Carbon and environmental impacts of poultry production: 2020 and beyond

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Foreword

This project is being conducted to baseline environmental impacts for Australian egg production. This report is the result of a section of the study focusing on an opportunity analysis of carbon mitigation options and the supply chain pathway for carbon neutral and 'low carbon' eggs.

This project was funded from industry revenue, which was matched by funds provided by the Australian Government.

This report is an addition to Australian Eggs Limited's range of peer-reviewed research publications and is an output of our R&D program, which aims to support improved efficiency, sustainability, product quality, education and technology transfer in the Australian egg industry.

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Abbreviations

ACCU	Australian Carbon Credit Unit
AD	Anaerobic digestion/digester
ARENA	Australian Renewable Energy Agency
B_O	Methane potential
BAU	Business-as-usual
C	Carbon
c	Cent
CAP	Covered anaerobic pond
cfm	Cubic feet per minute
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CP	Crude protein
DAP	Diammonium phosphate
DISER	Department of Industry, Science, Energy and Resources
dLUC	Direct land-use change
ERF	Emissions Reduction Fund
FCR	Feed conversion ratio
FR	Free range
GHG	Greenhouse gas
GWP	Global Warming Potential
GWP_{100}	Global Warming Potential over one hundred years
ha	Hectare
HFC	Hydrofluorocarbons
HRT	Hydraulic retention time
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kg^{-1}	per kg, the -1 signifies per in an equation
kWh	Kilowatt-hour
LCA	Life cycle assessment
LU	Land use
LPG	Liquefied petroleum gas
MMS	Manure management system
N	Nitrogen
N_2O	Nitrous oxide
NGGI	National Greenhouse Gas Inventory
NIR	National Inventory Report
NO_3-N	Nitrate Nitrogen
P	Phosphorous
PFC	Perfluorocarbon
RD&E	Research, development and extension
SF_6	Sulphur hexafluoride
SOC	Soil organic carbon
t	Tonne
TS	Total solids
VFD	Variable frequency drive
VS	Volatile solids

Executive Summary

Climate change action is a global priority for governments, business and industries. The egg industry produces highly efficient, high-quality food products with a relatively low environmental footprint but along with every sector, there is an imperative to reduce impacts over time. In particular, the industry has sought to benchmark the carbon footprint of eggs and identify options to reduce emissions. This report presents findings from a baseline carbon footprint study for the industry and an investigation of emission mitigation options, with a view to the development of a technically and economically viable pathway to low carbon or carbon neutral eggs.

Baseline modelling utilised inventory data collected as part of a broader LCA study that aimed to assess the environmental impacts of the industry. Impacts for the baseline scenario and each of the mitigation stages were determined using a custom modelling platform, which was consistent with ISO standards (ISO 14044, 14046 and 14067) and used the National Greenhouse Gas Inventory (NGGI) methods for industry-specific emission sources. Emissions were reported as scope 1, scope 2 and scope 3 emissions. Scope 1 emissions represent emissions arising directly from within the operational control of a business. Scope 2 emissions relate to those arising from electricity use. Scope 3 emissions relate to those emissions arising from purchased inputs. Scope 3 emissions in poultry are predominantly associated with purchased feed inputs. As a special case, we have also identified separately emissions that arise from land use (LU) and direct Land Use Change (dLUC), which refers to the loss of vegetation or soil carbon in agricultural production systems. In the present analysis, this arose in the production system for imported soy meal, and contributed a significant portion of the carbon footprint. Following international guidance, these emissions were reported separately because they have a higher degree of uncertainty than other emissions in the carbon footprint.

A broad range of potential mitigation strategies that targeted different emission sources were identified and evaluated via a screening process. Each option was screened based on its technical mitigation potential and feasibility in the context of a typical layer farm. Strategies deemed prospective for the industry were incorporated into emission reduction pathways, which included a timeline for implementation leading to the delivery of low carbon and/or carbon neutral eggs for free range and cage-free farms. The pathways also included the incremental ongoing emissions reduction, which has been, and will continue to be, brought about by the decarbonisation of the electricity grid.

Results and key findings

Scope 1 and 2 emissions accounted for 27% of the 2020 total, with scope 3 (37%) and LU and dLUC emissions (36%) making up the bulk of the impacts. The vast majority of scope 3 was attributable to feed production and effectively all the LU and dLUC impacts modelled in this study were due to imported soy meal. These findings show that significant potential exists for the reduction of emissions.

A total of 18 technologies and strategies were screened, of which seven were suitable for integrating into emission reduction pathways. The difference between the number of strategies screened and those found to be prospective reflects that, whilst each strategy could theoretically reduce emissions, those screened out either resulted in a negligible reduction, or were cost-prohibitive and/or required further research to be viable. In some cases, mitigation strategies targeted the same emission source (for example, solar and anaerobic digestion both replaced grid electricity), meaning these technologies were competitors and were generally not suitable to implement concurrently on the model farm. Consequently, selected technologies were grouped into complementary ‘technology modules’ that could be implemented consecutively in the model emission reduction pathways (depicted in Figure 1 and Figure 2).

Mechanisms by which reductions can be brought about are summarised (and grouped by emission scope) in Table 1.

Table 1 Mechanisms to deliver a moderate or major reduction in emissions from egg production by 2030

	Mechanisms to achieve moderate or major emission reduction by 2030
Reduction in LU, dLUC emissions from imported soy meal	Use of accredited soy meal from sources that do not result in LU, dLUC (soil carbon loss) Use of alternative protein sources that do not result in LU, dLUC emissions, such as field pea, canola, animal protein meal Reversal of LU, dLUC losses by improving soil carbon in cropland, resulting in offsets
Reduction in feed grain emissions	Use of low-GHG diet ingredients Development of low-GHG feed formulations Progress in the grains sector to reduce emission intensity via improvement in fuel efficiency, N efficiency, yield, etc.
Reduction in scope 1 and 2 emissions	Energy efficiency at grading floor and layer farm Solar power installation at layer farms Purchase agreements for green electricity Reduction in manure emissions via reduced dietary N

Emission reductions of 47–51% of scope 1, 2, and 3 emission sources were observed in the model pathways. Through a reduction in scope 1 and 2 emissions, this came close to achieving net zero emissions within the farm boundary (i.e. not including scope 3 emissions from purchased inputs). Although these were significant changes, it was noted that unless low carbon or carbon neutral grain becomes available, it will be impossible to deliver carbon neutral eggs without purchasing or self-generating carbon offset credits to move from emission reduction to net zero.

In the present study, ‘low carbon’ was assumed to be the point at which a producer has implemented all viable strategies to mitigate on-farm emissions, which was in the order of a 40–50% emission reduction. Pathways to carbon neutrality required generation or purchase of carbon offset credits.

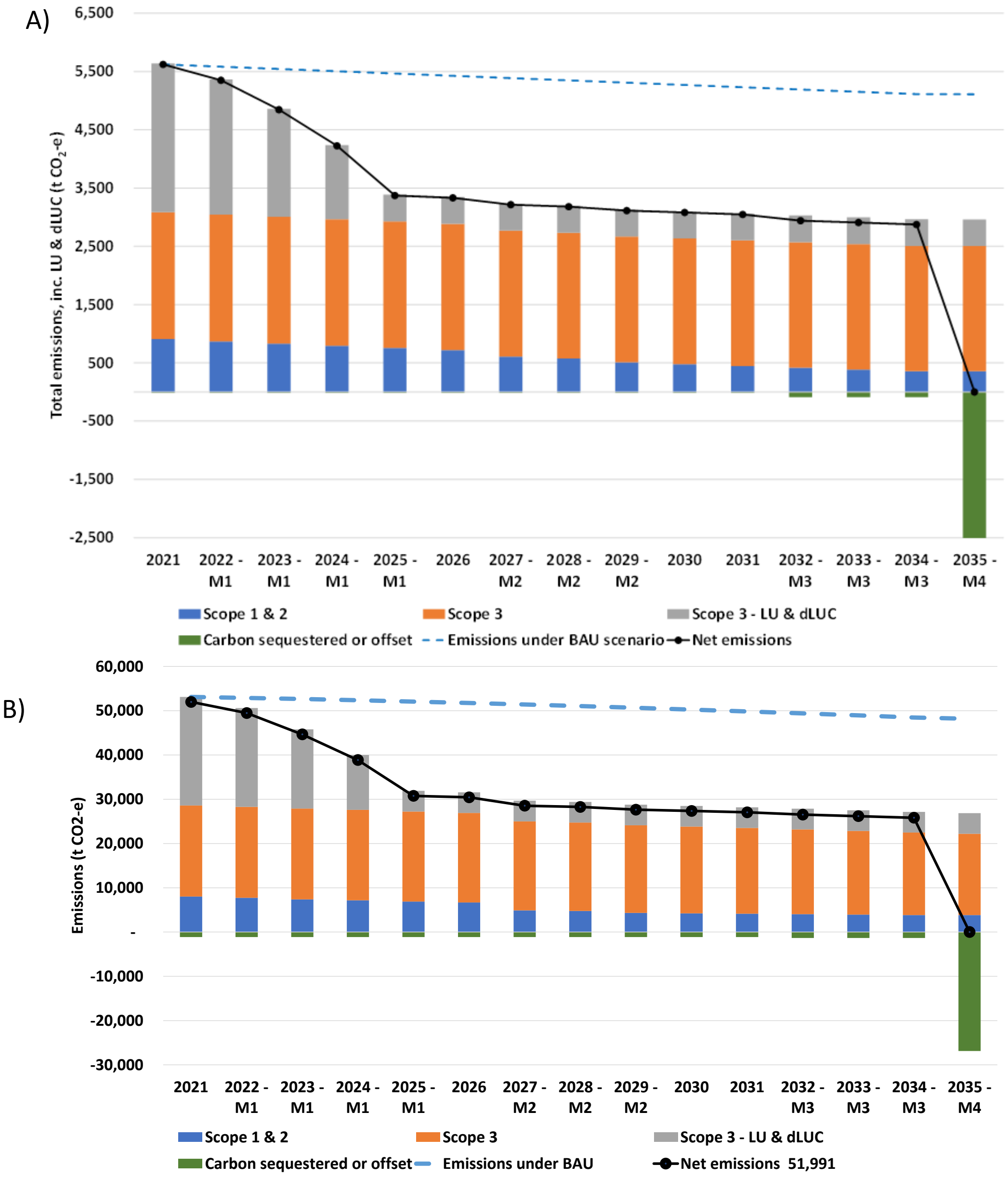

Figure 1 A) Emission reduction pathways for a model 100,000 layer hen free range facility, including pullet rearing and grading; B) Emission reduction pathways for a model 1,000,000 layer hen cage-free facility, including pullet rearing and grading

Note: Total emissions include scope 1, 2 and 3 emission sources, and include LU and dLUC.

Further research is needed to determine the cost-effectiveness of these strategies, and to inform the industry and individual enterprises about the business case for reducing emissions. In most instances, the interventions are expected to have a negative impact on profitability in the short-term due to higher production costs and in the long-term due to capital investments with a long payback period. To maintain profitability and deliver better environmental performance, higher costs would need to be passed onto consumers. Considering these factors and the timeframe to implement these changes, careful consideration is required by industry and individual enterprises before committing to targets, and exploration of opportunities to market products at a higher value in return for better environmental performance should be a key focus.

Overall Conclusions

Conclusions

Emission reductions of almost 50% were achieved in ‘model’ free range and cage-free farms due (primarily) to changes in diets and fossil energy consumption. Egg production was found to be heavily exposed to emissions associated with feed production. At present, the Australian grain industry has not established a pathway for emission reduction, and it is difficult to estimate emission reduction potential in this area. Although incremental improvements in FCR would offset some emissions (less feed = fewer emissions from feed production), other considerations also influence progress in reducing FCR and further improvement options need to be affordable. Moving from ‘low’ carbon to ‘carbon neutral’ is likely to be a high-cost endeavour as it would require either carbon neutral purchased inputs (such as grain and protein meal) or the purchase or self-generation of carbon credits.

The major limitation to emission reduction is expected to be the significant increase in cost-of-production, which requires further analysis to inform the preferred pathway. As a low-margin production system, it will be difficult for the egg industry to absorb the current expected costs that would be incurred by emission reduction activities. Three options for managing these cost increases have been identified: i) costs are passed onto customers and ultimately to consumers; ii) increased costs are borne by taxpayers via government subsidies; or iii) costs are absorbed by businesses along the supply chain, resulting in lower profitability. Cost models to handle these increases need to be explored through the supply chain.

More broadly, dialogue is needed with customers, consumers and government around the potential for emission reduction to increase food costs. Research and development is also required to identify and establish cost-effective mitigation options that increase productivity, maintain or lower costs while also reducing emissions. To date, research into the development of carbon neutral grains and the cost to the egg industry of sourcing this grain has been limited; joint livestock and feed grains research would be beneficial.

Recommendations

There are two principal recommendations from this project, which were relevant to both the chicken meat and egg assessment:

1. Establishment of defined emission reduction goals. Progress is only made when there is a target. Setting an agreed emission reduction target will bring about progress that otherwise cannot be guaranteed. Tracking performance against this target regularly (annually, biennially) will keep the industry focused on environmental performance. This will also allow the industry to engage other stakeholders (supplier industries, government, customers) and the general public over plans to reduce emissions. Ongoing work is needed to support the analysis here with detailed economic modelling.
2. Supporting the above recommendation, a research and engagement program is needed to support tracking and reducing emissions over the next two decades. This should consider a mix of readily implementable and blue-sky options to deliver in five to ten years from now. Many options that are currently unavailable have barriers to adoption, either because of technology or cost limitations. Solutions are needed to overcome these barriers and provide technological solutions into the future.

Specific research options arising from this research, that could be addressed in a program, are listed in the recommendations section together with further engagement recommendations.

1 Introduction

1.1 Background

With multiple industries and the Australian Government already having set emissions reduction, net zero or carbon neutral targets, and devised roadmaps to that end, the Australian egg industry recognises the need to examine emission reduction options for the industry. Part of a broader study, this report relies on updated carbon benchmarking collected in an industry-wide life cycle assessment (LCA) to model the effects of selected emissions reduction technologies and practices on a model production network. This report evaluates a range of mitigation strategies and technologies, and provides an estimate of the mitigation potential for case study farms.

The industry is already relatively 'low carbon' compared with other major animal protein sources. Further reductions, however, may be achieved by focusing on the major hotspots, including emissions from imported soy meal in diets, electricity and gas use.

1.2 Objectives

This work aimed to develop mitigation options and the supply chain pathway for carbon neutral eggs. The intention is that this report and the other project outputs will be useful resources for all levels of the industry in both the short- and long-term.

As the industry looks more closely into emission reduction, further work will be required to analyse the marginal costs of implementing the pathway in future decades.

1.3 Greenhouse gas emissions

Greenhouse gases (GHGs) in the atmosphere increase the retention of the Earth's outgoing energy, holding heat in the atmosphere and causing changes in the radiative balance between energy received from the sun and energy emitted from Earth. This can cause significant alterations in climate and weather patterns.

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

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

Methane and nitrous oxide have much higher warming potentials than carbon dioxide. Warming potentials are typically assessed in terms of radiative forcing, a measure of the immediate impact on atmospheric radiation balance from incremental increases in the gas (World Meteorological Organization 1985). A positive radiation force indicates that the incoming energy is greater than the outgoing energy, whilst a negative radiation force indicates that outgoing energy is greater than incoming energy.

GHGs are standardised using the Global Warming Potential (GWP) system, which allows for comparison between the quantity and potency of each gas. GWPs are a measure of the average warming impact of each gas over 100 years (reported as GWP_{100}). Each GWP is reported based on its carbon dioxide equivalent (CO_2-e). The GWP_{100} value for methane, for example, is 28, meaning that methane has 28 times the global warming potential of CO_2. The GWP_{100} value for nitrous oxide is 265. Although there are other metrics for determining the relative impacts of different GHGs, GWP_{100} values are the most commonly used system in global GHG accounting.

1.4 Emission benchmarks

GHG emission benchmarks are useful as they allow for comparison between different production systems and estimation of the emissions reduction potential of various technologies and strategies.

For egg production, the GHG emissions associated with an individual operation will vary significantly depending on the housing system and its energy requirements, ration composition, bird performance (especially feed conversion), and manure management.

1.5 Measuring emissions

The GHG Protocol (Ranganathan et al. 2004), a framework commonly used in business GHG accounting, defines three scopes of emissions:

- **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 distribution of eggs.

Figure 2 breaks down emissions by scope for a typical layer farm that performs grading on-site. Transport emissions post-grading floor are assumed to be downstream emissions, i.e. the eggs are sold and collected as property of a third party from the grading floor, and that party is then responsible for transporting them to the next destination.

