soils world-wide is 24 times the amount of stored in the atmosphere and four times the amount stored in plants (Bell and Lawrence, 2009). Due to the large masses involved in soil carbon storage, small variations in soil organic carbon (SOC) can lead to large impacts on the carbon cycle.

Australian soils are generally very low in soil organic carbon with agricultural soils typically ranging from 0.4 – 4% (Tow, 2011), and carbon storage in the top 30cm is typically in the range of 25.8-67 for the main states where pigs are produced (Viscarra Rossel *et al.*, 2014). The lower rainfall regions will have carbon storage levels at the lower end of this range, and higher rainfall regions will be at the upper end of this range. Effluent utilisation areas that have long-term, established pastures may have organic carbon levels exceeding 3%, though often this will also correspond with elevated nutrient levels and under-utilisation of biomass production. Where cultivation is practiced, this is generally lower, though levels of > 2% have been recorded which is quite good for cultivated Australian cropping soils.

5.2.1 Factors that influence soil carbon sequestration

Soil carbon increase is determined by how much carbon is added to the soil and how much is retained. The factors influencing carbon inputs, losses and retention are shown in the following diagram (Figure 13) which shows a bucket with two taps. The bucket represents the potential quantity of carbon that can be stored in the soil. The top tap represents inputs into the soil, which contribute to increased carbon in soils, and the other represents losses. Carbon storage will occur if more carbon is added than lost. This process generally happens after a management change, and soil carbon will generally then change over a period of time before stabilising once more at a new level.

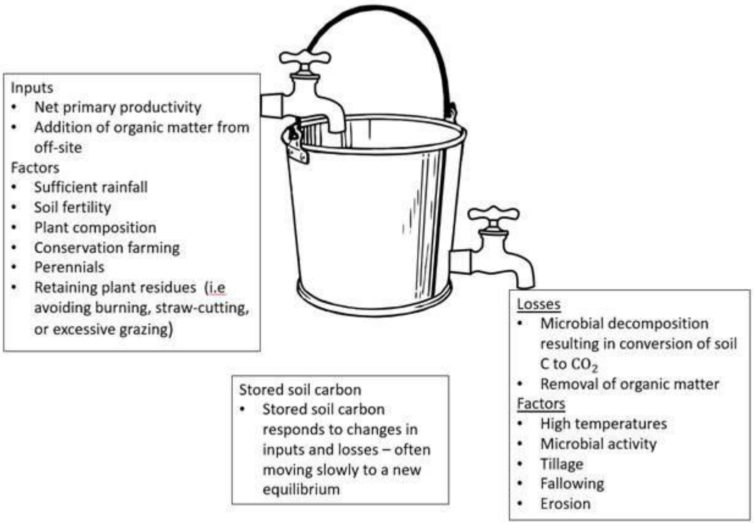


Figure 13. The storage of soil carbon determined by potential storage, inputs into the soil and losses from the soil (adapted from Liddicoat et al., 2010)

Soil type and climatic factors that influence carbon sequestration are shown in Table 12.

Table 12. Likelihood of soil carbon sequestration with differing soil type and climatic factors

Location factors – natural conditions	**Likely increase in soil organic carbon**	**Unlikely increase in soil organic carbon**
Soil type	High clay content, high soil fertility, high porosity	Low clay content, low soil fertility, low porosity
Mean annual rainfall	> 600 mm per year	<600 mm per year
Seasonal climate	Consistent rainfall, average conditions, moderate temperatures	Increased volatility, frequent extreme weather events

5.2.2 The impact of management practices on soil carbon

Figure 14. The effect of different management practices on soil carbon levels (adapted from Cotching, 2009) shows the impact different management practices have on soil carbon levels. Compost, manure and effluent application promote soil carbon storage in two ways: firstly by directly adding carbon to the soil, and secondly by increasing nutrient levels to promote plant growth, resulting in more carbon inputs.

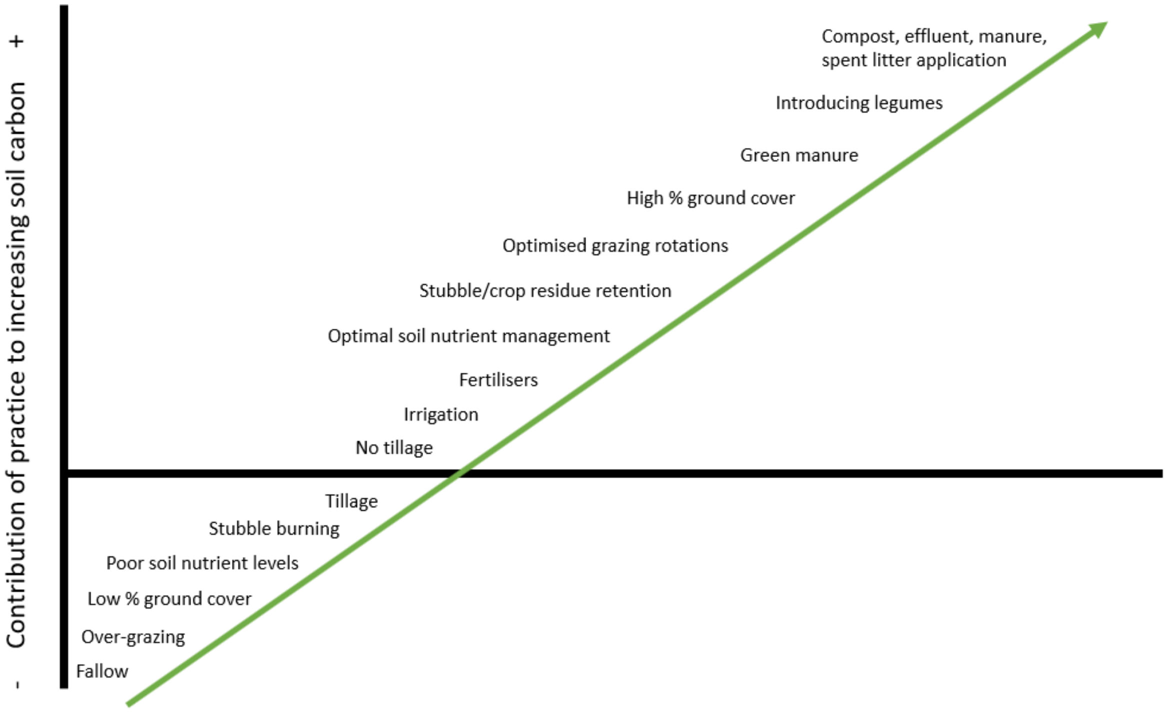


Figure 14. The effect of different management practices on soil carbon levels (adapted from Cotching, 2009)

5.2.3 Application of piggery by-products

The pig industry is in a unique position because it has manure and effluent that is available for reuse, which can promote an increase in soil carbon. However, application rates should take into account nutrient levels as well, to ensure other environmental priorities are not overlooked. At an application rate for spent litter of 10 t ha, at 70% dry matter and 28% carbon, about 2 t C would be added per ha. At the same time, about 70 kg P and 150kg N would be added per ha. While it is hard to estimate the rate of breakdown of carbon in soil, it is reasonable to assume <30% of this carbon will remain in the stable fractions of carbon in the soil. The end result is about 0.6 t C stored in the soil from this manure application.

When considering application rates of manure and effluent, the Piggery Manure and Effluent Management and Reuse Guidelines (Tucker, 2015) can assist in helping set sustainable rates.