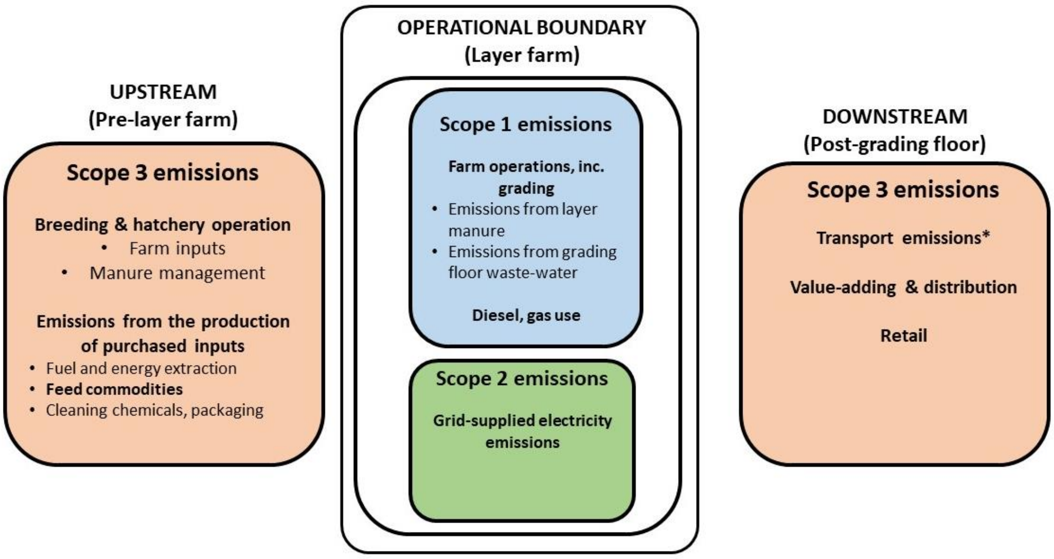

Figure 2 The operational boundary and emission sources by scope for a layer farm which operates a grading floor

* In some cases, transport to the next point in the supply chain may be within the operational control of the business.

Agri-food supply chains also differentiate emissions based on the contribution from land use (LU) and direct land-use change (dLUC). Emissions associated with LU relate to soil carbon losses from cultivation for crop production which, under some conditions, can lead to CO_2 emissions from soil. Emissions from dLUC refer to emissions that arise when land is converted from one use (e.g. forest or pasture) to another (such as cropland). This generally results in carbon losses from vegetation and soil. Where management practices result in carbon storage (e.g. conversion of cropland or pasture back to forest), the dLUC is negative, i.e. carbon is stored. LU and dLUC impacts are reported separately as part of a carbon footprint as there is an acknowledged higher level of uncertainty in determining these emission sources.

LU and dLUC impacts for poultry production in Australia tend to be dominated by impacts from imported soy meal in feed. In some instances, these impacts can exceed the carbon footprint of all other aspects of egg production.

1.5.1 Carbon footprint

Carbon footprinting is an analysis system defined in ISO standards (14067). The system is based on life cycle analysis and is effectively a ‘single issue’ LCA study. A carbon footprint is typically focused on a product (e.g. eggs) rather than a business or organisation, though it can be applied in that setting also. By definition, a carbon footprint includes scope 1, 2 and 3 emissions sources. This method is distinct from business carbon accounting which may be limited to only scope 1 and 2 sources.

A product carbon footprint reports impacts per kilogram of product (e.g. kilograms of CO_2-e kg^{-1} of eggs), which is commonly referred to as an emission intensity. Often used for benchmarking and comparisons, a carbon footprint is important when comparing products or marketing the low carbon credentials of a particular product.

In this report, the carbon footprint is scope 1, 2 and 3 emissions, incl. LU and dLUC emissions (as a type of scope 3).

1.5.2 Business accounting – scope 1 and 2 emissions

Scope 1 and 2 emissions are the most relevant emission sources for businesses, as they represent the emissions within direct operational control. Because these terms are relative to the operational boundary, they are typically not comparable between businesses. Some emissions that are 'scope 3' for one business may be 'scope 1' for another. Care must therefore be taken in comparing results and typically an emission intensity number is only reported for scope 1, 2 and 3 to ensure comparability.

1.6 Setting targets

There are broadly two types of common emission targets. The term 'carbon neutrality' is most common for a product. The term 'net zero' is most common for a business. They are described below.

1.6.1 Carbon neutrality

There are several definitions of carbon neutral and multiple standards through which market accreditation can be gained. Fundamentally, each relies on the same basic concept of no net release of GHG emissions into the atmosphere.

Market-facing carbon neutral certifications in Australian and internationally, such as Climate Active and PAS 2060, require the determination of a baseline carbon footprint (scope 1, 2 & 3) and then for emissions to be reduced before any remaining emissions are offset. Offsetting can be performed by either generating carbon credits through on-site carbon storage (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 products that have reached carbon neutrality by calculating, reducing, and offsetting their carbon emissions. To receive certification, the business or production system must meet the Climate Active Carbon Neutral Standard requirements. A mandatory step in the certification process is an independent third-party verification of 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.

While it is possible to certify a business or organisation as carbon neutral under the Climate Active program, this is challenging because of the requirement to offset scope 3 emissions that arise from other businesses.

Product carbon neutral certifications do not necessarily cover the full enterprise that produces the product. It is possible to assess only a particular product line (e.g. free range eggs) rather than all products. Carbon neutrality of a product is also necessarily related to the emission intensity of that product.

1.6.2 Net zero scope 1 and 2 emissions

Business targets typically focus on emissions within operational control (i.e. scope 1 and 2 emissions), though assessment of scope 3 emissions and target setting are considered best practice if these exceed 40% of total emissions.

Business targets are usually set for the total emissions from the business rather than on the emission intensity of the products sold. This reflects the global need to reduce absolute emissions, and not only to reduce the emission intensity of production. This has important implications as, for most agricultural businesses, total emissions are directly related to total production and as a business grows, emissions also increase. Where a future target is set, it is therefore necessary to project emissions under a business-as-usual (BAU) scenario so that company growth is taken into account. The differences between emission intensity and total emissions are described in Table 2.

Table 2 Emission intensity vs total emissions - implications of example business targets

	Emission intensity ***(kg CO_2-e kg^{-1} eggs)***	**Total production** ***(kg eggs)***	**Total emissions** ***(t CO_2-e)***
Baseline	1.5	20 million	30,000
Target: *5% reduction in emission intensity* *10% growth in production*	1.425	22 million	31,350
Target: *10% reduction in emission intensity* *10% growth in production*	1.35	22 million	29,700

1.6.3 Summary

Both the intensity and total emissions associated with a particular product and business are important measures of their environmental performance.

Determining and reporting emission intensity is important for communicating with the supply chain (customers and consumers) and for benchmarking performance.

Determining and reporting total scope 1 and 2 emissions is important for setting emission reduction targets for a business and for communicating with investors.

Understanding the different emission ‘scopes’ is useful for understanding a carbon account, and being able to switch between different targets and objectives.

2 Methodology

2.1 Baseline assessment

The methods and data used to generate the baseline assessment were outlined in Copley & Wiedemann *in preparation*), and these methods have not been repeated here in detail. In this study, total emissions were calculated using the weighted average emission intensity of cage, cage-free and free range eggs, and the total eggs produced (by mass) in 2020. The system boundary (from which emissions by scope were determined) was the 'cradle-to-grading floor-gate'.

Development of the baseline, or the BAU, scenario relied on weighted average industry data collected from six major egg producers operating in each of the major Australian production regions.

Based on the emissions profile of egg production, a broad range of potential mitigation strategies that targeted different emission sources were identified and evaluated. Each option was assessed based on its technical mitigation potential and economic feasibility in the context of a typical layer farm. Prospective mitigation options for the industry were included as steps in the low carbon and carbon neutral pathways.

Pathways were devised for two 'model' case study layer farms. These differed in scale and production system. A free range (FR) farm with 100,000 hens and a cage-free farm with 1,000,000 hens were used. Both farms were assumed to operate breeding and pullet rearing, layer sheds and grading on-site. Feed milling was assumed to be conducted off-farm.

2.2 Screening of potential mitigation options

A review was completed of a wide range of potential mitigation options that could be suitable for the industry (see Appendix 1). Screening was performed by identifying the emission source to be reduced (e.g. on-farm energy use), the mitigation strategy (e.g. solar) and the mitigation potential. An adoption rate was then considered, based on the likely uptake of the strategy or technology. Adoption was based on an assessment of feasibility, including a subjective consideration of economic feasibility, likelihood of productivity benefits, availability (i.e. is it currently commercially available or not), compatibility with other mitigation strategies, RD&E requirements and any other considerations, such as disbenefits or caveats around the strategy. Based on these criteria, options either screened 'in' or 'out'. Options that were screened in were subsequently developed into scenarios, as described in the following section.

2.3 Modelled scenarios

As New South Wales is home to a large proportion of the Australian flock and has a mid-range emission intensity electricity grid, the model farms were assumed to operate in that state. Key inventory parameters for each of the BAU scenarios are presented in Table 3.

Table 3 Key inventory parameters for the baseline free range and cage-free farms (BAU scenario)

Parameter	Free range	Cage-free
Location	NSW	NSW
Hen number	100,000	1,000,000
Stocking density (birds ha^{-1})	10,000	-
kg of eggs per yr	1,900,000	19,000,000
FCR	2.4	2.3
Imported soy meal (% of layer ration)	15	15
Layer shed grid electricity consumption (kWh yr^{-1})	469,805	4,682,143
Grading floor grid electricity consumption (kWh yr^{-1})	187,922	1,108,990
Manure belt removal	No	Yes

Timelines for emission reduction were set for an intermediate period of time (i.e. to 2035). This time period is considered the longest practical timeline for business planning purposes.

A distinction was made between low carbon and carbon neutrality, where low carbon is the point at which all feasible emissions reduction strategies have been implemented (see Module 3), barring purchased carbon offsets to achieve carbon neutrality (Module 4).

Where industry- and economy-wide trends have been observed, these are assumed to continue in the BAU and each module scenario. More specifically, the pathways assume that the decarbonisation of the state electricity grids will continue (see assumptions in Appendix 1). The BAU scenario also assumes a minor reduction in the emission intensity of feed grains (due to decarbonisation of the grid).

3 Results and discussion

3.1 Emission baseline

Greenhouse gas emissions (excl. LU and dLUC) were 1.2, 1.4 and 1.5 kg CO_2-e kg^{-1} eggs for cage, cage-free and free range production, respectively. Emissions from LU and dLUC were 0.7, 0.8 and 0.8 kg CO_2-e kg^{-1} eggs for cage, cage-free and free range production (see Figure 3). The carbon footprints (greenhouse gas emissions, incl. LU and dLUC) for cage, cage-free and free range eggs were 2.0, 2.1 and 2.3 CO_2-e kg^{-1} eggs. The weighted average emission intensity of Australian eggs was 1.4 kg CO_2-e kg^{-1}, with LU and dLUC emissions of 0.8 kg CO_2-e kg^{-1}, yielding a total emission intensity, incl. LU and dLUC, of 2.2 kg CO_2-e.

Feed production was the greatest contributor to emissions (71–74%, incl. LU and dLUC). Layer farm operations accounted for 14–16% of impacts, the upper bound being for free range production, which had the highest emissions from manure. Pullet production, including feed production, accounted for 7–9% of emissions. Grading (4–5%) and breeding (1%) were less significant sources of emissions.

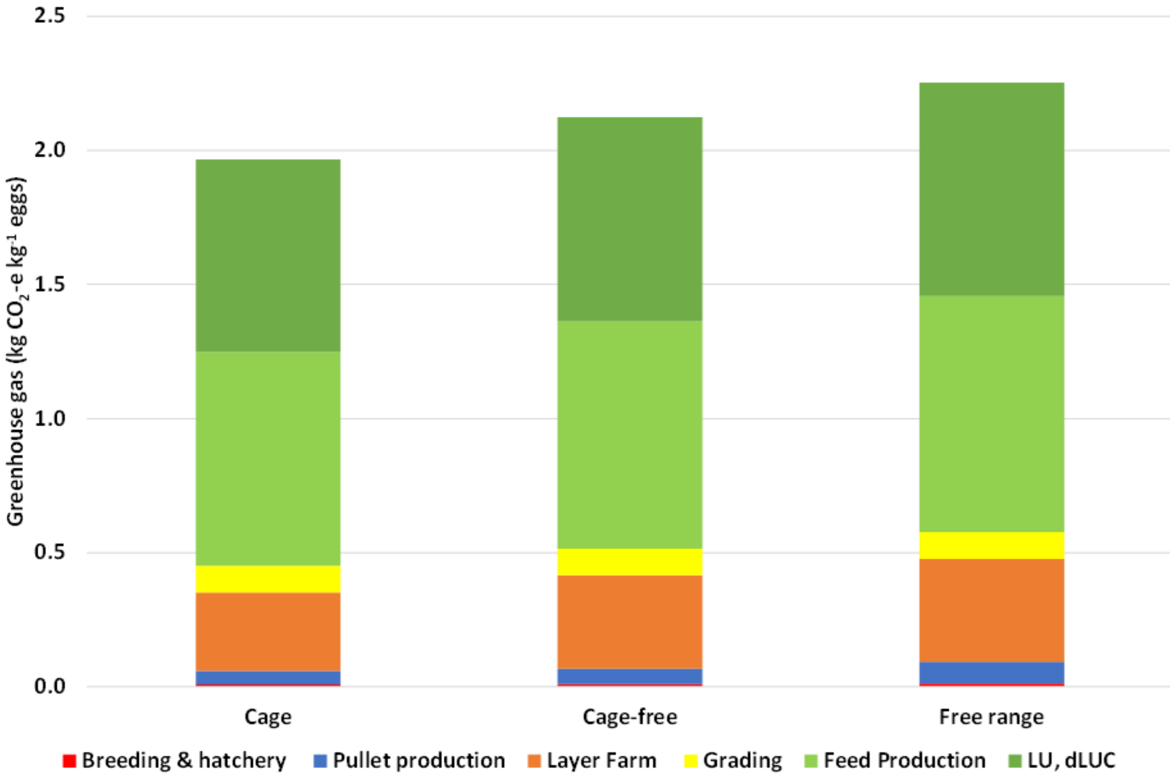

Figure 3 Emission intensity of cage, cage-free and free range eggs

Figure 4 depicts total emissions for the Australian egg industry in 2020, classified by scope 1, 2 and 3 emissions, incl. LU and dLUC. Scope 1 and 2 emissions accounted for 19% of total emissions. Scope 2 emissions were emissions associated with grid electricity consumption, whilst the major contributor to scope 1 emissions was energy (other than grid electricity consumption) with a smaller contribution from manure-related emissions.

Scope 3 emissions, driven by feed production, represented 43% of the total. Feed production, particularly production of cereal grains, was the largest contributor to scope 3 emissions.

Scope 3 – LU and dLUC emissions, which represented 36% of the total, were driven by the inclusion rate of imported soy meal in diets.

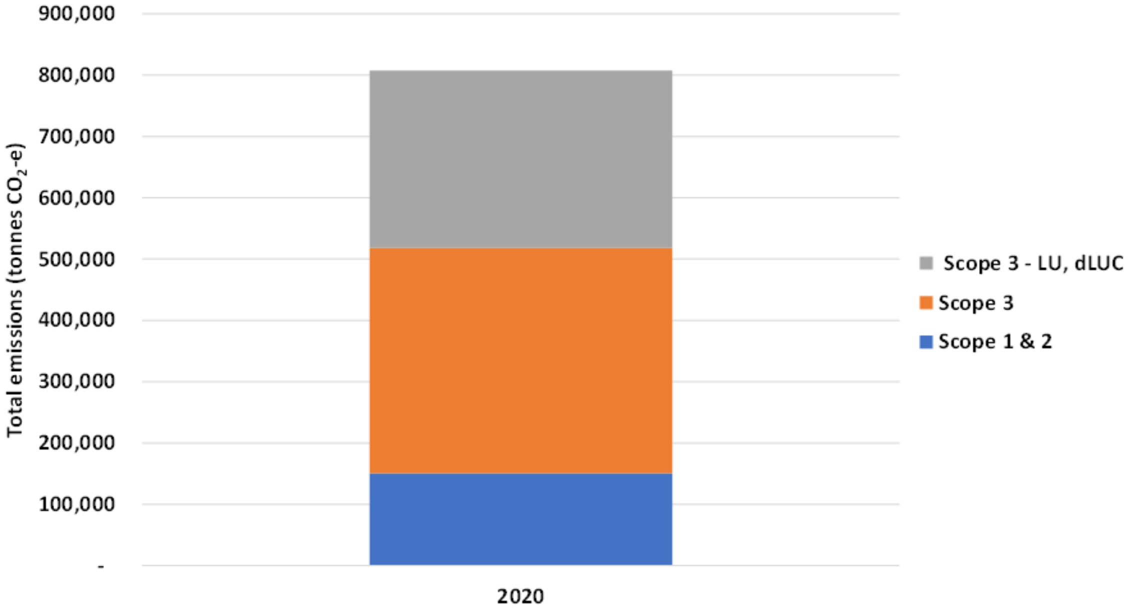

Figure 4 Emissions for the Australian egg industry, reported as scope 1, 2 and 3 (incl. LU and dLUC) emissions

3.2 Cost estimate of carbon neutral eggs

A preliminary estimate of the cost of producing carbon neutral eggs through purchased offsets was performed. The costs under two scenarios are outlined in Table 4, the first scenario being where the only purchased offsets were Australian Carbon Credit Units (ACCUs), and the second being where 30% of purchased offsets were ACCUs and the rest were international carbon credits.