5.2.4 Quantifying increases in soil carbon

Measuring soil carbon requires sampling (typically to 30cm depth or deeper) and taking measurements of soil bulk density. This allows the carbon stocks in the soil to be calculated. Change over time can only be measured by taking a baseline and comparing it to samples taken in later years. The biggest difficulty in measuring the change over time is getting enough representative samples to be confident a change in carbon has occurred.

For farmers interested in producing carbon credits from soil, a soil carbon method is available as part of the Emission Reduction Fund (ERF). This requires a substantial process, summarised below:

1. **Prepare** – Research and understand the benefits and obligations of the program, determine suitability of the land and prepare a land management strategy documenting practices that will impact soil carbon.
2. **Register** – Register project through the Clean Energy Regulator, and contact and approved auditor.
3. **Baseline Sampling** – Engage carbon service provider to assist with mapping and sample planning and engage soil technicians to collect soil samples to establish baseline carbon levels.
4. **Implementation** – Commence implementation of land management strategy to increase soil carbon.
5. **Reporting** – Every three to five years, soil sampling must be undertaken to quantify increases in soil carbon. These results are then be audited and submitted to the Clean Energy Regulator for verification and issue of carbon credits. This reporting continues every three to five years until the end of the 25 year crediting period.

The biggest challenge currently with producing carbon credits is the difficulty in confidently measuring very small changes in soil organic carbon over time. If measuring soil carbon change for your own purposes, it is possible to track carbon levels with a relatively small number of sample points taken at the same point each year, or every few years. However, for generating ERF carbon credits, random sampling is required, and statistically significant results need to be proven. This makes sampling costly, especially where the change in carbon over time is only modest. Generally for carbon purposes, testing soil every 3-5 years is sufficient to track change, and it will be more beneficial to sample a larger number of points, less frequently, than to sample a small number of points each year.

To learn more about generating carbon credits, see http://www.cleanenergyregulator.gov.au/ERF. GrainGrowers and Grains Research and Development Council have also both generated helpful guides about organic matter and soil carbon in cropping. For further information see "Carbon and Cropping" (Grain Growers, 2021) and Managing Soil Organic Matter: A Practical Guide (GRDC, 2013).

6. Marketing Low Carbon and Carbon Neutral Pork

Recently, significant market attention has been directed toward GHG emissions associated with food, leading retailers and brand owners to investigate verifiable carbon neutral claims for food products, and emission reduction targets to meet environmental, sustainability and governance (ESG) priorities. This commitment is occurring across supply chains, with both suppliers working towards producing low carbon or carbon neutral products and retailers committing to carbon reduction targets across their operations and supply chains.

Achieving a verifiable low carbon or carbon neutral status may provide the opportunity to differentiate products in the competitive consumer market. Market differentiation around low emission products and businesses is expected to continue and gain pace, with many new products currently undergoing carbon neutral certification.

Whilst the term low carbon does not have a regulatory definition or clear compliance standards, carbon neutral is a certifiable term through several regulatory agencies. This chapter outlines the process to deliver a certified carbon neutral product via the Australian Government's Climate Active scheme.

6.1 Becoming Carbon Neutral

The basic concept of carbon neutral is zero net release of GHG emissions into the atmosphere. Carbon neutral is achieved through reducing emissions through avoidance and mitigation and then offsetting the remainder of the emissions, either by generating carbon credits through carbon storage on the site (i.e. vegetation or soil carbon sequestration) or purchasing carbon credits available in the carbon market.

6.1.1 Climate Active certification process

Climate Active is managed by the Australian Government (DISER). Climate Active certifies businesses that have credibly reached a state of carbon neutrality by measuring, reducing and offsetting their carbon emissions. Certification is available for business operations, products and services, events, buildings and precincts. To be certified, a business must meet the requirements of the Climate Active Carbon Neutral Standard. Piggery operators can obtain a Climate Active accreditation (for a product or as an organisation) if they have achieved carbon neutrality.

The Climate Active carbon neutral certification process has seven steps (Figure 15. Steps toward carbon neutrality (Department of Industry Science Energy and Resources, 2021)), including:

1. **Identify**: register the project (product or organisation*).

2. Once registration is reviewed and approved by Climate Active, sign the **licencing agreement**. This ensures Climate Active is alongside your commitment to carbon neutrality and the obligations of achieving certification are fully realised.

3. **Measure**: prepare a carbon account (carbon footprint) for the baseline year. Climate Active provides all of the reporting templates, once a project has been approved in step two.

4. **Reduce**: develop and maintain an emissions reduction strategy. As part of Climate Active's certification, an emissions reduction strategy must be made publicly available—this is included in the Public Disclosure Statement (PDS), which is completed as part of the certification. The emissions reduction strategy must include tangible actions being implemented to reduce emissions and the timeframes in which the reductions will be undertaken.

5. **Offset**: purchase offset units to balance remaining emissions. Under the Climate Active Carbon Neutral Standard, offsets can be purchased for the baseline year (in arrears) or the first year of certification (forward purchasing).

6. **Validate**: independent validation and verification of the carbon account to ensure accuracy.

7. **Report**: public disclosure statement (PDS). Climate Active provide template guidance for the PDS, which once the certification process is completed, is published.

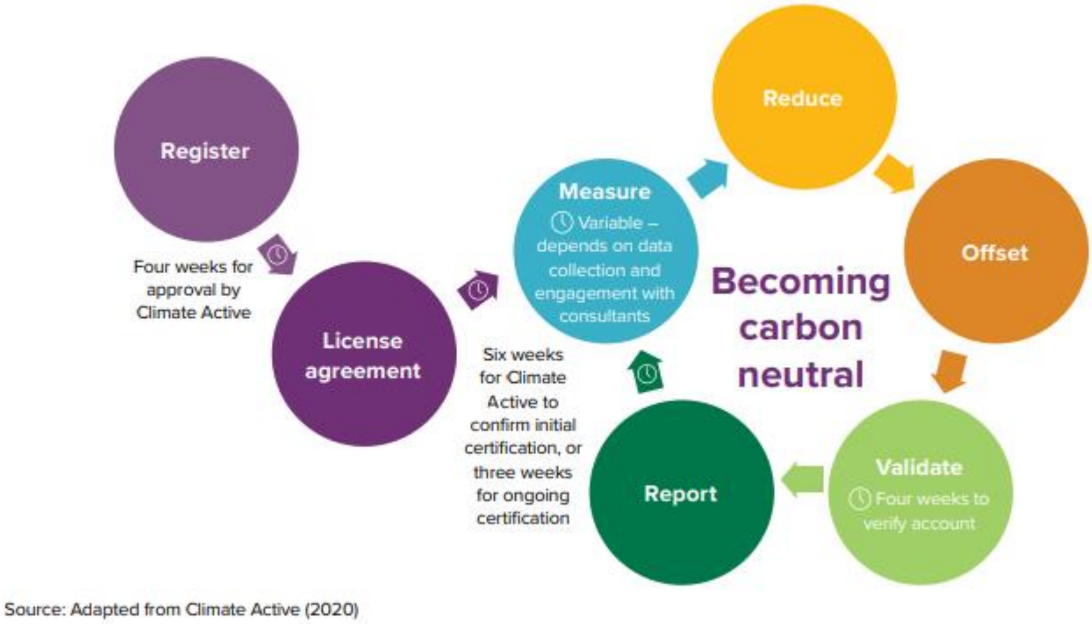


Figure 15. Steps toward carbon neutrality (Department of Industry Science Energy and Resources, 2021)

Carbon offsetting can be achieved by purchasing approved carbon credits or retiring existing carbon offset credits owned by the entity.