The ACCU price was an approximate mid-point for the first half of March 2022. This estimate was preferred over the spot price, as significant macroeconomic events and uncertainty can lead to fluctuations in the price of carbon.

Note that the cost of carbon neutral products will vary according to:

- the carbon footprint of the product
- the price of carbon offsets
- the scale of the project (e.g. carbon neutral product volume).

Table 4 Cost estimate for carbon neutral accredited eggs

	Scenario 1 *ACCUs only*	**Scenario 2** *ACCUs (30%) and international credits (70%)*
Emission profile of the product *(kg CO_2-e/kg)*	2.2	2.2
ACCU price *(\$/tonne CO_2-e)*	40.0	40.0
International carbon credit price *(\$/tonne CO_2-e)*	-	10.0
c/kg product ***(Total)***	8.8	4.2

3.2.1 Cost of carbon neutral certification

Further costs that were not included in Table 4 due to the high degree of variation, were the costs associated with engaging a registered consultant to develop a carbon neutral project, licence fees for accreditation through Climate Active, and fees for the audit of the assessment. Assuming that these costs were in line with the following estimates:

- project development fees of $40–70,000
- licence fees for Climate Active of ~$8,000 (dependent on the carbon footprint)
- auditor fees of $10–20,000.

At 1,000,000 kg of carbon neutral product, this would add a further 0.06–0.1c per kilogram of product, taking the cost to ~8.9 and 4.3c/kg of carbon neutral eggs for scenarios 1 and 2, respectively. Note that the greater the volume of carbon neutral product, the smaller this fee-related cost per kilogram of product.

3.3 Emission mitigation screening

To reach low carbon or carbon neutrality, the industry requires implementable mitigation options that can be applied as a pathway. This chapter details the list of strategies identified for investigation. After the options were reviewed, they were either screened in or out for pathway development based on mitigation potential, technical and economic viability. The reduction strategies were grouped into four categories: diet and performance, energy, manure management and utilisation, and carbon storage (see Figure 5).

Table 5 outlines the results of the screening assessment for each strategy. Detailed explanations of each mitigation strategy are provided in Appendix 1. In Table 5, both the technical mitigation potential and the likely mitigation potential in the industry to 2035 have been determined. The technical mitigation is the rate that could be achieved at a facility if the technology was 100% effective (for example, it could be applied across the whole site at full efficiency), while the industry mitigation to 2035 assumes a lower level of effectiveness and a proportional adoption rate, depending on how readily adopted and cost-effective the technology is likely to be. For the emission reduction pathways, the effective mitigation potential for a facility was used.

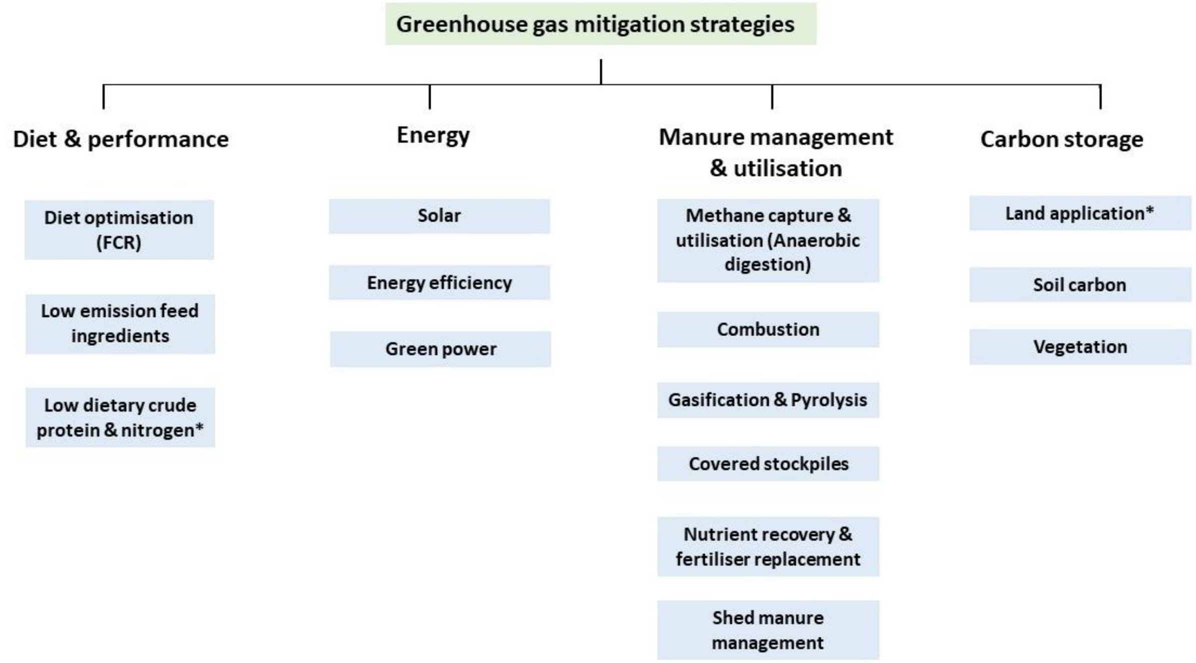

Figure 5 Greenhouse gas mitigation options for Australian layer farms

Note: Strategies marked with * are multi-category, i.e. manure application to land is also manure management related.

Table 5 Screening assessment of emission reduction strategies, described by emission source targeted and implementation timeline

H1 = Horizon 1 (0–2 years), H2 = Horizon 2 (3–5 years), H3 = Horizon 3 (6–10+ years)

Category	Strategy	Emission source targeted	Emission source as percentage of total emissions*	Technical mitigation potential & viability	Estimated industry adoption to 2035	Projected reduction in industry emissions to 2035	Economically viable	Productivity benefits	Available for implementation	Compatibility with other mitigation strategies	RD&E required	Other considerations	Priority for implementation
Diet & performance	Improve FCR	Feed production	80%	13%	10%	1%	Depends on other considerations.	Yes, depending on other considerations.	Genetic advances are ongoing; FCR improvement via amino acid optimisation also ongoing.	Generally compatible. Results in an overall efficiency improvement.	Competing breeding and management objectives have reduced potential improvements in FCR. Research needed to identify best environmental outcomes.	Other breeding and management objectives such as longer laying periods may counteract potential improvement in FCR.	**OUT**
	Low emission feed ingredients - imported soy meal	Feed production - LU, dLUC	36%	100%	100%	36%	Imported soy meal is the marginal global protein. Almost all other products that can deliver equivalent performance increase other costs.	None.	Available.	Compatible.	Research to quantify impacts from imported soy. Cost effective alternatives or certified soy meal.		**H1**
	Low emission feed ingredients - Australian grain	Feed production	7%	40%	50%	1%	It may be possible to source lower emission grain without a cost impact because this is influenced to some extent by production region & other non-productivity related factors.	None.	Available.	Compatible.	Selection of low GHG grain regions. Certified low GHG grain.	Currently grain is traded as a bulk commodity with low traceability and information on environmental practices would be needed to source low GHG grain.	**H1**
	Protein alternatives - insect protein	Feed production	9%	30%	25%	0.6%	Not currently viable.	None expected.	Trials underway. Limited commercial volumes in 2021.	Could reduce reliance on imported soy meal.	Feed value, safety, GHG emissions from the production system, cost effectiveness.	Needs to be produced from waste materials to be effective. Cost is currently a major barrier & little is known about GHG from production.	**H3**

	Low dietary CP	Emissions from manure	8%	10%	25%	0.25%	Generally more expensive to reduce CP with higher amino acid inclusion rates.	May result in better shed conditions from lower ammonia.	Available.	Compatible.	Cost effectiveness & productivity impacts.	Also provides benefits for ammonia emission rates impacting bird & worker health.	**Out**
Energy	Solar - layer farm (layer sheds, pullet rearing, grading)	Energy (grid electricity)	12%	30%	80%	2.6%	Yes, depending on site specific conditions.	Cost reduction.	Available.	Generally not compatible with other energy strategies on the same site.	Case studies to promote uptake.	Needs to be matched with energy profile of farm.	**H1**
	Energy efficiency	Energy	25%	10%	75%	1.9%	Yes depending on management, maintenance and upgrade requirements.	Cost reduction.	Available.	Reduces the need for solar/other renewables.	Most effective options & case studies of progress that has been made.	Should be part of BAU but can be limited by labour to carry out best practice management.	**H1**
	GreenPower	Energy (grid electricity)	12%	100%	25%	3.0%	High cost.	None.	Available.	Reduces the need for solar/other renewables.		Cost needs to come down or customers may need to absorb higher cost-of-production	**Out**
	Methane capture & utilisation (AD)	Energy	14%	95%	15%	1.8%	High cost and site dependent.	Generate electricity & heat energy on-site.	Well established for pigs, but work required to implement in poultry.	Will generally only work if it offsets 100% of on-site power.	Cost effective commercial demonstration incl. ammonia stripping & possibly improved efficacy with straw not shavings. Business case, including funding.	Depending on technology, this may generate effluent, which causes a problem for environmental management & planning. Will only suit very big farms.	**Out**
	Combustion	Energy	14%	100%	0%	0%	High cost and not suited to layer farm manure.	Generate electricity & heat energy.	Ash and moisture content of manure are inhibitory.	Will generally only work if it offsets 100% of on-site power.	Not viable.	Requires manure with low moisture & ash levels. High levels of moisture result in very low energy potential. High levels of ash in floor manure make it a marginal substrate compared to high carbon biomass.	**Out**

	Gasification & Pyrolysis	Energy	14%	100%	0%	0%	High cost and not suited to layer farm manure.	Generate electricity & heat energy.	Ash and moisture content of manure are inhibitory.	Will generally only work if it offsets 100% of on-site power.	Not viable.	High cost & unproven in Australian context. Problems noted for combustion also exist for gasification & pyrolysis.	**Out**
Manure management & utilisation	Covered stockpiles	Emissions from manure	1%	100%	10%	0.1%	Yes, depending on labour	Will reduce N losses & odour.	Available.	Targets same emissions as low CP diets.	Are reductions maintained during land application?	Nitrogen retained in stockpiling may be lost during land application.	**Out**
	Nutrient recovery	Fertiliser requirements for grain	6%	75%	15%	0.3%	Not currently viable.	Circularity, cost recovery, solves low demand for spent litter.	Has been successfully implemented overseas, not Australia.	Implementation needs to occur with waste-to-energy.	Technology, cost effectiveness, market suitability of product, business case.	Targets small emission source. Benefits for grain industry around low emission fertiliser & soil health, circularity.	**Out**
	Better shed litter management using litter additives	Emissions from manure	8%	1%	0%	0%	Cost of additives & labour.	Possibly decreased odour.	Available.	Targets same emissions as low CP diets.	Considering low mitigation potential, research not warranted.	Nutrients retained in shed may be lost in stockpiling or land application.	**Out**
Carbon storage	Land application of manure	Offset	-	2%	95%	0.4%	Quantification costs can be high, especially if aiming to develop carbon offset credits. Dependent on site specific considerations, particularly scale and sequestration potential.	Yes, if applied to land used for grain production, which flows back into feed.	Available.	Not compatible with waste-to-energy projects, which utilise the carbon & would reduce supply for soil carbon projects.	Investigate potential to increase use by grain industry to reduce synthetic fertiliser. Quantify carbon benefits.	Nutrient loading must be managed through appropriate application rates.	**Out**
	Soil carbon on ranges	Offset	-	0%	15%	0%	Carbon storage, however, requires soil testing. Quantification costs can be high for small areas.	Soil carbon benefits soil health.	Available.	Yes.	Nil.	Other considerations such as nutrient loss risk and soil health are also important.	**Out**
	Vegetation	Offset	-	1%	57%	0.6%	Cost dependent on planting size, which determines storage potential. Quantification costs are high if aiming to develop carbon offset credits.		Available.	Yes.	Nil.	Requires trees that don't attract wildlife & birds. Other benefits as veg buffers, but generally areas are small making it difficult to implement cost-effectively.	**Out**

*Inclusive of LU and dLUC emissions.

3.4 Pathways to low carbon and carbon neutrality

Scenarios were modelled to investigate the emissions reduction and carbon storage potential of key operational changes: the adoption of on-site solar energy generation, a change to layer rations with low levels of imported soy meal and crude protein, tree plantings, application of manure to land and, for free range, carbon storage on ranges. The structure of each mitigation module is described in Table 6.

Table 6 Emissions reduction scenarios – key assumptions

	Business-as-usual	**Module 1**	**Module 2**	**Module 3 *(Low carbon)***	**Module 4 *(Carbon neutral)***
Decarbonisation of energy grid	🟩	🟩	🟩	🟩	🟩
Soil carbon storage on ranges/land application		🟩	🟩	🟩	🟩
Low GHG diets		🟩	🟩	🟩	🟩
Renewable energy (on-site solar)			🟩	🟩	🟩
Vegetation carbon storage				🟩	🟩
Purchased offsets					🟩

Case study pathways to low carbon and carbon neutrality are provided for both a model free range farm and a cage-free farm.
Table 7 and Table 11 outline the key assumptions for each model farm's BAU scenario.

The tables at the start of each section describe the key assumptions for each mitigation module. Only the assumptions contained in the table in each section are assumed to have changed from the baselines in
Table 7 and Table 11. The stages are assumed to be additive, i.e. stage 1 is a low GHG diet, and stage 2 is a low GHG diet and adoption of on-farm solar, etc. The chapter makes a distinction between 'low carbon' and carbon neutral. Low carbon is assumed to be the point at which all technically viable operational scenarios have been implemented. The carbon neutral pathway is the low carbon pathway plus the additional mitigation required to be purchased as carbon offsets.

Results are reported in tonnes of CO_2-e, presented as net emissions, inclusive of LU and dLUC, for the whole supply chain (i.e. feed production and farm operations – laying, breeding, pullet rearing, grading). For each module, emissions are reported for the final year in that module, e.g. emissions reported for Module 1 are for 2025.

3.5 Free range case study

The assumptions for the BAU and each module are outlined below. Given the assumptions for the baseline farm (see Table 7), the pathway does not include anaerobic digestion, as it is highly unlikely to be a viable option for this model farm due to scale (hen numbers) and shed/manure management type.

3.5.1 Baseline scenario

Table 7 Model free range farm assumptions, including energy consumption

Factor	Model value	Notes
Operations	Breeding, pullet rearing, grading floor, free range layer farm	No feed mill on farm
Location	New South Wales	
No. of layers	100,000	No manure belts in sheds; birds based on litter
Stocking density (birds ha^{-1})	10,000	
kg. of eggs yr^{-1}	1,900,000	Based on 19 kg eggs hen^{-1} yr^{-1}
FCR	2.4	kg feed kg^{-1} eggs
Imported soy meal (% of layer ration)	15	Assumed to be an Australian import market product (majority Argentinian origin)
Dietary crude protein (%)	17.4	
Layer shed grid electricity consumption (kWh yr^{-1})	469,805	0.25 kWh kg^{-1} eggs
Grading floor grid electricity consumption (kWh yr^{-1})	110,899	0.06 kWh kg^{-1} eggs
GHG emissions (t CO_2-e)	**3,085**	
LU, dLUC emissions (t CO_2-e)	**2,550**	Driven by impacts from imported soy meal included at 15% of diet
Carbon storage (t CO_2-e)	**-13**	13 tonnes of carbon is stored on ranges each year from manure
Net emissions (t CO_2-e), incl. LU & dLUC	***5,622***	

3.5.2 Pathway to low carbon free range eggs

3.5.2.1 Module 1 – Low GHG diet

Based on the parameters described in Table 8, adopting a low emission intensity ration reduced emissions (from the 2021 baseline) for the whole supply chain (i.e. to grading floor gate) by 40%, inclusive of LU and dLUC. The bulk of the reduction was from the decreasing LU and dLUC impacts, driven by the reduction in imported soy meal in the ration.

Table 8 Key assumptions for low impact free range layer rations

Factor	Model value	Description
Period of implementation	2022–2025	
Imported soy meal (% of layer ration)	1.5	A 90% decrease from the baseline scenario over 3 years
Dietary crude protein (%)	15.6	A 10% decrease from the baseline scenario over 3 years
GHG emissions (t CO_2-e)	**2,926**	
LU, dLUC emissions (t CO_2-e)	**459**	
Carbon storage (t CO_2-e)	**-13**	
Net emissions (t CO_2-e), incl. LU & dLUC and carbon storage	***3,372***	

For emissions that arose within the farm's operational boundary (i.e. excluding emissions from feed production), the reduced dietary CP reduced emissions from manure (which fell within the farm's scope 1 emissions).

3.5.2.2 Module 2 – Low GHG diet and on-site solar

Adopting on-site solar in addition to the low GHG diet yielded a 7% reduction in emissions from 2026 (a year after Module 1 had been fully implemented and the year before Module 2 commenced). As outlined in Table 9, more than half of the electricity demand for the grading facility and 30% for the layer sheds was reduced under this module.

Table 9 Key assumptions for solar adoption on a free range farm

Factor	Model value	Description
Period of implementation	2027–2029	
Grid electricity consumption, layer shed (kWh yr^{-1})	187,922	30% of grid electricity consumption reduced by solar
Grid electricity consumption, grading floor (kWh yr^{-1})	44,360	60% of grid electricity consumption reduced by solar
GHG emissions (t CO_2-e)	**2,735**	
LU, dLUC impacts (t CO_2-e)	**459**	
Carbon storage (t CO_2-e)	**-13**	
Net emissions (t CO_2-e), incl. LU & dLUC	***3,113***	

As this module directly reduced grid electricity consumption, the emission reduction is realised as decreased scope 2 emissions.

Depending on the state grid and the contribution of grid electricity consumption to any producer's carbon footprint, the mitigation potential of this scenario will vary.

3.5.2.3 Module 3: Low carbon – Low GHG diet, on-site solar, vegetation carbon storage

The farm also had 10ha of tree plantings for linear plantings on ranges, buffer areas and tree lines along roads (see Table 10). The carbon storage in these areas was assessed, assuming annual sequestration rates of 7.5t CO_2-e ha^{-1}. This resulted in carbon sequestration (negative emissions) of 75t CO_2-e.

With the addition of Module 3 (vegetation carbon storage) to the mitigation pathway, emissions were 49% below the 2021 baseline and a further 3% below emissions after implementation of Module 2.

Table 10 Key assumptions for carbon storage on a free range farm

Factor	Model value	Description
Period of implementation	2032–2034	
% of manure deposited on range	13.6	Clarke and Wiedemann 2020
Digestibility of feed (%)	75	
Soil carbon retention rate	30%	30% of the soil organic carbon deposited on the range as manure is retained in the soil
Vegetation carbon sequestration rate, t CO_2-e ha^{-1} yr^{-1}	7.5	
Area for monocultural plantings (ha)	25	
Total GHG emissions (t CO_2-e)	**2,505**	
Total LU, dLUC impacts (t CO_2-e)	**459**	
Carbon storage (t CO_2-e)	**-88**	
Net emissions (t CO_2-e), incl. LU & dLUC	***2,876***	

3.5.3 Pathway to carbon neutral free range eggs

3.5.3.1 Module 4: Carbon neutral – Low GHG diet, on-farm solar, vegetation carbon storage, purchased offsets

Following Module 3, producers would need to purchase carbon offsets to achieve carbon neutrality. Although total emissions in 2035 were 2,964 t CO_2-e, net emissions were 2,876 t CO_2-e due to carbon storage via manure on ranges and carbon sequestration from vegetation provided carbon storage is recognised. The producer would need to purchase 2,876 carbon offsets (where one offset is equivalent to one tonne of CO_2-e).

3.5.3.2 Emissions reduction at each stage of the pathway

The emissions reductions brought about by each module are outlined in Table 22 (see Appendix 2), both as net values for the tonne contribution of each stage and as the sum total. Figure 6 presents the total emissions (by scope, including LU and dLUC) at each stage of the pathway, and presents the equivalent emissions for each year under the business-as-usual scenario (i.e. no change except for the decarbonisation of the energy grid). The pathways are presented as total tonnes of emissions and carbon sequestered or offset each year. Net emissions are also marked.

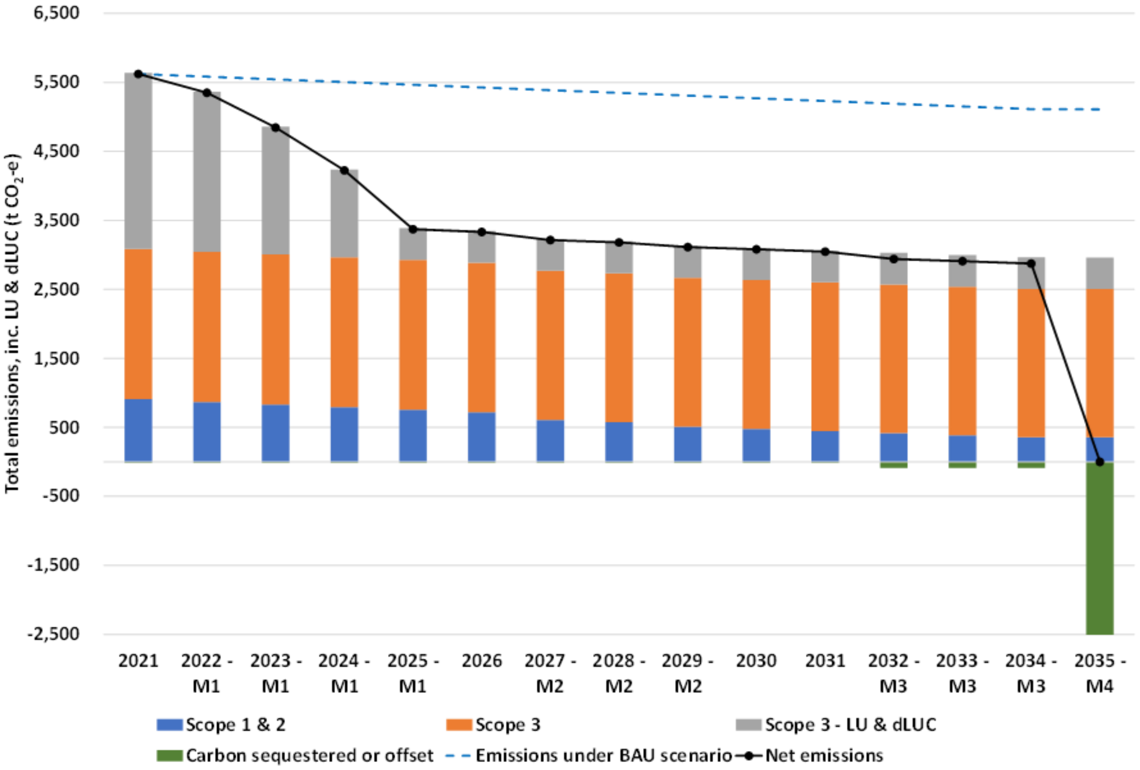

Figure 6 Emission reduction pathway for a model 100,000 layer hen free range facility, including pullet rearing and grading

Note: Total emissions include scope 1, 2 and 3 emission sources, incl. LU and dLUC.
Data provided in Table 22 (Appendix 2).

3.6 Cage-free case study

The assumptions for the baseline and each stage of emissions reduction are outlined below (see Table 11). Note that the assumptions for the model farm, including farm size and shed design, differ significantly from the model farm for the free range case study (see
Table 7).

As the adoption of a CHP anaerobic digester is only likely to be feasible under a specific set of circumstances (farm size, manure volume and moisture content, working capital, etc.), and the technology is also not compatible with solar, adoption is not included in this case study. The following section includes the adoption of solar instead of AD.

The BAU scenario assumes that manure is applied to land owned by the producer. In practice, if manure was sold as a substitute (at least in part) for synthetic fertilisers and applied to land which produced grains that were then used for layer or pullet feed, this would also reduce scope 3 emissions. In this way there would be an indirect benefit to the egg producer through lower emission intensity feed grains (refer to 3.6 Fertiliser replacement in Appendix 1 for further detail).

3.6.1 Pathway to low carbon cage-free eggs

3.6.1.1 Baseline scenario

Table 11 Model cage-free farm assumptions, including energy consumption

Factor	Model value	Description
Operations	Breeding, pullet rearing, grading floor, free range layer farm	No feed mill on farm
Location	New South Wales	
No. of layers	1,000,000	Birds on slats, manure belts in sheds
Kg of eggs yr^{-1}	19,000,000	Based on 19 kg eggs hen^{-1} yr^{-1}
FCR	2.3	kg feed kg^{-1} eggs
Imported soy meal (% of layer ration)	15	Assumed to be an Australian import market product (majority Argentinian origin)
Layer shed grid electricity consumption (kWh yr^{-1}*)*	4,682,143	Based on 0.25 kWh kg^{-1} eggs
Grading floor grid electricity consumption (kWh yr^{-1}*)*	1,108,990	Based on 0.06 kWh kg^{-1} eggs
GHG emissions (t CO_2-e)	**28,608**	
LU, dLUC emissions (t CO_2-e)	**24,524**	Driven by impacts from imported soy meal
Carbon storage (t CO_2-e)	**-1,141**	Land application of manure
Net emissions (t CO_2-e)	***51,991***	GHG emissions + LU, dLUC emissions + carbon storage

3.6.1.2 Module 1 – Low GHG diet

Based on the parameters described in Table 12, adopting a low emission diet would yield a 40% reduction in emissions, inclusive of LU and dLUC and relative to the 2021 baseline. The bulk of the reduction (approx. 80%) is from the decreasing impacts driven by the reduction of imported soy meal in the ration.

Table 12 Key assumptions for low impact cage-free layer rations

Factor	Model value	Description
Date of implementation	2022–2025	
Imported soy meal (% of layer ration)	1.5%	A 90% decrease from baseline scenario (2021) by 2024
GHG emissions (t CO_2-e)	**27,234**	
LU, dLUC emissions (t CO_2-e)	**4,667**	
Carbon storage (t CO_2-e)	**-1,141**	
Net emissions (t CO_2-e)	***30,760***	

3.6.1.3 Module 2 – Low GHG diets, on-site solar

After transitioning to a low GHG diet, adopting solar-generated electricity to reduce grid electricity consumption in layer sheds and subsequently at the grading floor (see Table 13) yielded a 9% reduction in emissions from 2026 (after Module 1 had been completed).

Table 13 Key assumptions for on-site solar on a cage-free farm

Factor	Model value	Description
Period of implementation	2027–2030	
Grid electricity consumption, layer sheds (kWh yr^{-1})	1,872,857	60% of grid electricity consumption offset by solar
Grid electricity consumption, grading floor (kWh yr^{-1})	443,596	60% of grid electricity consumption offset by solar
Total GHG emissions (t CO_2-e)	**24,124**	
Total LU, dLUC impacts (t CO_2-e)	**4,667**	
Carbon storage (t CO_2-e)	**-1,141**	
Net emissions (t CO_2-e)	***27,650***	

3.6.1.4 Module 3: Low carbon – Low GHG diets, on-farm solar, vegetation carbon storage

The farm also had 25ha of tree plantings for buffer areas and tree lines along roads (see Table 14). The carbon storage in these areas was assessed, assuming annual sequestration rates of 7.5 t CO_2-e ha^{-1}. This resulted in carbon sequestration (negative emissions) of 187.5 t CO_2-e.

The scenario was re-run to further examine the potential for trees on-farm to demonstrate the tree plantings required to reduce emissions by 5%. This revealed that more than 1,500 ha of tree plantings at moderate sequestration rates were required.

Table 14 Key assumptions for vegetation carbon storage on a cage-free farm

Factor	Model value	Description
Date of implementation	2028	
Soil carbon sequestration rate, t CO_2-e ha^{-1} yr^{-1}	7.5	
Area for monocultural plantings (ha)	25	
GHG emissions (t CO_2-e)	**22,489**	
LU, dLUC emissions (t CO_2-e)	**4,667**	
Carbon storage (t CO_2-e)	**-1,328**	
Net Emissions (t CO_2-e)	***25,827***	

3.6.2 Pathway to carbon neutral cage-free eggs

3.6.2.1 Module 4: Carbon neutral – Low GHG diets, on-site solar, vegetation carbon storage, purchased offsets

Following Module 3 (described in section 3.6.1.4 above), which exhausts the viable on-farm emission reduction and offsetting options, the producer would need to purchase carbon offsets to achieve carbon neutrality. These offsets would amount to 48% of the 2021 baseline net emissions.

With 26,876 t CO_2-e of the carbon account remaining, the producer would need to purchase 25,548 carbon offsets (one offset is equivalent to one tonne of CO_2-e) as 1,328 t CO_2-e is offset through vegetation and land application.

3.6.2.2 *Emissions reduction at each stage of the pathway*

The emissions reductions brought about by each stage are outlined in Table 23 (Appendix 2), both as net values for the tonne contribution of each stage and as the cumulative total. Figure 7 presents the total emissions for the baseline and at each stage of the pathway to carbon neutral, including LU and dLUC emissions.

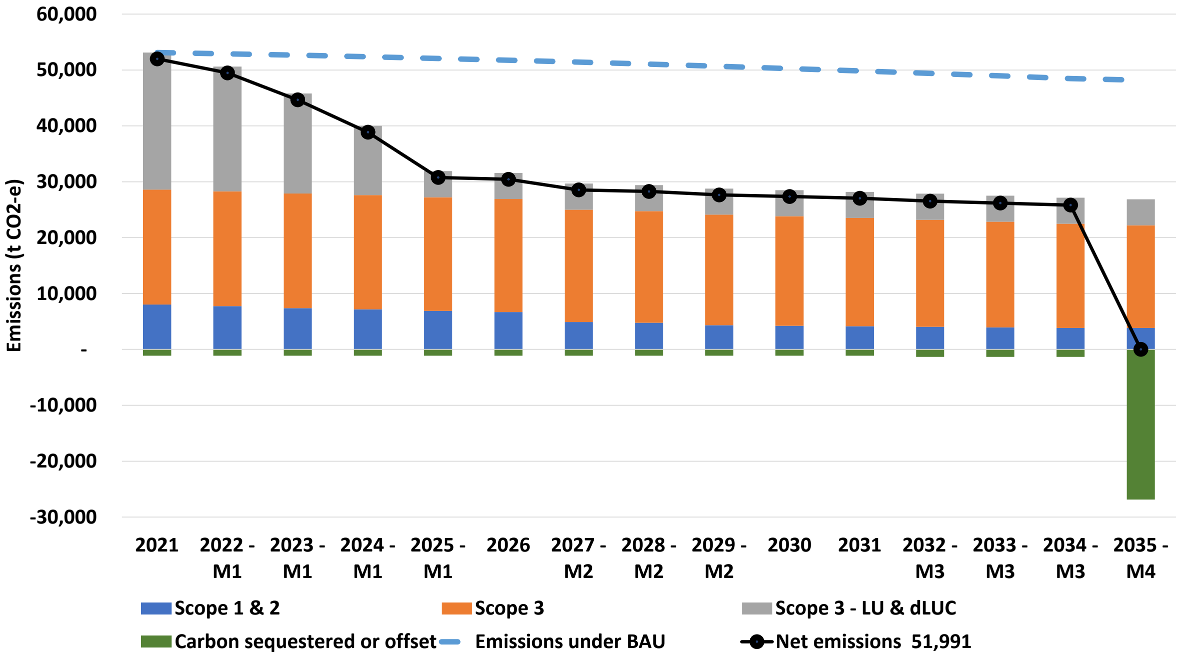

Figure 7 Emission reduction pathways for a model 1,000,000 layer hen cage-free facility, including pullet rearing and grading

Note: Total emissions include scope 1, 2 and 3 emission sources and LU and dLUC.

4 Conclusions and recommendations

Eggs are a relatively low-emission production system. For larger businesses, however, total emissions are still substantial, and pressure exists to reduce the carbon footprint of eggs and business scope 1 and 2 emissions. Emission reductions of approximately 50% were achieved in 'model' free range and cage-free farms due (primarily) to changes in diets and fossil energy consumption.

The model farms (and by extension, the industry) are heavily exposed to emissions associated with feed production. Moving to low emissions or carbon neutrality for eggs will likely require ongoing decarbonisation of the grain industry or else it will be necessary to offset emissions via purchased or self-generated carbon credits.

Such increases in cost-of-production are the major limitation to emission reduction, raising the need for further analysis to inform the preferred pathway. As a low-margin production system, it will be difficult for the egg industry to absorb the current expected costs that will be incurred by emission reduction activities. The three options identified in this study to manage these cost increases are: i) passing costs onto customers and ultimately to consumers; ii) taxpayers bearing the costs via government subsidies; or iii) businesses along the supply chain absorbing the costs, resulting in lower profitability. Cost models to handle these increases need to be explored through the supply chain.

More broadly, dialogue is needed with customers, consumers and Government around the potential for emission reduction to increase the cost of staple food products, such as eggs. Research and development is also needed to identify and establish cost-effective mitigation options that increase productivity, maintain or lower costs whilst also reducing emissions. To date, research into the development of carbon neutral grains and the cost to the egg industry of sourcing such grain has been limited. Joint livestock and feed grains research would be beneficial.

Recommendations

Some options in the present study were screened out because of current limitations, and other options are likely to be high cost or difficult to implement for individual producers. Industry research should focus on overcoming technical barriers and reducing costs, while also looking for new 'blue sky' options to reduce emissions.

There are two principal recommendations from this project, which were relevant to both the chicken meat and egg assessment:

1. Establishment of defined emission reduction goals. Progress is only made when there is a target. Setting an agreed emission reduction target will bring about progress that otherwise cannot be guaranteed. Tracking performance against this target regularly (annually, biennially) will keep the industry focused on environmental performance. This will also allow the industry to engage other stakeholders (supplier industries, government, customers) and the general public over plans to reduce emissions. Ongoing work is needed to support the analysis here with detailed economic modelling.
2. Supporting the above recommendation, a research and engagement program is needed to support tracking and reducing emissions over the next two decades. This should consider a mix of readily implementable and 'blue sky' options to deliver in five to ten years from now. Many options that are currently unavailable have barriers to adoption, either because of technology or cost limitations. Solutions are needed to overcome these barriers and provide technological solutions into the future.

We have outlined specific research and extension recommendations below.