Note: Carbon credits generated through an ERF project on-farm and sold into the carbon market, cannot then be used to also offset emissions from the enterprise. The GHG Protocol Agricultural Guidance (Greenhouse Gas Protocol, 2014) states that if a company sells an offset that has been generated within its organisational boundaries, then the company must remove the emission reductions from its carbon account to avoid double counting and to conform to the GHG Protocol Corporate Accounting and Reporting Standard. This avoids 'double counting' of carbon credits.

There are multiple types of carbon credits that can be generated or purchased. Eligible carbon credits for the Climate Active program currently include:

- **Australian Carbon Credit Units** (ACCUs) are regulated financial products under the Carbon Credits (Carbon Farming Initiative, CFI) Act 2011 administered by the Clean Energy Regulator through the ERF.
- **Non-ACCU Offsets** allowed under the Australian Government Climate Active Carbon Neutral Standard. These credits are issued under the Kyoto Protocol or other acknowledged international systems and are approved by Climate Active. For example, Verified Emissions Reductions (VERs) issued by the Gold Standard, and Certified Emissions Reduction (CERs) issued under the Clean Development Mechanism (CDM) are both -aligned with the Kyoto Protocol.

Climate Active's certification requires independent third-party to verify the carbon footprint and offset strategies. Businesses are required to meet ongoing certification and reporting requirements (e.g. annual reporting) to use the Climate Active trademark on their products.

6.2 Other Certified Carbon Programs

Globally there are now several credible carbon neutral certification providers and providers of tradable carbon offsets. This section describes the main international certifying and carbon offset agencies:

6.2.1 Carbon Trust - PAS 2060 Carbon neutral certification

Carbon Trust is an independent certification body that provides carbon neutral accreditations aligned with international standards including PAS 2060, ISO 14067 and the GHG Protocol Product Standard. Carbon Trust are a global company that provide a product or organisation carbon neutral certification that accounts for Scope 1, Scope 2 and Scope 3 emissions. The Carbon Trust only recognises carbon credits generated through the Gold Standard, Verified Carbon Standard and Woodland Code UK for offsetting emissions. The carbon neutral certification for a product can be licenced to use the Carbon Trust's carbon neutral label on products.

6.2.2 The CarbonNeutral Protocol – Carbon neutral certification

The CarbonNeutral protocol is an independent certification body that follows a similar approach to the Australian government's Climate Active accreditation. It follows the GHG Protocol and ISO standards. It involves defining the carbon footprint and emissions boundary, measuring the GHG account based on international and national standards, creating an emissions reduction target, reducing internal emissions, and purchasing offsets to balance unavoidable emissions and providing public transparency. Participants must include at least Scope 1, Scope 2, and Scope 3 upstream emission sources. Similar to the Climate Active accreditation, the CarbonNeutral Protocol requires auditing by an independent third-party to verify the carbon account.

6.2.3 Clean Development Mechanism – Carbon offsets

Established by the United Nations in 2006, the Clean Development Mechanism allows emission-reduction projects in developing countries to earn certified emission reduction (CER) credits, each equivalent to one tonne of CO_2. These CERs can be traded and sold, and used in developed countries to assist in offsetting emissions to achieve emission reduction targets.

6.2.4 Gold Standard – Carbon offsets

Gold Standard was established in 2003 by the World Wildlife Fund and other international NGOs to ensure projects that reduced carbon emission featured a high level of environmental integrity and also contributed to sustainable development. Gold Standard has a portfolio which includes Verified Emission Reductions (VERs) from project developers who choose to donate a portion of their carbon credits to Gold Standard rather than paying the full fee for certification. Proceeds go to supporting initiatives and innovations for ongoing improvement of Gold Standard.

7. Navigating the Carbon Market

7.1 Understanding the Carbon Market

The carbon market allows producers to generate carbon credits (Australian Carbon Credit Units, or ACCUs) and trade these in the market. This is an alternative path to creating a low-carbon or carbon neutral product, where the benefit is gained by 'selling' the carbon benefit to another business, or the Australian government. As noted, it's not possible at the present time to both sell a carbon credit, and claim low-carbon or carbon neutral status in the marketplace using the same carbon credits. However, selling carbon credits is a viable and important option for piggeries to finance investments such as covered ponds.

The carbon market is regulated by the Clean Energy Regulator (CER) which administers national carbon markets for:

- The Emissions Reduction Fund (ERF), which supplies Australian carbon credit units.
- The Renewable Energy Target, which creates tradable large-scale renewable energy certificates (LGCs) and small-scale technology certificates (STCs).

The Emission Reduction Fund is a voluntary program that provides financial incentives for companies to adopt approved methodologies to reduce emissions, or by removing carbon dioxide from the atmosphere and sequestering carbon in soil or vegetation.

The Renewable Energy Target consists of two schemes: the Large-scale Renewable Energy Target (LRET) that provides incentives for large-scale renewable energy power stations and the Small-scale Renewable Energy Scheme (SRES) that creates incentives to install small-scale renewable energy systems. Demand for renewable energy certificates is set in legislation each year. However, there is increasing demand from businesses and other levels of government for LGCs to offset emissions.

The following sections detail how the ERFs and the Renewable Energy Target are applicable to pork production, and how these schemes can be leveraged to achieve the goals of a business.

7.2 Emission Reduction Funds for Piggeries

When considering an emission reduction project, initial contact should be made with CER to determine eligibility and timing requirements for registration. A brief summary of the steps needed to register and claim carbon credits under an ERF mitigation project are:

1. **Register** - Prior to registering any project with the CER, the producer needs to apply to become an ERF participant. This includes a 'Forward Abatement Estimate' which is the amount of emission reduction that the project is likely to achieve. Registering also involves a fit and proper person status and opening an Australian National Registry of Emissions Units (ANREU) account.
2. **Contract** - Participants may establish a carbon abatement contract to sell their ACCUs to the CER, or they may sell their credits through the secondary, private market.
3. **Reporting** - The project needs to be undertaken according to the approved method of the project and uses the government supplied emissions calculator relevant to the project. To receive ACCUs, regular reports will need to be submitted to the CER for the registered projects, including reporting on emission reductions. The project will

need to be regularly audited by an independent Category 2 Greenhouse and Energy Auditor, with a minimum of three scheduled audits across the seven-plus year crediting period. General recording requirements specify that records must be kept for seven years.

4. **Payment** - If a contract has been established, participants must deliver ACCUs according to the agreed schedule and are paid according to the auction price. These transactions occur in ANREU and are made from your ANREU account.

Under the ERF, the rules for estimating emission reductions are termed methodology determination (methods). These standards define how to gain carbon credits for reductions and the reporting requirements of projects. These methods are required to ensure reductions are valid and verifiable strategies, and the methods applicable to pig production are outlined in the below sections.

As of September 2021, the Clean Energy Regulator is in the process of developing an Australian Carbon Exchange that will make the trading of ACCUs simpler, supporting the rapidly increasing demand from the corporate sector. It will help foster the growth in Australia's vibrant carbon markets, where ACCUs credited from approved Emissions Reduction Fund projects can be traded among individuals and businesses. The Australian Carbon Exchange is expected to be launched in 2023.

7.2.1 Animal effluent method

This method provides an opportunity for crediting emissions through the capture and/or destruction of GHG emissions from animal effluent systems.

An ***emissions destruction*** project is where effluent in treated in an anaerobic digester/s that generates and captures methane. The captured methane must then be destroyed via a combustion device (i.e. flare, boiler generator). The method is flexible in that allows ***ineligible*** material to be added in an emissions destruction facility, provided it is less than 10% of the total material. Ineligible material is generally other organic effluent which is non-animal effluent derived.