Research

1. Research should be undertaken to understand the emission profile and emission reduction opportunities associated with imported soy meal. This may include working with the industry (or other livestock industries exposed to imported soy meal) to develop carbon accreditation systems to reduce emissions and provide confidence in low-emission soy meal.
2. Investment in further (and ongoing) public-access research into low emission intensity rations and diet formulations is required. Research could be directed at amino acid optimisation to facilitate reductions in dietary crude protein and emission intensive protein meals.
3. Investigation of the Australian feed grains sector's emissions and emission reduction opportunities would be beneficial, particularly if emission intensities were reported on a regional basis. This type of project would suit a partnership with other intensive livestock industries and the feed grains sector within the grain industry.
4. Research into methods to overcome the barriers to anaerobic digestion (AD) would be valuable as a longer-term priority to provide options for the industry to generate power and open options for nutrient recovery. This would require overcoming limitations from methane leakage, inhibitory effects of ammonia, and the current high costs. Further to this, establishing a full-scale anaerobic digester at a demonstration site would benefit the industry, especially as a commercial model through which studies to limit methane leakage could be undertaken. Establishing a working anaerobic digester would also allow for the investigation and feasibility assessment of nutrient recovery. Research to overcome these barriers to AD could attract joint funding from ARENA and could leverage green financing.
5. For smaller producers, access to cost-benefit analyses of scalable emission reduction technologies, including itemised costs would give smaller producers access to information and feasibility studies that are largely only accessible to larger enterprises.
6. The highly topical nature of soil carbon warrants investigation into the carbon storage potential of land application of manure, e.g. how much carbon is likely to be sequestered, and whether there is a market opportunity in relation to this.

Policy, extension and engagement

7. The pathways to low carbon or carbon neutral eggs and any accompanying explanation must acknowledge that low carbon and/or carbon neutrality needs to be developed cost-effectively and that, in most cases, this will increase the cost of production, at least in the short-term. Reducing costs into the future and exploring avenues to share higher costs for better environmental performance with consumers and/or major customers should be considered as part of establishing a low-carbon accreditation scheme. Research must focus on cost-neutral or reduced costs as a primary objective in parallel with emission reduction.
8. Monitoring progress will be essential to progressing towards meaningful emission reductions or improvement against other environmental impact categories. A simplified model should be developed to allow for more frequent but cost-effective monitoring of industry performance and to track progress against the projections made in this report.
9. The industry would benefit from the re-release of simplified fact sheets developed previously, which covered key aspects of environmental performance.
10. Further simple fact sheets or webinars could be developed, which clearly communicate what emission mitigation strategies (particularly waste-to-energy) work in the egg industry and which do not.

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6 Plain English Summary

Project Title:	**Carbon and environmental impacts of poultry production: 2020 and beyond**
Australian Eggs Limited Project No.	31RS005IA
Researchers Involved	M. A. Copley, S.G. Wiedemann and E.J. McGahan
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Objectives	To develop mitigation options and the supply chain pathway for carbon neutral eggs.
Background	With multiple industries and the Australian Government already having set emissions reduction, net zero or carbon neutral targets, and devised roadmaps to that end, the Australian egg industry recognises the need to examine emission reduction options for the industry. The industry is already relatively 'low carbon' compared with other major animal protein sources, although further reductions may be achieved by focusing on the major hotspots. A comprehensive review of the technical mitigation potential and feasibility of mitigation strategies and technologies is needed, however, in order determine viable options for the industry.
Research	Part of a broader study, this report relies on updated carbon benchmarking collected in an industry-wide life cycle assessment (LCA) to model the effects of selected emissions reduction technologies and practices on model egg producers. This report evaluates 17 mitigation strategies and technologies, which target different sources of emissions, provides an estimate of the mitigation potential for case study farms, and models pathways to carbon neutral eggs by 2035.
Outcomes	Emission reductions of almost 50% were achieved in model free range and cage-free farms due primarily to changes in diets and fossil energy consumption. Egg production was found to be heavily exposed to emissions associated with feed production. Although incremental improvements in FCR would offset some emissions (less feed = fewer emissions from feed production), moving from 'low' carbon to 'carbon neutral' is likely to be a high-cost endeavour as it would require either carbon neutral purchased inputs (such as grain and protein meal) or the purchase or self-generation of carbon credits. More broadly, adoption of solar and energy efficiency measures, reducing dietary crude protein or substituting imported soybean meal with alternative proteins were found to be viable mitigation strategies. Waste-to-energy technologies such as combustion, gasification and pyrolysis were not found to be prospective mitigation options. Anaerobic digestion may be feasible for a limited number of large producers (though

	subject to high costs and site specifics) but further research is required to overcome methane leakage.
Implications	The major limitation to emission reduction is expected to be the significant increase in cost-of-production, which requires further analysis to inform the preferred pathway. As a low-margin production system, it will be difficult for the egg industry to absorb the current expected costs that would be incurred by emission reduction activities. Three options for managing these cost increases have been identified: i) costs are passed on to customers and ultimately to consumers; ii) increased costs are borne by taxpayers via government subsidies; or iii) costs are absorbed by businesses along the supply chain, resulting in lower profitability. Some mitigation options were screened out because of current limitations, and other options are likely to be high cost or difficult to implement for individual producers. Industry research should focus on overcoming technical barriers and reducing costs, while also looking for new ‘blue sky’ options to reduce emissions.
Key Words	Greenhouse gas, emissions, baseline, egg, mitigation
Publications	Copley, M.A. & Wiedemann, S.G. (*in preparation*). Resource use and environmental impacts from Australian egg production.

Appendix 1

1 Reducing GHG emissions associated with feed ingredients and production

The baseline assessment for this study found that emissions from feed production represented 65–69% of the carbon footprint (excl. LU and dLUC) of egg production. When the LU and dLUC impacts of imported soy meal were included, feed accounted for 77–81% of emissions. Similarly, Wiedemann and McGahan (2011) found that feed production contributed 50% of the carbon footprint of egg production (excluding LU and dLUC). Of that, approximately two-thirds was CO_2 from fertiliser manufacture and fuel use, with N_2O emissions from crop production making up the remainder.

A key supply chain hotspot and challenge for Australian poultry production is the reliance on imported soy meal as a cost-effective, high protein ration commodity, which has high levels of emissions from soil carbon loss. It is noted, however, that exact emission levels are difficult to ascertain.

Mitigation may be possible through improving feed conversion ratios (FCRs), reducing crude protein or nitrogen, and sourcing lower emission feed inputs, particularly soy meal. These processes are described in the following sections.

1.1 Diet optimisation to improve feed conversion ratios

Mitigation potential*	Cost	Type
10%	Variable depending on available options	Operating

* Mitigation potential of FCR improvement for eggs produced from a single model facility, reported as emission reduction for scope 1, 2 and 3, incl. LU and dLUC. Mitigation of total emissions from 2020 to 2035.

FCR is a key productivity metric and influences environmental performance, as feed requirements and manure directly affect GHG emissions. Increases in hen productivity have previously been found to have significant potential to reduce GHG emissions. Wiedemann and McGahan (2011) found that a 2.5% improvement in FCR could yield a 1.7% reduction in total GHG emissions, assuming no other changes. The reduction is attributed to the dual impacts of reduced feed requirements (and the associated upstream impacts) and reduced manure production, leading to lower manure emissions. Improvements may be achieved at some facilities via management practices that reduce FCR, provided that other factors (such as diet composition, shed type or shed energy inputs) are unaffected.

As FCR is a closely monitored and highly sensitive productivity indicator, special care must be used when calculating and reporting it. Interestingly, the trend in FCR may not be positive in the egg industry. Comparison of FCRs from 10 years ago (Wiedemann & McGahan 2011) with data collected in 2020–21 indicated that FCRs were in the order of 10–25% higher in the most recent period compared to a decade ago. These higher FCRs corresponded to changes in bird production targets and were also related to different diet specifications: for example, higher dietary fibre. The dietary changes may result in slightly lower emission intensity diets, as there is a general correspondence between higher digestible energy and protein and higher emission intensity. However, the current datasets and models do not have the granularity to assess fine resolution differences in diet specifications and the interaction with environmental performance, which was a weakness in assessing changes in FCR.

Notwithstanding the increase in FCR in recent years, mitigation may still be achieved if FCR could be reduced via management or diet interventions. Analysis indicates that a 5% reduction in FCR would result in a corresponding decrease in net emissions of 2–3%.

As the FCR increase is reportedly due to changes in management practices to prolong the layer period, increase standard egg size and reduce bird stress in non-cage housing types, the pathways do not include FCR improvements as a mitigation strategy. It is noted that there may be other environmental benefits from these management strategies, i.e. fewer pullets required or fewer mortalities due to cannibalism. These improvements can contribute to lower impacts from pullet production.

Longer production cycle

Feedback from industry stakeholders suggests that, in line with changing advice from some breeds' geneticists, there is an economic incentive to prolong the production cycle, contributing to the apparent increase in FCR. With the average production cycle in Australia currently 65 weeks, and European geneticists working towards a 100-week cycle (according to industry stakeholders), there may be positive implications for emissions from egg production through reduced impacts for pullet rearing. It is not clear how much impact this has on the carbon footprint but it is expected to partly compensate for the poorer production phase FCR.

High fibre diets

The apparent increase in FCR discussed in the Diet optimisation to improve feed conversion ratios section may also be attributed to an effort to reduce instances of cannibalism in cage-free and free range housing systems as consumer demand for cage eggs begins to fall.

Discussions with producers and nutritionists also indicated that they are now willing and able to feed birds more as rations are significantly lower cost than they were previously. The cost of feeding birds on a high fibre diet is subject to fluctuation based on grain prices, which are influenced by local supply and global demand. Drought puts significant upward pressure on the availability and cost of key inputs, i.e. millrun, in these high fibre rations.

1.2 Lower emission feed ingredients

Mitigation potential	Cost	Type
Up to 35%*	Likely to be a net cost	Operating

* Mitigation potential of choosing lower impact feed ingredients. The lower limit is achievable from lower emission cereal grains. The upper limit represents a 50% reduction in the standard rate of soy meal inclusion.

Argentina is the dominant Australian import market for soy meal for stockfeed. Land use and land-use change impacts (LU & dLUC) for soy grown in Argentina are high as production tends to occur on land that was once grassland or rainforest, and has only relatively recently been converted to cropland, meaning that the resulting loss of soil carbon is high (Arrieta et al. 2018). With most soy meal in poultry rations imported from Argentina, and inclusion rates ranging from 4–16% of the total ration, this is a significant source of emissions and a challenge for the egg industry. In terms of nutrition, the amino acid profile and digestibility of soy meal makes it preferable to alternative protein sources, such as canola, cottonseed or sunflower meals, and the low cost and comparatively ready availability of imported soy meal are also an advantage over the fluctuating price and availability of domestically produced alternatives. That said, high performance, affordable diets can be developed with minimal imported soy meal.

Assuming that high impact soy meal was fully substituted for alternative proteins or soy meal produced in regions not associated with high LU and dLUC emissions (see Table 1), there would be a 35% reduction in emissions.

Changing ration inputs may require the inclusion (or change to the inclusion rate) of synthetic amino acids to balance the amino acid profile. Although synthetic amino acids have a high emission intensity due to fossil energy used in their manufacture, the emission intensity is typically lower than that of the soy meal they replace, i.e. the overall emission intensity of the ration is expected to be lower. Benavides et al. (2020) reported the emission intensity of synthetic methionine, threonine, and lysine as 2.7 kg, 6.79 kg and 6.79 kg CO_2-e kg^{-1}, respectively. Similarly, Marinussen and Kool (2010) reported a carbon footprint for synthetic lysine as 6.1–8.0 kg CO_2-e kg^{-1}, depending on source region (e.g. Germany, Denmark or France).

1.3 Low crude protein and nitrogen diets

Mitigation potential	Cost	Type
<1%	May be cost neutral or a cost-saving depending on current formulations	Operating

Commercial layer hen diets are formulated to maximise the growth or productivity of the bird at each stage of life. These phase diets vary in energy and protein depending on the physiological requirements of the bird at each stage of production. Reducing protein levels can sometimes be achieved through using higher levels of amino acids in the diet to more closely match requirements. This has the potential to reduce ammonia and possibly nitrous oxide emissions from manure (Wiedemann 2016). One benefit of a strategy that reduces crude protein levels is that this reduces emissions throughout the manure management system; there is no risk of emissions declining in one area and increasing in another.

In terms of mitigation potential, Wiedemann et al. (2016) found that reduced crude protein diets in Australian meat chickens yielded a 27% reduction in ammonia emissions from sheds. Acknowledging the difference in production systems and housing conditions between meat chickens and eggs, the principles leading to emission reduction are nonetheless the same. A 10% reduction in dietary crude protein for layers should correspond with 1% lower emissions via reductions of indirect nitrous oxide associated with ammonia. It is also possible that direct manure nitrous oxide could be reduced using this strategy, but more research would be required to be confident of this. Although rations with reduced dietary CP tend to be higher cost, Wiedemann et al. (2016) found that, in meat chickens, productivity gains justified higher diet costs.

2 Energy efficiency and renewable energy

Energy is a significant input in Australian egg production due to most hens being housed in environmentally controlled sheds, where large fans supply air cooling and mixing to optimise the thermal comfort of the birds. Other major energy inputs of heat and electrical energy on a farm include pullet rearing, grading floors, and feed milling. Approximately 25% of the carbon footprint of eggs is attributable to fossil energy. Wiedemann and McGahan (2011) found that approximately 19% of emissions from egg production were associated with fossil energy use, of which electricity and gas were the largest inputs.

Reducing fossil energy consumption and or transitioning to renewable forms of power generation are viable options to reduce the carbon footprint of egg production. Sustained decarbonisation of the energy grid, as more of the power supply is sourced from renewables over fossil fuels, will result in reduced impacts over the long term, but this can be accelerated through adoption of renewables on-site. The most prospective options include solar power installation and improving on-farm energy efficiency. Longer-term options such as waste-to-energy projects will be investigated in the section Waste-to-energy and manure management system emissions.

2.1 Solar

Mitigation potential	Cost	Type
2.6%	can be achieved with a reasonable payback (3–5 yrs)	Capital

* Mitigation potential of 30% of layer farm electricity demand offset by solar or 60% of grading floor electricity demand.

Shifting to solar reduces emissions from purchased electricity and can be cost-effective with reasonable payback periods. The reduction in GHG emissions by offsetting grid electricity, however, is dependent on which state of Australia electricity is supplied from. Farms located in states with a high renewable component of electricity supplying the grid (e.g. Tasmania) will have lower emission reduction opportunities than farms located in a state with a lower proportion of renewables in the grid (e.g. Victoria). Table 15 provides the current state/territory electricity grid scope 2 and 3 emission factors.

Table 15 State/territory electricity grid emission factors (scope 2 and 3)

	Scope 2 emission factor	Scope 3 emission factor
State or Territory	kg CO2-e kWh^{-1}	kg CO2-e kWh^{-1}
New South Wales/ACT	0.79	0.09
Victoria	0.96	0.1
Queensland	0.80	0.12
South Australia	0.35	0.1
Southern Western Australia	0.68	0.04
Northern Western Australia	0.58	-
Tasmania	0.16	0.04
Northern Territory	0.57	0.08

Solar can be a useful source of electrical energy for egg farms as peak diurnal energy demand mirrors peak solar energy production. Additionally, if grading and feed milling occur on-farm, activities can be scheduled to match peak solar energy production.

Many egg farms have reduced a significant component of grid electricity with solar power, with reductions in the order of 30–60%. These reductions could be increased with battery storage; however, batteries are still very capital intensive and are not currently a cost-effective means to provide substantial backup power. A 500 kWh battery, for example, would cost in the order of $1,000,000 and only have enough capacity to provide a couple of hours of storage.

Solar systems require spare areas for mounting panels, with most egg farms ideally suited to this with large available spare space for roof-top installations, or land immediately surrounding the production area, to install ground-mounted tracking solar systems.

The cost of solar systems has reduced substantially in the last decade due to improvements in panel efficiency and cost reductions. Many poultry farming operations have installed solar systems with paybacks in the three-to-five-year range.

For a 100,000 hen facility that grades eggs on-farm, the annual electrical energy usage could range from 200 to 360 kWh per tonne of eggs. Case studies of on-site solar adoption reported by Australian Eggs indicate that 30–40% of a typical farm's electricity demand could be offset with solar (see Australian Eggs Ltd (2020)), yielding an average reduction in emissions of 2%. Other industry stakeholders have reportedly managed to offset more than 60% of farm electricity demand through solar. At the grading floor, offsetting 60% of grid electricity demand with solar would also yield an approximate reduction in emissions of 2%. The mitigation potential of this technology will vary depending on electricity demand and which Australian state/territory grid electricity is replaced (see Table 15).

2.2 Improved energy efficiency

Mitigation potential	Cost	Type
1.9%	Low	Capital/operating

* Based on a 10% reduction in grid electricity demand at the layer farm through improved energy efficiency.

Energy efficiency measures are a viable option for reducing on-farm energy demand. Improvements in energy efficiency can only be accurately assessed and confirmed by measuring usage. Measuring energy use can be aided by installing additional power and gas meters to allow measurement of individual sheds, components within sheds and other farm infrastructure (grading floor, feed mill, etc.). Power usage meters provide a measurement of energy demand and record total energy consumed. This provides an invaluable tool for assessing the electrical performance between sheds and reviewing energy efficiency measures.

For environmentally controlled sheds, fan energy is the largest source of electrical demand at between 60 and 70% of the total. Thus, ventilation fans represent the greatest opportunity for potential electrical energy savings through improved ventilation efficiency. Methods for improving fan performance and hence reducing fan operating costs include:

- General maintenance of pulleys and belts.
- Regularly cleaning fan blades, motors, and shutters.
- Replacing burnt-out motors with energy-efficient motors.
- Maintaining and cleaning cool pads to ensure airflow is not restricted.
- Investment in more capital (e.g. energy-efficient fans and cowlings). This decision should be based on potential payback.
- Ensuring shed ventilation (fan performance) is meeting manufacturer requirements.
- When constructing new ventilation sheds, choosing energy-efficient fans, and paying attention to the fan’s energy-efficient rating (cfm/watt) and airflow ratio.
- Reducing the fan speed with a variable frequency drive (VFD) unit reduces airflow rate and the fan's energy consumption; operate in accordance with ventilation requirements.

Lighting represents the second-highest electrical energy use in sheds. Lighting technology has evolved rapidly in the last decade, and modern lighting can be very energy efficient. For example, replacing the 36-watt fluorescent tubes with 18-watt LED tubes can save 100 to 200 kWh week^{-1} in a shed.

For most layer farms, reductions of at least 10% electrical energy use could be achieved. With 75% implementation, this would result in an average reduction in emissions of 1.9%.

2.3 Green power

Mitigation potential	Cost	Type
3 %	High	Operating

Another option to reduce emissions is to purchase ‘green’ power agreement, where all or some of the energy supply comes from renewable sources rather than fossil fuels. No energy provided in Australia can claim to sell only renewable power. All retailers sell electricity from a supply that is a mix of renewable energy and energy generated from fossil fuels (Wrigley 2021). However, some providers offer options such as GreenPower and carbon offsetting. GreenPower is a government-led initiative where retailers agree to purchase some or all of a customer’s power usage through accredited renewable generators.

Where GreenPower is purchased, it is not received directly from a renewable generator. Instead, the power comes from the grid. GreenPower comes at an additional cost of approximately five to 8c kWh, depending on the retailer (Wrigley 2021).

At the current price, initial analysis suggests that paying for green power to offset emissions from electricity would be more expensive than offsetting the emissions by purchasing carbon credits; assuming the additional cost per kWh is 5c, the estimated cost of offsetting per one tonne of CO_2-equivalent would be ~ $42 compared with the current spot price for an Australian Carbon Credit Unit (ACCU) of $37 t^{-1}.

An important point to note is that green power is not zero-emission energy. The power still has an emission intensity from the infrastructure required to generate and transmit it.

Scope 2 emissions represent, on average, 12% of the emission intensity of eggs (incl. LU and dLUC), The theoretical emission reduction potential is up to 12%, assuming that 100% of the grid electricity is transferred to green power. Assuming 25% adoption, mitigation potential is 3%. The contribution of grid electricity consumption to the emission profile of a producer varies depending on which state/territory they are in and their relative grid electricity consumption. The mitigation of this strategy will therefore be highly variable across the industry.

3 Waste-to-energy and manure management system emissions

10–14% of the carbon footprint of eggs was attributable to emissions from layer farm manure (or approximately 6–9% of emissions when LU and dLUC impacts are included). There are three broad groups of options related to manure management: i) waste-to-energy projects, which reduce emissions from energy via renewable energy generation on-farm; ii) direct emission reduction from manure management on-farm; and iii) offsetting fertiliser emissions via better utilisation of manure as a fertiliser replacement in crop production. These are investigated in the following sections.

Waste-to-energy produces electricity and heat from residual energy in feed that the bird cannot utilise. This technology has been successfully adopted in the Australian pig industry. When assessing waste-to-energy options, one important consideration is that only a very small potential saving in GHG emissions is possible. Layer hen systems have relatively low emissions manure management. Where in layer systems, this contributes approximately 10% to the carbon footprint of eggs (excl. LU and dLUC), in conventional piggeries with uncovered anaerobic ponds, this contribution is > 50%. The key difference is that pig manure is handled in a liquid system that is anaerobic and generates large volumes of methane, while in layer hen facilities, manure is handled aerobically, and methane emissions are comparatively low. For this reason, most of the benefit from waste-to-energy is not from manure emission reduction but from renewable energy production on-farm. Additionally, it is not possible to gain carbon credits from these systems because the emission reduction is negligible and, in some cases, can be reversed (manure emissions from leakage could exceed BAU emissions).

Several technology options are described below (anaerobic digestion, combustion, and gasification/pyrolysis), each suited to a different type of material, which is largely related to initial moisture levels and energy density. For the thermal treatment processes (combustion, gasification/pyrolysis), the energy value of layer manure is low due to its high moisture content, as shown in Figure 8. Even with anaerobic digestion, the various available technologies have differing optimum feedstock ranges, as shown in Figure 9.

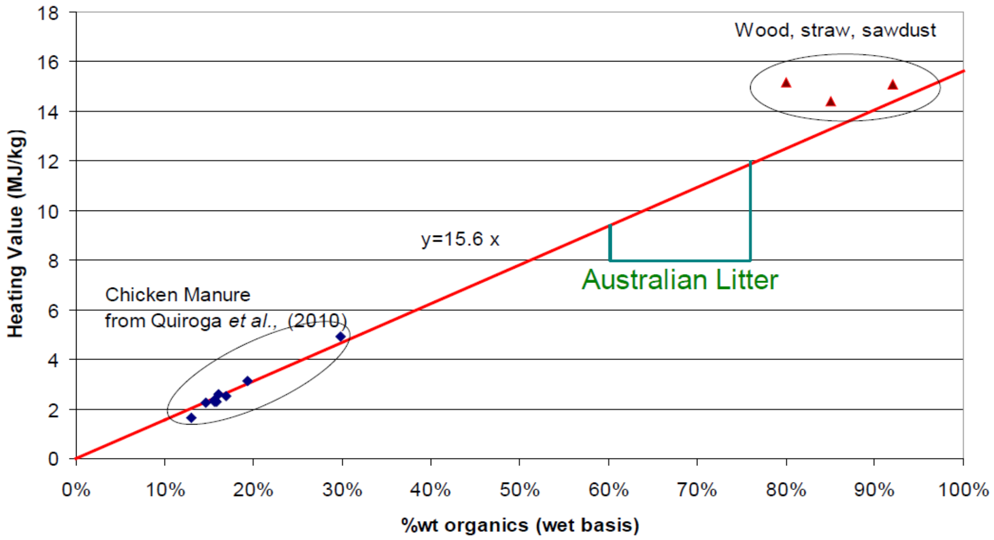

Figure 8 Moisture content vs calorific value for a range of carbohydrate-type materials, including chicken manure (from Quiroga et al. 2010)

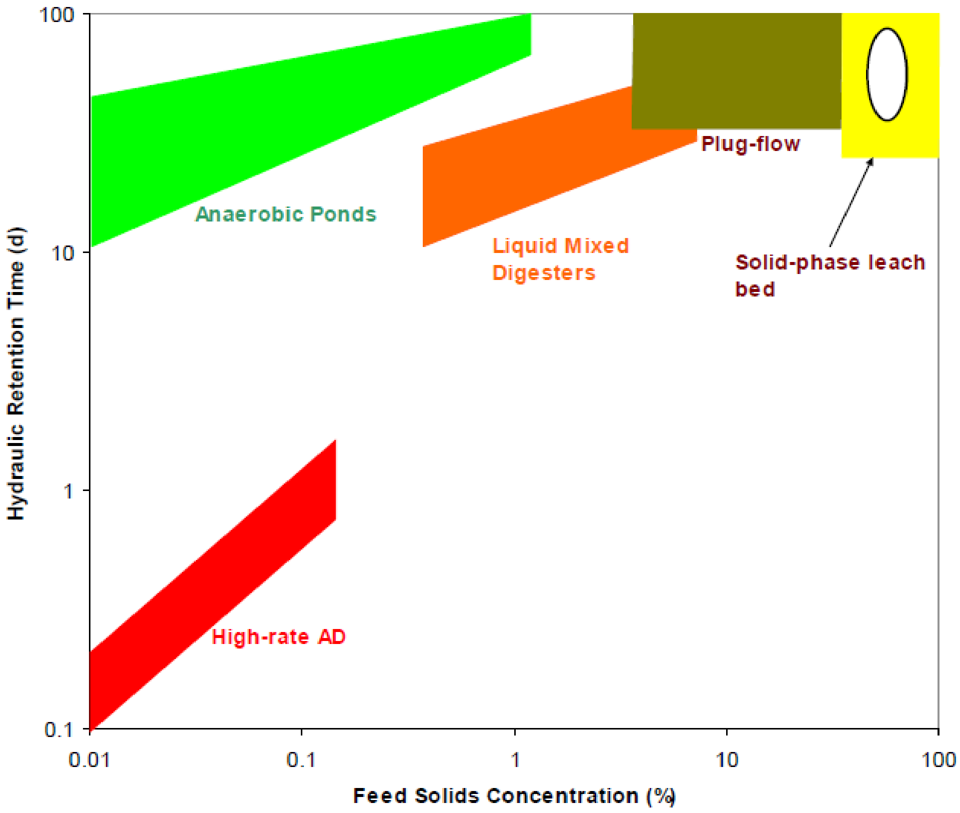

Figure 9 Moisture content ranges for various anaerobic treatment technologies (reproduced from McGahan et al. 2013)

Note: Yellow circle shows the range for layer manure and litter.

3.1 Anaerobic digestion

Mitigation potential (%)*	Cost	Type
1.8%	High	Capital

Mitigation is primarily achieved via energy saving rather than a direct reduction in manure emissions. Mitigation potential here is calculated at an estimated 15% adoption rate. At full adoption mitigation would be a maximum of 8%.

Biogas production is a mature technology utilised worldwide for generating energy from manure and other biomass. However, several specific attributes of poultry manure have made it more difficult to integrate into poultry systems, with only a few operational systems anywhere in the world that utilise 100% layer hen manure. Biogas production using Anaerobic Digestion (AD) is ideal for high-moisture materials such as manure removed from layer sheds with belts, typically having a 60–70% moisture level. Systems can range from simple covered pond designs to advanced, in-ground or above-ground anaerobic digesters. The process for all systems works by capturing the biogas generated from the anaerobic digestion of manure, which can be burnt to generate electricity and or heat. An additional benefit from biogas capture systems is potential odour reduction.

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 digesters are custom-built inground installations or above-ground tanks that typically have heating and mixing to maximise the biogas generation. Conditions within the digester 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 et al. 1992). High ammonia levels are limiting for AD of layer hen manure. Ammonia stripping, where ammonia is removed and recovered from the effluent, is generally necessary for layer manure biogas systems to remove and reduce the inhibitory effects of ammonia.

Two Australian studies have previously reported the methane potential of layer hen manure. Tait (2014) and Pratt et al. (2015) performed biological methane potential testing of fresh manure, yielding substantially different results. Tait (unpublished data, pers. comm.) reported 0.30 $m^3 kg^{-1}$ VS, while Pratt et al. (2015) reported only 0.16 $m^3 kg^{-1}$ VS. Both these reported values are lower than the value of 0.39 $m^3 kg^{-1}$ VS applied in the Australian NIR (Commonwealth of Australia 2021b) and IPCC (Dong et al. 2006). It is not clear why the Pratt et al. (2015) values were so much lower than those of Tait (2014). With the variability in the reported results, it is suggested that if an enterprise was considering anaerobic digestion technology, the methane potential of their manure (and any other feedstock) is first determined by laboratory analysis.

Tait (2014) extended the research beyond theoretical gas yields using a laboratory-scale leach bed digester. The leach bed operates by spraying water over a manure column and collecting the product, leachate, which is then transferred to the digester. This way, the material can be managed as a solid rather than being diluted for treatment in the digester, while the most degradable organics are entrained with the leachate. The author found that layer hen manure could produce reasonable methane yields (0.25 $m^3 kg^{-1}$ VS – see Figure 10). Tait, however, noted that ammonia might be inhibitory, meaning that systems would need to be fitted with ammonia stripping equipment.

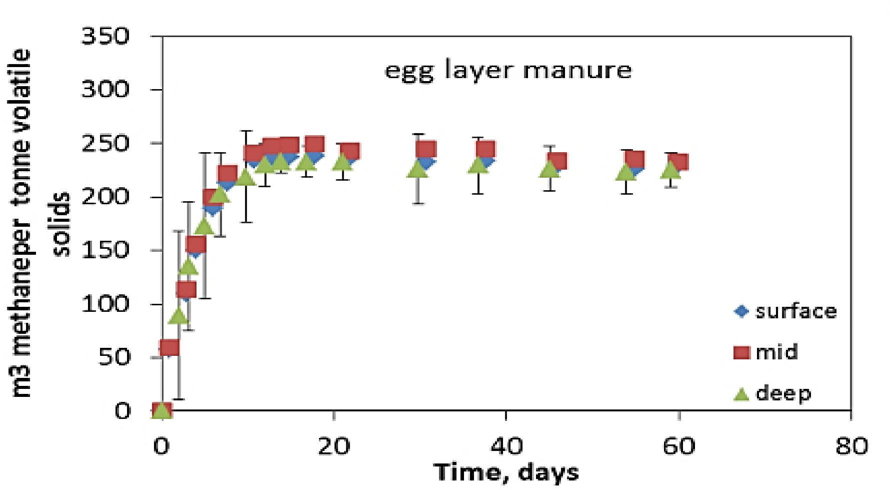

Figure 10 Methane production from layer hen manure leachate (reproduced from Tait 2014)

Methane potentials are summarised in Table 16, showing values from Australian research compared to the potentials recommended in the Australian NIR and values for pig manure for comparison.

Table 16 Methane potential of layer hen manure determined by Australian research with comparison to default inventory values and values for pig manure

Manure	**Methane potential (m^3 kg^{-1} VS)**	**Research**	**Reference**
Layer hen	0.16	measured	Pratt et al. (2015)
Layer hen	0.25–0.3	measured	Tait (2014)
Layer hen	0.39	default	Commonwealth of Australia (2021b)
Pig manure	0.26–0.47	measured	Gopalan, Jensen and Batstone (2013)

Energy production from methane

Methane produced from a covered anaerobic pond or digester is generally combusted in a generator to produce electricity. The electrical energy efficiency of methane generators is generally 30–35%. A further option is to combust the methane in a combined heat and power (CHP) unit that generates electrical energy (30–35% efficiency) and heat energy (50–55% efficiency). This heat can be used as a replacement for LPG or natural gas to provide heating for water at a grading floor or for pullet rearing.

Energy production potential for the layer hen industry can be determined from the combined results of Wiedemann et al. (2015) and Tait (2014) as follows:

Manure production per 100,000 birds yr^{-1}:

- VS production = 20.8 g hen^{-1} d x 100,000 x 365 / 1,000,000 = 760 t yr^{-1}
- Methane yield range = 760 t yr^{-1} x 150 m^3 t^{-1} to 760 t yr^{-1} x 250 m^3 t^{-1}
  = 114,000 to 190,000 m^3 yr^{-1}
- Total energy = 4310 to 7180 GJ yr^{-1}
- Electrical energy = 359,100 to 598,50 kWh yr^{-1} (at 30% electrical efficiency)

Wiedemann and McGahan (2011) and McGahan et al. (2013) reported electricity consumption for Australian layer hen facilities of 2.3 and 2.6 kWh hen^{-1} yr^{-1} respectively, with more recent data ranging from 1.73–5.0 kWh hen^{-1} yr^{-1}. If grading and feed milling is conducted on-site, approximately 0.8 kWh hen^{-1} yr^{-1} is added. Based on these data, the energy demands for 100,000 birds are expected to range between 318,680 and 795,000 kwh yr^{-1}. The calculations above show that biogas can produce the required energy in most cases, however, seasonal fluctuations in energy demand would need to be managed. These seasonal variations are substantial and can be exacerbated in warmer climatic zones, e.g. in Queensland.

Considering the variation in energy requirements by layer farms, it may be possible to vary gas production to match supply and demand. While energy is very difficult to store, manure may be stored easily. Considering the low methane production levels from manure stockpiles reported by Naylor et al. (2016), it appears that manure may be stored either with or without covers with little degradation. It is possible that covering manure piles could inhibit breakdown by limiting gas exchange whilst simultaneously inhibiting anaerobic breakdown due to high ammonia levels (Naylor et al. 2016; Rowlings 2016), which may effectively preserve the energy content in the manure.

Managing electricity production would require the digester to be designed for summer energy generation requirements. However, peak load is likely to exceed energy production during hot summer days when sheds are operated with full tunnel ventilation, and this could be managed by utilising small contributions from grid electricity, solar energy or back-up generators running on diesel.

One important area of uncertainty currently exists with AD. Leakage of methane from digestors is estimated at 10% (Commonwealth of Australia, 2021b) and while this value has not been measured with Australian systems, it represents a large potential emission source that is additional to normal MMS emissions, reducing the mitigation potential of biogas.