An ***emissions avoidance*** project is where effluent is managed in a way that reduces the total emissions compared to if the effluent had been treated in an uncovered anaerobic pond. This must occur via the use of solids separation devices to remove VS from the effluent and treat the removed VS in stockpiles (solid storage) or as compost that can be used for field application. The treatment of the VS must ensure that it is undertaken aerobically that results in fewer emissions of methane than would occur if the VS were only treated in an uncovered anaerobic pond. ***Ineligible*** material must not be added to emissions avoidance facility.

It is possible for a facility to combine emissions avoidance and emissions destruction. Each treatment facility must treat animal effluent and may also treat other effluent. The net abatement amount of CO_2-e for a project under the Animal effluent method is the quantity of methane emissions destroyed or avoided because of the project, minus GHG emissions from the use of electricity and fuel used to operate the any equipment to run the project. In addition, for emissions avoidance projects, any of methane and nitrous oxide GHG emissions arising from the post-diversion treatment of material diverted from the project must be deducted.

Eligible projects that do not generate electricity for more than 7 years (cumulative total of 84 calendar months) can have a **crediting period** length of 12 years. These can be emissions avoidance projects or projects that only flare without generating electricity. It also allows for projects to start with flaring and move to generating electricity when they have more information on the quality of the gas flow from the project.

Some piggeries had or still have projects under previously approved methods that have now been revoked, including:

- *The Carbon Credits (Carbon Farming Initiative) (Destruction of Methane Generated from Manure in Piggeries—1.1) Methodology Determination 2013.*
- *The Carbon Credits (Carbon Farming Initiative) (Destruction of Methane from Piggeries Using Engineered Biodigesters) Methodology Determination 2013.*

New piggery projects can transition projects registered under these previously approved methods. For projects transitioning into the method, the calculation of the months of generation includes the calendar months that were part of the project's crediting period or periods on earlier methods. Crediting periods are summarised in Table 13 for existing and transitioning projects.

Table 13. Crediting periods for existing and transitioning projects under the Animal Effluent Method

Transitioning Projects		
Activity	**Crediting Period**	**From**
Flaring only	Balance of 12 years	Start of current crediting period
Heat Generation	Balance of 12 years	Start of current crediting period
Electricity Generation	Balance of 84 months of generation (but not shorter than 7 years or longer than 12 from start of current crediting period)	Start of first crediting period OR first demonstrated date of generation
New Projects		
Flaring only	12 years	Start of current crediting period
Heat Generation	12 years	Start of current crediting period
Avoidance (composting) only	12 years	Start of current crediting period
Electricity Generation	84 months of generation; up to 12 years*	Start of current crediting period
Combined activities with Electricity Generation	84 months of generation; up to 12 years*	Start of current crediting period

* The 84 months of electricity generation is cumulative, not necessarily consecutive. Electricity is presumed to begin in the first crediting month and once generated in a month, generation is presumed to continue in subsequent months unless evidence is provided to the contrary. Electricity is considered to be generated in a month if it is generated for 3 or more days in a calendar month.

pH modification of effluent and short HRT ponds/tanks were considered as potential avoidance technologies when the method was developed. A decision was made to not include these in the method, with the possibility of then being included at a later stage, as they needed further assessment as to their viability as an activity under the ERF.

7.2.2 Measurement of soil carbon sequestration in agricultural systems method

This method accounts for crediting emissions through the sequestration of soil carbon under pasture, crops or mixed farming systems. This method involves random soil sampling in at least three defined Carbon Estimation Areas (CEAs) for baseline and subsequent sampling rounds to measure the change in soil carbon levels. Improved soil carbon levels may be achieved through increasing soil fertility, remediation of acidic or sodic soils, improving pasture or introducing permanent pastures, altering stocking rates, grazing rotations, no-tillage systems, stubble retention and remediation of land. Manure and effluent application areas around piggeries may be suitable locations for a soil carbon project. For more information, please see the link below:

http://www.cleanenergyregulator.gov.au/ERF/Pages/Choosing%20a%20project%20type/Opportunities%20for%20the%20land%20sector/Agricultural%20methods/The-measurement-of-soil-carbon-sequestration-in-agricultural-systems-method.aspx

7.2.3 Vegetation methods

These methods account for crediting emissions through the sequestration of carbon from the atmosphere by plants. This includes reforestation, revegetation or the protecting native forest or vegetation that is at risk of land clearing. There are several ERF vegetation methods that may be relevant to farming systems but these are less likely to be suitable for piggeries, unless large areas of additional land is owned. For more information, please see the link below:

http://www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-the-land-sector/Vegetation-methods

7.2.4 Biomethane method

The biomethane method will provide an opportunity utilising waste or agriculturally generated biomethane as a natural gas substitute. As last updated on 21 July 2021, this new method is in the draft development and technical and expert consultation phase of the ERF approval process with the CER.

7.3 Renewable Energy Target

Large scale renewable energy credits (LGSs) can be acquired from the Clean Energy Regulator for eligible power generators. Eligible electricity is electricity generated from a power station's renewable energy sources. Within a piggery operation power generation from an anerobic digestor would, in most cases, be eligible for LGCs. LGCs are allocated on a basis of one unit per megawatt hour (MWh) of eligible electricity generated. There are five steps involved with making and processing an LGC claim, including:

- **Prepare** - ensure project meets with criteria for LGC creation and prepare answers to standard validation questions

- **Data** – adding power generation data to the renewable energy certificates (REC) registry
- **Create** – create LGCs in the REC registry
- **Assessment and validation** – verification of claim by Clean Energy Regulator
- **Register** - register LGCs by paying creation fee

On registration of LGCs, they can be sold through the open LGC market. The trading price of LGCs is variable and has decreased significantly over the last five years. For the 2016-2017 period the price generally remained above $70. Since this time the decrease in value has been notable, with the current spot price as of 15 September 2021 being $35.80. The variability in commercial return would need to be factored into any capital investment feasibility study for the development of a reusable power generation system at any piggery.

7.4 Funding Options

Green loans are used by financial institutions for funds available to support projects, assets and activities with environmental benefits. The four major banks (nab, CommBank, ANZ and Westpac) have declared targets for green lending opportunities to boost credit supply. These targets are regularly revised and are expected to increase overtime. For example, nab have committed to:

"Providing a target of $70 billion of environmental finance by 2025"

This target increased in 2019 from the previous target of $55 billion. Many capital investment projects in the pig industry resulting in GHG mitigation would qualify under the green loans scheme with any of the big four banks.

Sustainability-linked loans (SLL) are a type of loan instrument which incentivise the borrower's achievement of ambitious, predetermined sustainability performance adjectives. They are target-based with the interest margin on the loan varying depending on the borrower's performance against predetermined environmental, social and/or governance targets. SLL works well for companies in 'high emission' sectors to transition to low carbon basis.

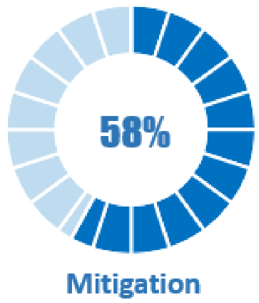
Australian Renewable Energy Agency (ARENA) fund projects which can help accelerate innovative renewable energy projects in Australia. The Clean Energy Innovation Fund draws on finance to provide equity to innovative business to lower emissions. Whilst no piggeries have received funding to date under this scheme, the fund would be suitable to support any innovative project with high potential environmental return in the industry.