3.2 Combustion

Mitigation potential (%)*	Cost	Type
0%	High	Capital

* Mitigation assumed to be zero because the technology is not feasible with layer manure.

Combustion involves burning manure or spent litter in the presence of oxygen to generate heat energy, which can then be transformed into other forms (e.g. steam, hot water or electricity). Heat energy is used to evaporate the fuel source’s moisture during combustion. Therefore, biomass with a high moisture content will be inefficient at producing heat as the parasitic demand will be high. With the optimal moisture content for a potential biomass fuel ranging from 15–20%, fresh layer manure from belts (typically 60–70% moisture content) is far from ideal and energy potential is very low (see Figure 8). In addition to the poor energy potential, poultry manure has the potential to foul combustion equipment and cause a build-up of carbon monoxide due to incomplete combustion.

Combustion plants have been successfully established for poultry litter from meat chicken production in the USA and UK. In these cases, the litter was a blend of manure and sawdust, shavings or straw and is relatively low in moisture and ash levels (McGahan et al. 2013).

Combustion may be technically possible for free range manure but is not expected to be optimal. While there may be similarities with litter from free range hens and meat chicken litter, the long batch time in free range layer hens compared to meat chickens results in the breakdown of volatile solids and higher ash levels in layer hen free range manure. A further limitation is scale. Combustion plants typically require large volumes and centralised systems, where biomass is transported from many farms. This has been achieved for meat chickens because many farms may be located in a single area. This is not typically the case with layer farms, which are often located at a large distance from other farms for biosecurity reasons. Transporting manure to a central facility from multiple farms would also present a biosecurity risk. It appears unlikely that combustion would be successful in the egg industry for these reasons.

3.3 Gasification and pyrolysis

Mitigation potential (%)	Cost	Type
<1%	High	Capital

Gasification is a thermal energy production system that converts materials, in this case, layer manure or spent litter, into a hydrocarbon gas, known as syngas, by heating with limited oxygen. Pyrolysis and gasification are similar processes that vary in heat used and the outputs generated. The major difference is that gasification uses oxygen as part of the treatment process, whereas pyrolysis operates in the absence of oxygen.

Gasification favours maximum gas output, while pyrolysis produces syngas, oil and biochar at different levels, depending on treatment temperature and processing time. When burnt, syngas produces steam or electricity with the potential to power normal combustion engines. Although gasification has long been used with non-renewable fuel sources, such as coal, the use of biomass or manure is relatively new. The system requires low moisture levels and low ash, as with all thermal processes. Layer manure from belt removal has much higher moisture levels than optimal and is unsuitable. As with combustion, parasitic energy demand to dry manure would reduce overall energy yield to negligible levels. Litter from free range sheds that is mixed with sawdust or straw may be slightly better but still has higher ash levels than optimal. Layer manure, which contains ash and potassium, can lead to the fusion of char, which has negative implications for operational efficiency and maintenance costs (Baranyai & Bradley 2008). More significantly, however, is the issue of cleaning the syngas of the impurities (tar, dust, ammonia, etc.) produced alongside it. The cost of doing so is, at present, prohibitive. Considering the technology is not mature and generally requires larger scale, it is not feasible for the industry at present.

3.4 Covered stockpiles

Mitigation potential (%)*	Cost	Type
0.1%++	Low	Capital

* Mitigation potential at 10% uptake. At 100% adoption mitigation will be approximately 1%. While mitigation is low, it would be substantially higher if composting was replaced entirely with stockpiling and covered stockpiles.

Covering manure stockpiles can significantly reduce the associated ammonia and nitrous emissions. Any impermeable material, e.g. tarpaulins, are a suitable cover that should be placed over the piles immediately after removing from the sheds.

Whilst covering stockpiles does not completely eliminate emissions, it is a practical means of reducing emissions whilst allowing some flexibility in the timing of manure spreading. It would almost completely eliminate emissions if manure was diverted from composting to stockpiling and this would result in much greater mitigation, but would also lose the benefits arising from composting.

Naylor et al. (2016) demonstrated that simple, low-cost emission reduction strategies exist in relation to manure storage. Ammonia emissions from a covered manure stockpile were found to be 3% of N added, compared with 24% from the control: a standard uncovered stockpile. Both stockpiles were found to have negligible nitrous oxide emissions, although methane production was marginally greater from the covered pile. The results of the trial led Naylor et al. (2016) to make three key conclusions. First, as GHG emissions from uncovered stockpiles were significantly lower than expected, stockpiling is a much less significant emission source than previously believed. Second, the authors concluded that, as covering stockpiles were found to reduce ammonia emissions by 88% and total GHG emissions by 74%, it is an effective mitigation strategy. Reducing manure GHG emissions by 74% would generate an 8% reduction in the farm carbon footprint. The total volume of emissions that can be mitigated, however, is small, and the method is not expected to be cost-effective (Wiedemann et al. 2016). Third, they concluded that as covering stockpiles was found to significantly reduce ammonia emissions, there were positive implications for higher nitrogen retention in manure. Thus, provided the nitrogen is not lost at the point of land application of the manure, it may be possible to recover more nitrogen as fertiliser.

3.5 Composting

Composting is used in some enterprises to reduce the mass of manure, dry the product out and reduce odour potential to improve saleability. Composting generates higher emissions than stockpiling manure, because it aerates the manure in the presence of high levels of nitrogen, and also generates large emissions of ammonia.

Rowlings (2016) determined emissions arising from stockpiling and composting of layer manure, the aim being to determine mitigation opportunities associated with composting. The study found that emission rates from composting were substantial, and it identified several options to reduce emissions.

Key recommendations made by Rowlings (2016) to reduce emissions from composting were:

- ensure adequate bulking materials are supplied to increase the porosity
- cease composting before the internal temperature falls below 50°C
- stop composting before significant nitrates accumulate
- avoid over-application of water to limit anaerobic conditions.

In the absence of further research that quantifies each approach's mitigation potential, the mitigation potential of the above cannot be confirmed. In the interim, composters could implement these strategies to reduce (to whatever degree possible) GHG emissions from the composting stage.

Based on the National Greenhouse Gas Inventory values, composting manure on a caged egg farm would increase manure management emissions above the baseline (stockpiling) by 28%, meaning that overall emissions would increase by 3%.

It may also be possible to reduce emissions by increasing the frequency of manure removal, provided it can be moved to a lower emission storage system. If such a practice is not anticipated to affect operating costs adversely, further investigation may be warranted to determine the emissions reduction potential.

3.6 Fertiliser replacement

Mitigation potential (%)*	Cost	Type
0.3–0.4%	Low	Operating

* Mitigation potential at 15% uptake. At 100% uptake mitigation is 2%.

Manure from egg production is a valuable resource, typically utilised through application to agricultural land. The nutrients (nitrogen, phosphorus, and potassium) and organic carbon contained within the material are beneficial to soil health, crops and pastures. Acting as a substitute for manufactured fertilisers, the application of manure reduces demand for manufactured fertilisers.

Synthetic fertilisers require a significant energy input for their manufacture, resulting in high emission intensity for the product. As layer manure has a lower fossil energy footprint than urea, its application may offer a reduction to the carbon footprint from the avoidance of CO_2 emissions associated with the manufacturing of the inorganic fertilisers.

3.7 Treatment and additives to reduce field emissions from manure

Field emissions from applying manure are generally not part of industry emissions unless they are used to produce grain that is subsequently used in the system. For this reason, mitigation is less relevant. Nonetheless, for those farms using manure on site, reducing emissions from field application was considered.

Laboratory trials conducted by Pratt et al. (2016) examined the mitigation of various manure and sorber products at different incorporation rates, finding reductions of 70% for some manure/sorber combinations and a strong inverse regression relationship; emissions were found to decrease as sorber rates increased (Figure 11) for most manure types, with the notable exception of layer manure.

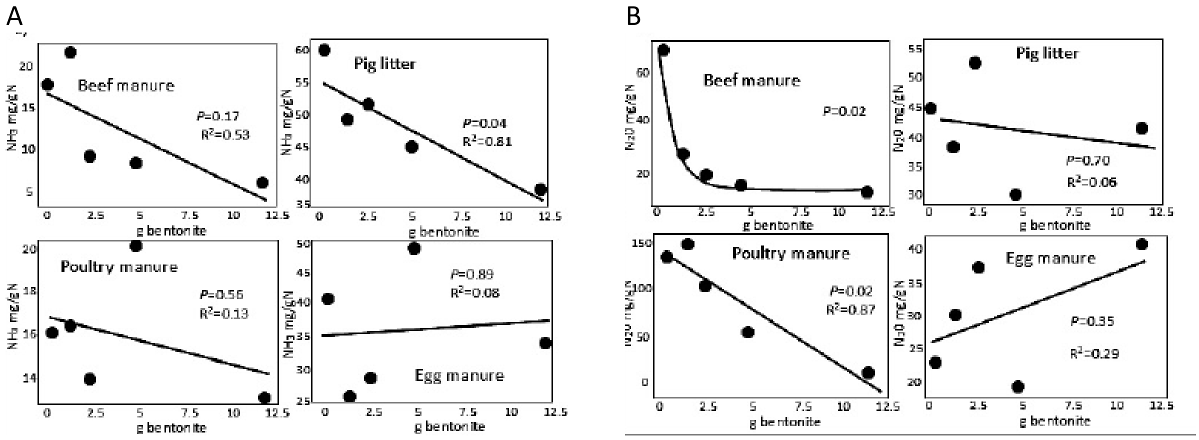

Figure 11 Regression analysis of cumulative ammonia (A) and nitrous oxide emissions (B) from manure mixed with bentonite (reproduced from Pratt et al. 2016)

Though disappointing for the egg industry, this research is significant as it demonstrated that mitigation strategies applicable to one manure type are not necessarily effective for others.

It should also be noted that whilst the approach could produce lower emissions for some manure types, large additions of sorber material were required. As bentonite reportedly cost approximately \$70 t^{-1} and vermiculite \$400–\$2,100^{-1} (ranging in quality from waste product to high-grade material), Pratt et al. (2016) concluded that this was not cost-effective, particularly as the additional transport costs of such a high bulk material were anticipated to be significant.

Jenkins et al. (2015) studied several potential mitigation options for reducing emissions from manure applied to the soil. The bulk of the study was conducted in the laboratory but included field scale verification. The authors found that on the sandy soils prevalent in Western Australia, the majority of emissions occurred in the 48 hours immediately following land application. Neither liming, blending with high C:N materials or incorporation of dry seeding treatments across all manure types were found to yield consistent, significant differences in total GHG emissions. In the layer hen manure trial, incorporating the manure was found to reduce emissions on sandy soils. However, similar results were not observed on soils with higher clay content. When layer manure was blended with a carbonaceous material, the application generated significantly higher GHG emissions (Jenkins et al. 2015).

In a further experiment, Jenkins et al. (2015) tested the effect of three different treatment methods on emissions from land application with several varieties of manure. The three treatments were: passive aeration composting; pelletising; and standard practice stockpiling. The authors reported mixed results for the application of the treated manures to two types of soil. For most manures, pelletising and composting were found to decrease land application emissions substantially. However, when layer manure was applied to land, it was found to generate higher emissions. Pelletising layer manure appeared to reduce emissions from land application. One difficulty in reviewing the data from the study is the apparent inclusion of biogenic CO_2 in some emissions estimates. As part of the short-term carbon cycle, biogenic CO_2 is generated by the breakdown of manure carbon in an aerobic environment but is excluded from all GHG inventories. It is possible that this influenced some of the high emissions measured.

Another study by De Rosa et al. (2016) found that, when applied with fertiliser to irrigated horticultural crops, emissions from composted manure were lower than from stockpiled manure. This result indicated that land application of composted manure was a viable mitigation strategy (Rowlings 2016). As noted earlier in the review of their comparison of stockpiling and composting emissions, however, indirect N_2O emissions from ammonia volatilisation were excluded, meaning that emissions associated with composting are likely under-estimated. In addition, the experimental method did not allow for the measurement of emissions generated during the turning of compost piles.

Analysis of the mitigation potential of this strategy was conducted using the assumptions outlined in Table 17.

Table 17 Manure characteristics and carbon storage assumptions

Key parameter	Value
kg of manure kg^{-1} of eggs	0.04
Dry matter (%)	70
Manure carbon (%)	0.29
Soil carbon retention rate (%)	10–30

Considering compost generates elevated emissions during the process and reduces plant available nitrogen, this does not appear to be an effective mitigation.

Nutrient recovery for fertiliser

Mitigation potential (%)	Cost	Type
0.3%	High	Capital

Layer hen facilities accumulate substantial amounts of nutrients in manure, which are invariably undervalued when sold as manure for crop production. An associated option, but one which would yield higher value fertiliser products, is that producers who adopt energy generation technology can also recover nutrients via chemical or physical means. In research undertaken for the pork industry, Murphy et al. (2016) found that phosphorus recovery via struvite precipitation and nitrogen recovery via struvite and ammonia stripping could be integrated into a biogas production system, where excess energy and heat are used to recover the nutrients.

At present, struvite precipitation is the most commercially adopted technology for phosphorus recovery from wastewater, with the recovered product used as a slow-release fertiliser. Struvite is a durable white crystalline granule of magnesium ammonium phosphate, with good nutrient (N and P) density and superior storage, transport, handling, and application characteristics, particularly in comparison to biosolids or compost. Struvite precipitation would ideally suit a biogas production system where the feedstock is a high concentration layer hen manure.

Murphy et al. (2016) determined that the viability of such a system was contingent on a market price for struvite-based fertiliser of AU \$506 t^{-1} (i.e. the break-even price). High capital and operating costs, particularly for the necessary input magnesium chloride, mean that the economic feasibility of struvite production is highly sensitive to these factors. With the price of diammonium phosphate (DAP) at AU \$906 t^{-1} in October 2021, struvite production may now be close to being cost effective (Rabobank, 2021).

Where nutrient recovery occurs alongside a biogas system, ammonia stripping is required to limit the inhibitory effects of ammonia. One variation is a mass transfer of ammonia from the liquid to the gas phase, known as gas-liquid ammonia stripping. The physiochemical process requires the dissolved ammonia to be mixed with air (extraction gas) in a gas-stripping tower, effectively transferring the ammonia from the effluent stream into the air. Sulphur acid or other strong acid solutions can absorb the ammonia gas, generating an ammonium salt which can be crystallised and sold as a fertiliser. However, the economic feasibility is closely tied to the market value of sulphuric acid. Murphy et al. (2016)'s analysis revealed that ammonium sulphate's break-even cost was AU \$306 t^{-1}. The authors concluded that were the cost of sulphuric acid to fall from AU \$276 to AU \$208 t^{-1}, the break-even point for ammonium sulphate would be AU \$256 t^{-1}. Based on N value only, ammonium sulphate would then need to sell at the cost of < AU \$250 t^{-1}. Accordingly, the authors concluded that fertiliser N prices would need to reach around AU \$680 t^{-1} urea for ammonia stripping to break even. With prices for urea pushing AU \$666 t^{-1} in October 2021 (up from AU \$364 t^{-1} in October 2020), the breakeven point has not yet been reached.

An analysis of the mitigation potential of N recovery was conducted using the assumptions detailed in Table 18.

The efficacy of the nutrient recovery is assumed to range from 30–50%, the recovery range under normal circumstances. The absolute theoretical maximum, however, is 100%. This level of efficacy would likely only be achievable if the nutrient recovery was conducted as a post-process to a complementary (and assisting) technology, such as anaerobic digestion.

Grains produced from enterprises that use layer manure or nutrients recovered from it to fertilise crops would (at least in part) flow back into the industry's scope 3 emission profile as lower emission intensity feed commodities.

Table 18 Key parameters for mitigation potential of N recovery from manure

Parameter	Value
kg manure kg^{-1} eggs	0.04
Dry matter (%)	70
Manure nitrogen (%)	4.6
Efficacy (%)	30–50

Recent research has revealed some methods to increase nutrient content (i.e. by covering stockpiles) and increase nutrient uptake by crops. Covering stockpiles may prove a cost-effective means of increasing manure N, provided that the value is recoverable at the point of land application. For producers who currently stockpile or compost manure as a means of improving nutrient content, this could be a viable means of improving nutrient value in their product. In future, opportunities to manufacture fertilisers (e.g. struvite) from layer manure may emerge. Such a technology would be complementary to biogas production. Although not yet available, the industry is encouraged to monitor and report developments in this area so that, when possible, producers are informed and as prepared as possible to capitalise on this.

3.8 Shed manure management

Mitigation potential (%)	Cost	Type
<1%	High	Capital

Systems that operate with belts typically remove manure from sheds 2–3 times per week. Reduced time in each manure management stage results in lower emissions. Emissions from manure are therefore lowest in sheds with manure belts.

Emissions from manure in cage-free production, which slats or litter, are typically lower than those from free range production but greater than sheds with manure belts. In comparison, free range production has the highest emissions from manure, as the 13.6% of manure deposited on ranges is associated with high levels of N_2O emissions.

4 Carbon storage

Carbon storage, also known as carbon sequestration, is the process of removing carbon from the atmosphere and depositing it in a reservoir. The two opportunities in this respect for the egg industry are vegetation and soils, and these are described in the following sections.