8. Case Studies

Case studies are provided to demonstrate the potential reduction in GHG emissions resulting from different emission reduction strategies for five different scales and types of production. Where possible, case studies have been based on operating farms within Australia. Where production data was not available or to demonstrate future emission mitigation scenarios, the case studies have been based on a "model" piggery.

8.1 Case Study 1 – Large conventional piggery using co-products and by-products as feed, covered anaerobic pond with CHP

This case study was completed to demonstrate the emissions reduction potential for an 1,800 sow farrow to finish conventional piggery that utilised by-products and co-products as a partial substitute for purchased feed. All effluent is directed to a covered anaerobic pond for methane capture and reuse through a CHP system.



8.1.1 Carbon account

A carbon assessment on all relevant GHG gas emissions was completed for the piggery operation, including emissions from Scope 1 and 2, upstream Scope 3 and downstream Scope 3 emissions to the point of delivery to the abattoir for processing. The carbon footprint is expressed in CO_2-e per kg live weight.

The use of by-products and co-products as feed reduces the GHG emissions associated with production of traditional feed ingredients (e.g. cereal grains, protein, meals). The GHG emissions attributed to the use of co-products and by-products is zero, as the materials are being diverted from the general waste stream. Case Study 1 farm was able to substitute 37% of the regular feed ration with by-products comprised of bread, pasta, fish and dairy waste.

Production data for the farm was accessed where possible from available records, with assumptions made for several parameters where the data was not readily available (Table 14).

Table 14. Key activity data for Case Study 1

Key Parameters	**Description**
Location	New South Wales
Herd Composition	1,800 sow farrow to finish operation
Housing	conventional
Pigs weaned/sow.year	23.2
FCR (whole herd)	3.3
Finisher pig weight	105 kg
Feed	Australian wheat/barley dominant (2% imported soybean meal) with 37% of total feed substituted with by-products – bread/ pasta /fish waste/dairy waste
Feed milling	onsite

Transport distance for feed	100 km
Transport distance for fuel	100 km
Transport distance to processing	200 km
Manure management system	covered anaerobic pond with CHP

8.1.2 Carbon emissions

Results are presented for the Case Study 1 baseline scenario and the reduced emission scenario associated with the use of 37% of feed substituted from by-products in conjunction with a covered anaerobic pond and CHP are presented in Table 15. The baseline scenario shows the piggery emissions without any emission mitigation measures in place.

Table 15. Case Study 1 – GHG from baseline scenario and combined by-products and covered anaerobic pond (CAP)

	Baseline		**37% By-products and CAP**	
Emission Source	**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**	**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**
Scope 1				
Piggery Enteric Methane	225	0.175	226	0.175
Piggery Manure Methane	4961	3.847	1470	1.140
Piggery Manure Direct Nitrous Oxide	0	0.000	0	0.000
Piggery Services	38	0.030	34	0.026
Feedmilling & Feed Production	62	0.048	46	0.036
Scope 2				
Piggery Services	211	0.163	0	0.000
Feedmilling & Feed production	69	0.053	0	0.000
GHG emissions - Scope 1 & 2	5566	4.32	1776	1.38
Scope 3				
Manure Indirect Nitrous Oxide	42	0.032	37	0.029
Piggery Services	25	0.020	2	0.001
Feedmilling & Feed Production	1413	1.096	1117	0.866
Transport	34	0.027	26	0.020
GHG Emissions - Scope 3	1514	1.17	1182	0.92
LU and dLUC Emissions	78	0.061	73	0.057
GHG emissions - Scope 1, 2 & 3	7159	5.55	3031	2.35
CARBON MITIGATION			**4128**	**58%**

The emission reduction for Scope 1 and 2 emissions was 68%, and the overall reduction in the carbon footprint was 58%.

An important consideration when using by-products is that the volatile solids content in manure is highly sensitive to changes is digestibility in diet. Reduced digestibility in diet will result in an increase in volatile solids in the waste stream, and correspondingly an increase in the GHG emission from the manure management system. This increase in GHG emissions could exceed the emissions mitigated through the utilisation of by-products as feed. As such, systems that are likely to realise the greatest benefit using by-products are when they are used in conjunction with a methane capture system and energy recovery system, which can benefit from increased volatile solids content.

8.2.3 Financial considerations

The financial considerations associated with the use of by-products and waste as a substitute for feed in conjunction with the covering of the anaerobic pond are detailed below based on the information available under the Shared Value Project Case Study (2020) Where available revenue and/or costs have been attributed to aspects of the project. In cases where quantitative values are not available, these have been noted for consideration when for the project.

- $880,000 per year reduction in feed costs
- $1.0m capital expenditure of biogas plant
- 2 year simple payback period for the biogas capital expenditure
- $29,000 per month saving on electricity and gas charges
- $5,700 per month from excess power returned to the grid
- Feed transport costs may increase or decrease depending on distance of feed mill, source of by-products and waste production and contractual arrangements with waste generator.
- Increase in feeding costs due to installation of liquid feeding system
- Increase in processing cost of feed, due to de packaging and preparation of feed rations including by-products.

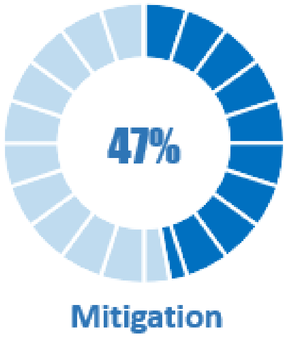
The use of by-products and waste in feed are likely to cause in a decrease feed digestibility, and as a result increase volatile solids in the waste stream. This will increase methane production and consequently energy generation from the CHP compared with standard diets that are typically used in case study assessments. This is likely to result have had a positive impact on the Case Study 1 farm with regard to the low payback period achieved.

In addition to financial the savings by Case Study 1 farm, the following benefits are also gained on a broader scale.

- $1.8m savings for food company partners from reduced landfill costs
- 8,000 tonnes of waste diverted from landfill

8.2 Case Study 2 – Small Conventional Piggery with Covered Anaerobic Pond

This case study was completed to demonstrate the emissions reduction potential for a small sized 535 sow farrow to finish conventional piggery located in Victoria. This piggery has a covered anaerobic pond for methane capture and reuse through a CHP system.



8.2.1 Carbon account

A carbon assessment on all relevant GHG gas emissions was completed for the piggery operation, including emissions from Scope 1 and 2, upstream Scope 3 and downstream to the point of delivery to the abattoir for processing. The carbon footprint is expressed in CO_2-e per kg live weight.

Production data for the farm was accessed where possible from available records, with assumptions made for several parameters where the data was not readily available (Table 16).

Table 16. Key activity data for Case Study 2

Key Parameters	Description
Location	Victoria
Herd Composition	535 sow farrow to finish operation
Housing	conventional
Pigs weaned/sow.year	23.2
FCR (whole herd)	3.3
Finisher pig weight	99 kg
Feed	Australian wheat/barley dominant (2% imported soybean meal)
Feed milling	offsite
Transport distance for feed	100 km
Transport distance for fuel	100 km
Transport distance to	200 km
Manure management system	covered anaerobic pond with CHP

8.2.2 Carbon emissions

Results are presented for the Case Study 2 baseline scenario and the reduced emission scenario associated with the introduction of a covered anaerobic pond and CHP are presented in Table 17. The baseline scenario shows the piggery emissions without any emission mitigation measures in place.

Table 17. Case Study 2 – GHG from baseline scenario and covered anaerobic pond and CHP

	Baseline		Covered Anaerobic Pond and CHP	
Emission Source	**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**	**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**
Scope 1				
Piggery Enteric Methane	193	0.148	193	0.148
Piggery Manure Methane	4241	3.259	1423	1.092
Piggery Manure Direct Nitrous Oxide	0	0.000	0	0.000
Piggery Services	36	0.028	36	0.028
Feedmilling & Feed Production	0	0.000	0	0.000
Scope 2				
Piggery Services	268	0.206	268	0.206
Feedmilling & Feed production	0	0.000	0	0.000
GHG emissions - Scope 1 & 2	**4738**	**3.64**	**1920**	**1.47**
Scope 3				
Manure Indirect Nitrous Oxide	34	0.026	34	0.026
Piggery Services	28	0.022	28	0.022
Feedmilling & Feed Production	1075	0.826	1077	0.826
Transport	40	0.031	40	0.031
GHG Emissions - Scope 3	1177	**0.90**	1178	**0.90**
LU and dLUC Emissions	75	0.058	75	0.058
GHG emissions - Scope 1, 2 & 3	**5990**	**4.60**	**3174**	**2.44**
CARBON MITIGATION			**2816**	**47%**

The emission reduction for Scope 1 and 2 emissions is 59%, and the overall reduction in the carbon footprint is 47%.

8.3.3 *Financial considerations*

This piggery was the subject of a case study undertaken by Tait et al (2020) which looked at the capital costs and simple payback period for the installation of the covered anaerobic pond and CHP system. As a result, actual financial data is available for the this case study which is not possible for the other case studies. The investigation by Tait et al (2020) for the 535 sow farrow to finish piggery provided details on the following economic outcomes:

- $615,000 capital, including the following key component, dam construction and sludge extraction, dam cover, generator, gas skid manufacture, hot water systems to sheds, electrical connection, automation system and commissioning.
- $17,000 per annum of estimated operating costs including oil replacement, general maintenance labour and parts.
- Revenue from the sale of large scale renewable energy credits (LGCs) was estimated at approximately $10,000 per annum at a market price of $41.00 in 2020. The LGC price has dropped since this time to around $35.00.

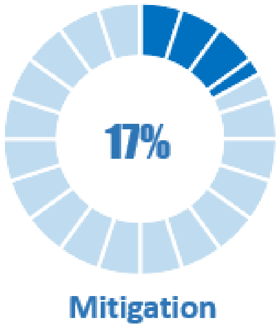
- 6.3 years simple payback period based on a nominal project life of 20 years and project funded without debt finance. With debt finance, the payback period extends to 7.7 years.

8.3.4 Future opportunities for reducing GHG emissions

The Clean Energy Regulator is currently in the process of evaluating and approving an ERF for biomethane. For a small sized operation such as the 535 sow farrow to finish farm, the processing of the biogas from the covered pond to produce biomethane may be an alternative to onsite power generation. Given in the case study scenario the biogas is used to offset grid supplied electricity the financial benefit of the biomethane option would have to be evaluated.

8.3 Case Study 3. Conventional breeder, deep litter grower with low GHG diet due to reduction in imported soybean meal

Case Study 3 was completed to demonstrate the emissions reduction for a 1,000 sow conventional breeder and deep litter grower piggery located in South Australia. The case study farm modified the herd diet from a high soybean meal content of ~9% to and zero soybean meal diet through the use of alternative proteins.



8.3.1 Carbon account

A carbon assessment on all relevant GHG gas emissions was completed for the piggery operation, including emissions from Scope 1 and 2, upstream Scope 3 and downstream to the point of delivery to the abattoir for processing. The carbon footprint is expressed in CO_2-e per kg live weight.

Production data for the farm was accessed where possible from available records, with assumptions made for several parameters where the data was not readily available (Table 20).

Table 18. Key activity data for Case Study 3

Key Parameters	Description
Location	South Australia
Herd Composition	1000 sow farrow to finish operation
Housing	conventional breeding and deep litter grower
Pigs weaned/sow.year	24.6
FCR (whole herd)	3.3
Finisher pig weight	100 kg
Feed	high soybean meal diet of 9.4% modified to 0% soybean
Feed milling	onsite
Transport distance for feed	100 km
Transport distance for fuel	100 km
Transport distance to processing	200 km
Manure management system	anaerobic pond for conventional breeding, and stockpiling deep litter for grower/finisher

8.3.2 Carbon emissions

Results are presented for the Case Study 3 high soybean meal diet and the reduced emission scenario associated with the replacement of soybean meal protein in the diet in Table 21. The baseline scenario shows the piggery emissions without any emission mitigation measures in place.

Table 19. Case Study 3 – GHG from baseline scenario and zero soybean meal diet.

	Baseline		No Soymeal Diet	
Emission Source	**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**	**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**
Scope 1				
Piggery Enteric Methane	362	0.157	365	0.159
Piggery Manure Methane	2884	1.254	2810	1.221
Piggery Manure Direct Nitrous Oxide	628	0.273	520	0.226
Piggery Services	24	0.010	24	0.010
Feedmilling & Feed Production	98	0.043	98	0.043
Scope 2				
Piggery Services	170	0.074	170	0.074
Feedmilling & Feed production	60	0.026	60	0.026
GHG emissions - Scope 1 & 2	**4226**	**1.84**	**4046**	**1.76**
Scope 3				
Manure Indirect Nitrous Oxide	67	0.029	56	0.024
Piggery Services	40	0.017	40	0.017
Feedmilling & Feed Production	2161	0.939	2479	1.078
Transport	57	0.025	57	0.025
GHG Emissions - Scope 3	**2324**	**1.01**	**2632**	**1.14**
LU and dLUC Emissions	1573	0.684	23	0.010
GHG emissions - Scope 1, 2 & 3	**8123**	**3.53**	**6702**	**2.91**
CARBON MITIGATION			**1421**	**17%**

The emission reduction associated with LU and dLUC for the change to a zero soybean meal diet is 1550 tonnes per year or a 98% reduction. Case Study 3 shows the significant impact of soybean meal content in diet on the total carbon footprint, with an overall reduction of 17%.

8.3.3 Financial considerations

The cost implications of including reducing soybean meal content in diet have been quantified by making some assumptions regarding the cost of alternative ingredients. It is estimated that the cost of zero soybean meal diet results in an increase of around $10/tonne for manufactured feed.

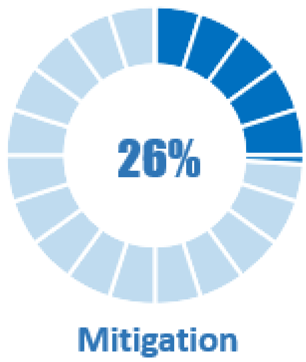
- $70,000 increase in the annual cost of feed as a result of utilising alternative protein sources to develop a zero protein diet.

8.3.4 Future opportunities for reducing GHG emissions

Addition emission reduction measures could be implemented for the breeding and growing production systems. The conventional system could implement a methane capture and reuse, while the deep litter could avoid stockpiling, both of which would have a significant impact on methane generation from the site.

8.4 Case Study 4. Conventional breeder, deep litter grower with improved FCR, solar power and litter off-farm and carbon credit offsets

This case study was completed to demonstrate the emissions reduction for a 1,000 sow conventional breeder and deep litter grower piggery located in South Australia. The case study farm implemented a number of emission reduction measures including reducing FCR, solar power and batteries to supply on-farm electricity demand and exporting litter off-farm for reuse.