4.1 The impact of management practices on soil carbon

Figure 12 shows the effect of different management practices on soil carbon levels. Compost and manure applications promote soil carbon storage in two ways: first, by directly adding carbon to the soil; and second, by increasing nutrient levels, which in turn promotes plant growth, resulting in more carbon inputs.

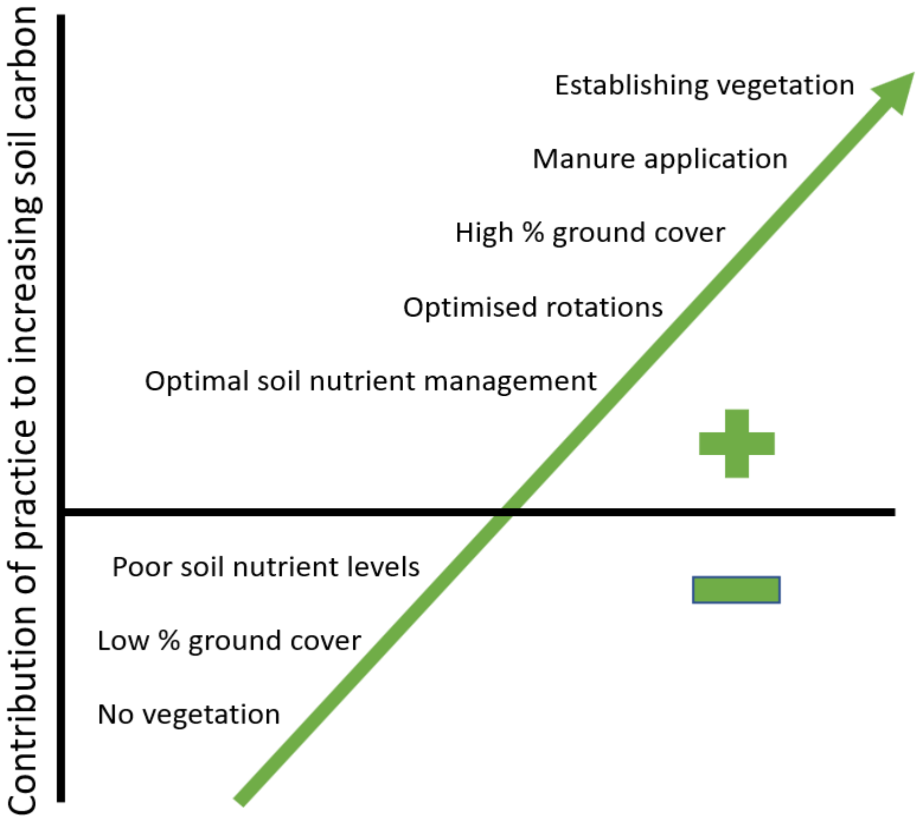

Figure 12 The effect of different management practices on soil carbon levels in free range areas (adapted from Cotching 2009)

4.2 Quantifying increases in soil carbon

Quantifying soil carbon requires sampling (typically to 30 cm depth or deeper) and taking measurements of soil bulk density. From there, the carbon stocks in the soil can be determined. To evaluate any change over time, a baseline must be established, and a comparable sample then taken in later years. The biggest challenge in measuring the change over time is collecting enough representative samples to be confident that a change in carbon has occurred.

For farmers interested in producing carbon credits from the soil, a soil carbon method is available in the Emission Reduction Fund (ERF). This is a lengthy process and is summarised below:

1. **Prepare** – Research and understand the benefits and obligations of the program, determine the suitability of the land, and prepare a land management strategy documenting practices that will impact soil carbon.
2. **Register** – Register the project through the Clean Energy Regulator and contact an 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 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, with periodic audits.

The biggest challenge to producing carbon credits at present is the difficulty in accurately and confidently measuring very small changes in soil organic carbon over time. If farmers were to measure soil carbon change for their own purposes without the need to generate carbon credits, they could do so with a relatively small number of sample points collected from the same point each year or every few years. However, random sampling is required for ERF carbon credits, and statistically significant results must be proven. This makes sampling costly, particularly when there is only a modest change in carbon over time. In general, testing soil carbon every 3–5 years is sufficient to track change, and it is more cost-effective to sample a larger number of points, less frequently, than to sample a small number of points every year.

4.3 Soil carbon storage via land application

Mitigation potential (%)*	Cost	Type
0.4%	Compliance costs to generate carbon credits can be high	Operating

* Mitigation potential with an estimated efficacy of 20% and 95% implementation. Full mitigation is 2%.

The egg industry is in an ideal position because it has manure and spent litter, which, when re-used appropriately, can promote an increase in soil carbon. At an application rate for spent litter from free range of 10 t ha^{-1} at 70% dry matter and 29% carbon for manure and 75% dry matter and 38% carbon for spent litter, between 2–2.9 t C ha^{-1} would be added. However, at the same time, between 105 and 140 kg of phosphorous (P) and 308 and 322 kg N ha^{-1} would be added, which is a capital application of phosphorus and should only be applied to address deficiencies every several years. Although it is difficult to estimate the rate at which carbon in the soil would break down, a reasonable assumption is that less than 30% of the available C will remain in the soil. Ultimately, this application would mean about 0.6–0.9 t of carbon would be stored in the soil.

Relying on the assumptions regarding manure volumes and characteristics detailed in Table 17, land application can yield a modest level of carbon storage (equivalent to 2% of emissions). The range in mitigation potential is heavily influenced by how much of the carbon is retained in the soil; the upper bound of the mitigation potential is a product of a soil carbon retention rate of 30%.

4.4 Soil carbon storage on free range areas

Mitigation potential (%)	Cost	Type
<0.1%	Compliance costs to generate carbon credits can be high	Operating

On free range farms, range areas may have slightly increased soil carbon due to organic matter deposited in manure. That said, sequestration relative to total emissions are minimal because of the small proportion of manure excreted in the range area (< 14%) relative to bird numbers and emissions from other sources. With typical stocking densities of 1500–10,000 birds ha^{-1}, total sequestration would only equate to less than 0.1% of total emissions. A recent study by Clarke and Wiedemann (2020) also found that there was a highly variable relationship between organic matter concentrations in soil and distance from the shed, which, combined with the findings of Wiedemann et al. (2018), mean soil carbon storage on ranges are highly variable, making it difficult to quantify.

4.5 Factors that influence soil carbon sequestration

Soil carbon is vital to soil health and many of the physical and chemical processes that occur in soil. Soils with higher carbon levels have a better structure and can store large amounts of nutrients, which release slowly to aid plant growth. Improved soil structure also aids infiltration and the soil profile's water storage.

Soil carbon results from the movement of CO_2 from the atmosphere into the soil via plant biomass processes (Ussiri & Lal 2017). At any given time, twenty-four times the amount of C in the atmosphere and four times the amount stored in plants is currently stored in soil (Bell & Lawrence 2009).

Australian soils are, in general, very low in soil organic carbon (SOC). SOC in agricultural soils, in particular, typically ranges from 0.4–4% (Tow 2011). 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.

Any increase in soil carbon is determined by how much carbon is added to the soil versus what is retained. Factors that influence this input, loss or retention are outlined in Table 19. Fundamentally, carbon storage will occur if more carbon is added than is lost. Such an occurrence generally follows a management change, with carbon changing over time before stabilising once more at a new (higher) level. Table 19 also outlines the soil and climatic factors that influence carbon sequestration.

Table 19 Likelihood of soil carbon sequestration with various soil and climatic factors

Location factors - natural conditions	**Potentially additive processes to soil carbon**	**Likely increase in soil organic carbon**	**Potentially limiting processes to soil carbon**	**Unlikely increase in soil organic carbon**
Soil type	Net primary productivity; addition of organic matter from off-site; perennials; conservation farming; retaining plant residues	High clay content, high soil fertility, high porosity	Microbial decomposition resulting in the conversion of soil C to CO_2; removal of organic matter; tillage; fallowing; erosion	Low clay content, low soil fertility, low porosity
Mean annual rainfall		>600 mm yr^{-1}		<600 mm yr^{-1}
Seasonal climate		Consistent rainfall, average conditions, moderate temperatures		Increased volatility, frequent extreme weather events

4.6 Vegetation carbon storage

Mitigation potential (%)	**Cost**	**Type**
0.6%	Moderate	Capital/operating

Atmospheric carbon dioxide (CO_2) can be sequestered by trees, reducing the net emissions of a particular production system substantially (Ramachandran Nair et al. 2010; Doran-Browne et al. 2016). The carbon storage potential of vegetation varies according to:

- the availability of land suitable for tree planting
- tree species planted
- soil fertility
- rainfall.

Typically undertaken for environmental purposes, tree plantings may be either monocultural plantings (single species) or a variety of species suited to the region can be used. Though the primary benefit of such plantings is increased biodiversity (e.g. by providing habitat for native wildlife), an additional benefit to the landholder is carbon storage. For maximised carbon credits, monoculture plantings are typically the best option, monoculture plantings tend to be fast-growing, meaning carbon storage rates increase sooner. The carbon benefit and biodiversity potential of each planting type are depicted in Figure 13. For free range layer farms, where biosecurity and the minimisation of any threat to birds is paramount, a monocultural planting is optimal. This method confers the greatest carbon benefit whilst offering the least attractive habitat to native birds, which may carry infectious diseases.

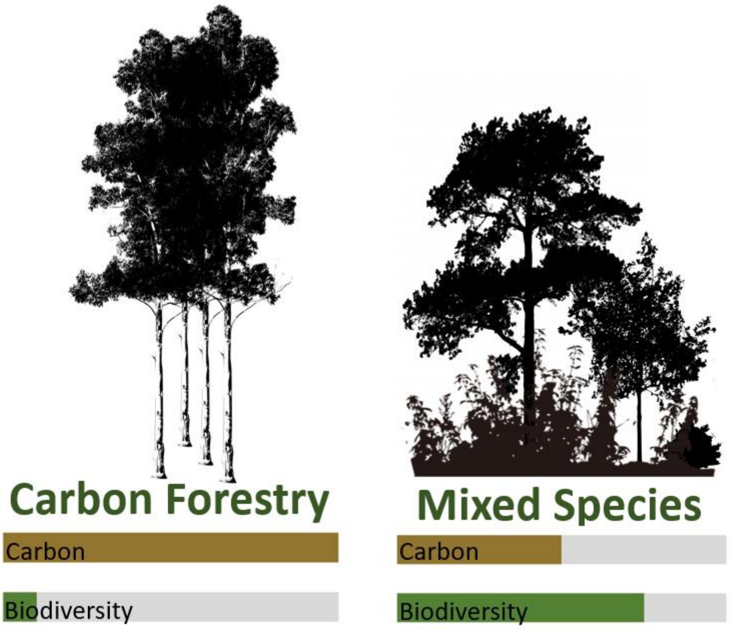

Figure 13 Graphical representation of biodiversity and carbon credit benefits of environmental and monoculture tree planting projects (reproduced from Government of South Australia 2017)

Vegetation carbon sequestration is a long-term emission reduction strategy as it requires several years of establishment before carbon benefits can be quantified. Besides carbon storage and increased biodiversity, benefits include erosion and salinity control and shelter for livestock.

Although higher carbon sequestration rates tend to occur in young plantations, mature plantations will continue slowly sequestering carbon over their lifetime as they reach maturity (Unwin & Kriedemann 2000).

The total carbon storage available in any given planting is determined by the area available and the rate at which carbon is sequestered. Sequestration rates vary between a low of about 2.5 t CO_2-e ha^{-1} yr^{-1} and a maximum of 30 t CO_2-e ha^{-1} yr^{-1}, with the upper limit representing a very high growth rate species in a high rainfall region. A rate of 7–10 t CO_2-e ha^{-1} yr^{-1} is a reasonable mid-point to estimate carbon sequestration potential. The area available for tree planting is determined by the land available at the site in question.

For many layer farms, tree plantings for vegetative buffers, range areas, or to line roads or fence lines are beneficial from an amenity perspective. This will rarely, however, amount to more than 10 ha on a small to medium farm. Additional land dedicated to planting is required to increase the level of carbon storage. For most layer farms, 25–50 ha would be a large planting. Carbon storage for 10 ha at a sequestration rate of 7.5 t CO_2-e ha^{-1} yr^{-1} would be 75 t CO_2-e yr^{-1}, increasing to between 187 and 375 t CO_2-e yr^{-1} for larger plantings. Note that this value could increase with high growth rate species in high rainfall regions or where irrigation can be used. Compared with the carbon account for a free range 100,000 hen layer farm, this represents between < 1 and up to a maximum of 3% of emissions. Table 20 outlines the land required to achieve various percentage reductions in total net emissions for the farm.

Table 20 Calculated area required for tree plantings to reduce emissions from a 100,000 hen free range layer farm

Emissions reduction		**Total area required (ha)**
%	***Total tonnes CO_2-e (annual) carbon storage***	***Monocultural plantings***
5%	282	37.6
10%	564	75.1
25%	1,409	187.8
50%	2,818	375.7
75%	4,227	563.5
100%	5,536	751.4

5 Reduction in grid emissions

Passive mitigation will occur over time in response to improvements in the energy grid. Each state in Australia set emission reduction goals to achieving net-zero emissions by 2050 or earlier. More recently, the Federal Government established a roadmap to reduce Australia's emissions to net-zero by 2050. These targets and the key reference documents for each jurisdiction are summarised in Table 21.

A fundamental element of each plan is the adoption of renewable energy generation over traditional fossil energy sources.

Table 21 Summary of Federal and state emission reduction targets

Jurisdiction	Target	Reference
Queensland	Net-zero emissions by 2050	Queensland's 2019 Greenhouse Gas Emissions and Targets, Queensland Climate Active (Queensland Governement 2021)
New South Wales	Net-zero emissions by 2050 50% below 2005 levels by 2030	Net Zero Plan, Stage 1: 2020–2030 (NSW Department of Planning Industry and Environment 2020)
Victoria	Net-zero emissions by 2050 45–60% below 2005 levels in 2030	*Climate Change Act 2017* (Vic) Interim Emissions Reduction Targets for Victoria 2021–2030 (Independent Expert Panel on Interim Emissions Reduction Targets for Victoria 2019)
Tasmania	60% below 1990 levels by 2050	Tasmania's Climate Change Action Plan 2017–2021 (Tasmanian Government 2021)
South Australia	Net-zero emissions by 2050 50% below 2005 levels by 2030	*Climate Change and Greenhouse Emissions Reduction Act 2007* (SA)
Western Australia	Net-zero emissions by 2040	Western Australian Climate Change Policy (The Government of Western Australia 2020)
Federal	26–28% below 2005 levels by 2030 (on target for up to 35%) Net-zero emissions by 2050	Australia's Long-Term Emissions Reduction Plan (Commonwealth of Australia 2021a)

Initial projections regarding the effect of this economy-wide decarbonisation of electricity grids indicate potential reductions in the emission intensity of eggs of between 5 and 10% between 2020 and 2035. These projections were performed under a business-as-usual scenario (i.e. no management changes, productivity improvements or emission-reducing technology adoption in the egg industry).

As the decarbonisation of the energy grid is also anticipated to have indirect effects on products and services that use grid electricity as an input, a 1.5% reduction in scope 3 emissions was assumed, recognising the slight reduction in the emission intensity of grain due to less fossil energy used to manufacture synthetic fertilisers.

Due to emission reductions elsewhere, the relative contributions of scope 3 LU and dLUC emissions are projected to increase over the decade. As there is no evidence of industry-wide improvement in FCRs between this study and the 2011 study by Wiedemann and McGahan, the projections did not include any FCR improvements over the coming decade. If an improvement trend were to eventuate, scope 3 emissions, incl. LU and dLUC emissions, would fall, reducing the carbon footprint of eggs. Note that FCR is only one means by which scope 3 LU and dLUC emissions could be reduced, the other being to reduce exposure to high impact imported soy meal. Table 1 describes three mechanisms by which LU and dLUC emissions could be reduced or offset.

Appendix 2

Table 22 Emissions reduction, in tonnes of CO_2-e (incl. LU and dLUC), at each stage of the free range pathway

Emissions abatement (t CO_2-e)															**Total (t CO_2-e)***
BAU	*M1*					*M2*					*M3*			M4	
2021	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*	*2031*	*2032*	*2033*	*2034*	*2035*	*2021–2035*
-	272	504	621	853	39	117	35	67	33	33	33	33	33	2	2,674

* Total emissions abated does not include carbon storage (from manure application or tree plantings in Module 3), as carbon storage offsets emissions rather than reducing them. Emissions reductions in the years in between Modules are due to the decarbonisation of the energy grid.

Table 23 Emissions reduction, in tonnes of CO_2-e (incl. LU and dLUC), offset at each stage of the cage-free pathway

Emissions abatement (t CO_2-e)															**Total (t CO_2-e)***
BAU	*M1*					*M2*					*M3*			M4	
2021	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*	*2031*	*2032*	*2033*	*2034*	*2035*	*2021–2035*
-	2517	4823	5793	8098	320	1900	271	618	290	309	328	346	363	280	26,256

* Total emissions abated does not include carbon storage (from manure application or tree plantings in Module 3), as carbon storage offsets emissions rather than reducing them. Emissions reductions in the years in between Modules are due to the decarbonisation of the energy grid.