This case study looks at the cost associated with achieving carbon neutral status by purchasing additional offset carbon credits was examined, with the aim of certifying all pork produced to the point of delivery to retail.

8.4.1 Carbon account

A carbon assessment on all relevant GHG gas emissions was completed for the piggery operation, including emissions from Scope 1 and 2, upstream Scope 3 and downstream to the point of delivery to the abattoir for processing. The carbon footprint is expressed in CO_2-e per kg live weight.

Production data for the farm was accessed where possible from available records, with assumptions made for several parameters where the data was not readily available (Table 20).

Table 20. Key activity data for Case Study 4

Key Parameters	Description
Location	South Australia
Herd Composition	1000 sow farrow to finish operation
Housing	conventional breeding and deep litter grower
Pigs weaned/sow.year	24.6
FCR (whole herd)	3.3 improved to 2.5
Finisher pig weight	100 kg
Feed	Australian wheat/barley dominant (2% imported soybean meal)
Feed milling	onsite
Transport distance for feed	100 km
Transport distance for fuel	100 km
Transport distance to	200 km
Manure management system	Anaerobic Pond for Conventional breeding, and Stockpiling Deep Litter for grower/finisher

8.4.2 Carbon emissions

Results are presented for the Case Study 4 baseline scenario and the reduced emission scenario associated with the reduced FCR, solar power and litter immediately off farm for reuse in Table 21. The baseline scenario shows the piggery emissions without any emission mitigation measures in place.

Table 21. Case Study 4 – GHG from baseline scenario and combined low FCR, solar power and litter off farm.

		Baseline		Improved FCR + Solar + Litter Off Farm	
Emission Source		**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**	**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**
Scope 1					
Piggery Enteric Methane		403	0.175	328	0.135
Piggery Manure Methane		2424	1.054	1885	0.774
Piggery Manure Direct Nitrous Oxide		645	0.280	321	0.132
Piggery Services		28	0.012	25	0.010
Feedmilling & Feed Production		110	0.048	88	0.036
Scope 2	0			0	
Piggery Services		170	0.074	44	0.018
Feedmilling & Feed production		67	0.029	0	0.000
GHG emissions - Scope 1 & 2		**3847**	**1.67**	**2691**	**1.11**
Scope 3	0			0	
Manure Indirect Nitrous Oxide		59	0.026	32	0.013
Piggery Services		40	0.017	11	0.005
Feedmilling & Feed Production		1951	0.848	1593	0.654
Transport		61	0.027	55	0.023
GHG Emissions - Scope 3		2111	**0.92**	1691	**0.69**
LU and dLUC Emissions		146	0.063	141	0.058
GHG emissions - Scope 1, 2 & 3		**6104**	**2.65**	**4523**	**1.86**
CARBON MITIGATION				**1581**	**26%**

The emission reduction for Scope 1 and 2 emissions was 30%, and the overall reduction in the carbon emissions to processing gate was 26%.

8.4.3 Financial considerations

Details of the financial impacts resulting from the implementation of GHG mitigation strategies, including with improved FCR, solar power and litter off-farm are not available from this farm, so assumptions have been made based on the best available information.

- 24% saving in feed costs resulting from an improvement in FCR from 3.3 to 2.5 results, based on a total feed purchase of 6,800 tonnes per year, and a estimated feed cost of $550/tonne delivered the expected annual saving could be $900,000.

- Costs associated with improving FCR may include the installation of new feeders and or feeding system to reduce feed wastage.
- The cost implications of immediately removing litter from farm are likely to be negligible, as arrangements can usually be made with landowners/processors who require the spent litter as process inputs.

8.4.4 Future opportunities for reducing GHG emissions

For Case Study 4, the expected cost associated with moving the operation to certified carbon neutral status at the point of delivery to retailer for the pork product. Based on the Case Study 1 assessment of 5,091 tonnes of carbon that would require offsetting to achieve carbon neutral status to the processing gate, which is the equivalent of 2.09kg C/kg LW. As this is a branded product, assumptions are made regarding the processing and retail of the product which is likely to increase the emission intensity of the pork product to approximately 5.8kg C/kg sold. The total carbon footprint of the operation to retail gate is 10,139 tonnes of carbon that would require offsetting.

To offset the carbon emission, carbon credits could be purchased on the open market. Table 22 shows the expected annual offset and fixed costs to achieve carbon neutral accreditation for the business using both the Australian Carbon Credit Units (ACCUs) and Certified Emission Reduction (CER) credits for both the first and second year of operation. The fixed costs associated with gaining carbon neutral certification, including auditing are significantly higher in the first year. The farm would also not be able to sell carbon credits derived from any ERFs of solar power generated onsite, and forgo the revenue associated with this offset.

Table 22. Carbon Offset Costs

	CERs	**ACCUs**
Carbon Credits ($/t CO2-e)	3.00	26.00*
Year 1		
Offset Only (c/kg)	1.7	15.8
Fixed Costs (c/kg)	2.7	2.7
Total (c/kg)	**4.5**	**17.8**
Year 2		
Offset Only (c/kg)	1.7	15.8
Fixed Costs (c/kg)	1.6	1.6
Total (c/kg)	**3.3**	**16.7**

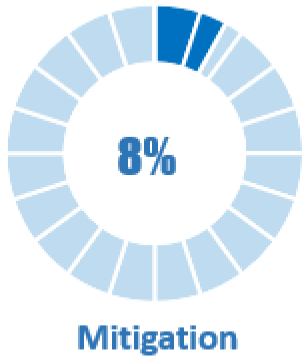
* Price of ACCUs as of 10 September 2021.

The offset costs vary significantly depending on the selected carbon credit. Based on a total pork production sold of 3,300 tonnes, the total annual cost to achieve carbon neutral in the first year would be approximately $78,000 using CERs and $312,000 using ACCUs. In the second year, these costs may decrease to $58,000 and $291,000 respectively.

The cost of achieving carbon neutral status is high, particularly if the loss due to retired ERF credits are also incorporated. The option of becoming carbon neutral may be more attractive to producers who are coming to the end of their ERF contract and looking to show benefit of being low carbon.

8.5 Case Study 5 – Small outdoor bred deep litter grown production with improved FCR and tree planting offset

This case study was completed for a 150 sow farrow to finish outdoor operation. The farm consists of outdoor bred pigs, which are transferred to deep litter shelters for grow-out and is located in southwest of Western Australia. The case study shows the potential emissions reduction resulting from an improved on-farm FCR. The carbon storage requirements associated with tree planting to offsets carbon emissions is also assessed.



8.5.1 Carbon account

A carbon assessment on all relevant GHG gas emissions was completed for the piggery operation, including emissions from Scope 1 and 2, upstream Scope 3 and downstream to the point of delivery to the abattoir for processing. The carbon footprint is expressed in CO_2-e per kg live weight.

The FCR of the baseline case was 3.7 and was improved to 3.3. Production data for the farm was accessed where possible from available records, with assumptions made for several parameters where data was not readily available (Table 23).

Table 23. Key activity data for Case Study 5

Key Parameters	Description
Location	Western Australia
Herd Composition	150 sow farrow to finish operation
Housing	outdoor bred and grown
Pigs weaned/sow.year	18.3
FCR - whole herd (kg feed/kg LW))	3.7 and improved to 3.3
Finisher pig weight	100 kg
Feed	Australian wheat/barley dominant (2% imported soybean meal)
Feed Milling	offsite
Transport distance for feed	100 km
Transport distance for fuel	100 km
Transport distance to processing	200 km
Manure management system	direct to land and stockpiled spent litter

8.5.2 Carbon emissions

Results are presented for the Case Study 5 baseline scenario and the reduced emission scenario associated with the improved FCR in Table 24. The baseline scenario shows the piggery emissions without any emission mitigation measures in place.

Table 24. Case Study 5 – GHG from baseline scenario and improved FCR

	Baseline		Improved FCR	
Emission Source	**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**	**Total Emissions (tonnes CO_2-e)**	**Emissions Intensity (kg CO_2-e/kg LW)**
Scope 1				
Piggery Enteric Methane	47	0.213	43	0.184
Piggery Manure Methane	14	0.064	13	0.056
Piggery Manure Direct Nitrous Oxide	153	0.694	135	0.575
Piggery Services	7	0.034	8	0.034
Feedmilling & Feed Production	0	0.000	0	0.000
Scope 2	0		0	
Piggery Services	0	0.000	0	0.000
Feedmilling & Feed production	0	0.000	0	0.000
GHG emissions - Scope 1 & 2	222	1.00	199	0.85
Scope 3	0		0	
Manure Indirect Nitrous Oxide	4	0.020	4	0.017
Piggery Services	0	0.002	0	0.002
Feedmilling & Feed Production	286	1.294	265	1.130
Transport	7	0.030	6	0.027
GHG Emissions - Scope 3	298	1.35	275	1.18
LU and dLUC Emissions	14	0.061	14	0.060
GHG emissions - Scope 1, 2 & 3	533	2.41	488	2.08
CARBON MITIGATION			**45**	**8%**

The emission reduction for Scope 1 and 2 emissions was 10% and the overall reduction in the emission intensity was 8%. Improved FCR could be achieved through the implementation of on-farm measures such as improved feeders, herd management and herd production.

8.5.3 Financial Considerations

Details of the financial impacts resulting from the implementation of GHG mitigation strategies, including with improved FCR, solar power and litter off-farm are not available from this farm, so assumptions have been made based on the best available information.

- 11% saving in feed costs resulting from an improvement in FCR from 3.7 to 3.3, based on a total feed purchase of 870 tonnes per year and an estimated feed cost of $600/tonne results in an expected annual saving of $57,000.
- Costs associated with improving FCR may include the installation of new feeders and or feeding system to reduce feed wastage.

8.5.4 Future opportunities for reducing GHG emissions

For Case Study 5, the expected requirements associated with establishing tree planting to act as carbon storage to offset the remaining carbon credits is assessed. Table 25 shows the area requirements to offset the remaining 661 tonnes of carbon emissions based on high growth rate plantings located in the south-west of Western Australia in sandy duplex soils.

Table 25. Tree Planting Requirements to Offset Emissions

Carbon Storage (tonnes/hectare)	15
Carbon Offset Required (tonnes)	611
Vegetation Planting Area Required (ha)	41

The expected area required to offset the remaining carbon emissions, after improved FCR has been implemented is 41ha. For the tree plantings to be recognised as a carbon offset, the project would need to be registered with the Clean Energy Regulator through their emissions reduction scheme.

Appendix A. Manure Management Emissions Calculations

This appendix provides supplementary information for the calculation of methane and nitrous oxide emission for different manure management systems.

Table 26. Methane conversion factors (MCFs) for different manure management systems (MMS) in Australia (Commonwealth of Australia, 2019)

MMS	NSW	QLD/ NT	SA	TAS	VIC	WA
Outdoor (Dry Lot)	0.01	0.03	0.01	0.01	0.01	0.01
Deep Litter	0.04	0.04	0.04	0.04	0.04	0.04
Stockpile (Solid Storage)	0.02	0.02	0.02	0.02	0.02	0.02
Effluent Pond (Uncovered Anaerobic Lagoon)	0.75	0.77	0.75	0.7	0.74	0.77
Anaerobic Digester/ Covered Pond	0.1	0.1	0.1	0.1	0.1	0.1
Short Hydraulic Retention System (<1 month)	0.03	0.03	0.03	0.03	0.03	0.03

Table 27: Nitrous oxide emission factors for different manure management systems (MMS) in Australia (Commonwealth of Australia, 2019)

MMS	N_2O
Outdoor (Dry Lot)	0.02
Deep Litter	0.01
Stockpile (Solid Storage)	0.005
Effluent Pond (Uncovered anaerobic pond)	0
Anaerobic digestor / covered pond	0
Short Hydraulic Retention System (<1 month)	0.002

Indirect nitrous oxide emissions are a result of atmospheric deposition of nitrogen to land and water, and through runoff and leaching (outdoor only). To quantify the nitrous oxide emissions through atmospheric deposition, first calculate the total nitrogen volatilised (MN_{atmos}) from a MMS:

$$MN_{atmos} = AE\ x\ FracGASM_{MMS}$$

Where:

MN_{atmos} = mass of N volatilised (kg N)

AE = total nitrogen (kg/year)

$FracGASM_{MMS}$ = fraction of N volatilised for the MMS (

Table 28)

Table 28. Fraction of nitrogen volatilised (FracGASM) by manure management systems (MMS) in Australia (Commonwealth of Australia, 2019)

MMS	FracGASM
Outdoor (Dry Lot)	0.3
Deep Litter	0.125
Stockpile (Solid Storage)	0.2
Effluent Pond (Uncovered anaerobic pond)	0.55
Anaerobic digestor / covered pond	0
Short Hydraulic Retention System (<1 month)	0.25

Using the total nitrogen volatilised, the indirect nitrous oxide emissions from deposited nitrogen (E_{atmos}) is calculated using.

$$E_{atmos} = MN_{atmos}\ x\ EF\ x\ C_g$$

Where:

E_{atmos} = indirect nitrous oxide emissions (kg N_20)

MN_{atmos} = mass of N volatilised (kg N)

EF = emission factor (0.002 kg N_2O-N/kg N) (Inorganic Fertiliser EF for non-irrigated cropping Table 5.25 in NIR 2019 (Commonwealth of Australia, 2021))

C_g = 44/28 factor to convert elemental mass of N_2O to molecular mass

Leaching and runoff from piggery facilities (with the exception of outdoor piggeries) is considered negligible in Australia because of strict environmental regulations in all states. As such, the emission associated with the below calculation are only relevant for outdoor operations. The mass of nitrogen lost through leaching and runoff for outdoor systems is estimated using:

$$MN_{leach} = AE\ x\ \ FracWET\ x\ Frac_{leach\_MS}$$

Where:

MN_{leach} = mass of nitrogen lost through leaching and runoff (kg N)

AE = mass of nitrogen in waste (kg/year)

$Frac_{WET}$ = fraction of N available for leaching and turnoff (Table 29)

$Frac_{leach\_MS}$ = fraction of nitrogen lost through leaching and runoff (0.24 kg N/kg applied (IPCC 2019))

Table 29. Fraction of pig manure available for leaching and runoff (FracWET) by state in Australia (Commonwealth of Australia, 2019)

State	FracWET
ACT	0.5
New South WalesFrac W	0.5
Queensland	0.25
South Australia	0.75

Tasmania	1.0
Victoria	0.5
Western Australia	0.4

Annual leaching and runoff emission (kg N_2O) calculated using the MN_{LEACH} by:

$$E_{leach} = MN_{leach} \ x \ EF \ x \ C_g$$

Where:

E_{leach}	=
MN_{leach}	= mass of nitrogen lost through leaching and runoff (kg N)
EF	= emission factor 0.011 (kg N_2O-N/kg N) (IPCC 2019)
C_g	= 44/28 factor to convert elemental mass of N_2O to molecular mass

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