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Using a gate-to-gate LCA to apply circular economy principles to a food processing SME

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Abstract:

The purpose of this study was to assess: what are the circular economy opportunities for small and medium-sized enterprises (SME) in the meat processing sector to reduce their environmental impacts, using Life cycle assessment (LCA) as the analytical method to prevent burden shifting; whether current life cycle inventories and LCA studies adequately represent SMEs such as the study plant; and whether climate change is a suitable proxy for impacts. Life cycle inventory data from a SME meat processing site in regional Australia was used for benchmarking with existing industry data and for risk and opportunity identification along the supply chain. A LCA was conducted of the current operation and possible future energy supply scenarios involving the use of tallow, wastewater methane and biomass production, to identify the best performing option as part of a PhD project on SMEs and sustainability in agribusiness value chains. System expansion was used to handle all coproducts and byproducts. The area of land required to produce biomass was calculated and was compared to the catchment area for livestock, and an estimate was made of the non-arable land area required to produce biomass to offset all greenhouse emissions for the supply chain. Inventory data and LCA results for this SME were significantly different to previous LCAs. The system expansion resulted in large credits, particularly for edible offal. Climate change may not be a suitable proxy for other midpoint impact categories due to the difference in contributing processes. The best future energy was the biomass scenario, which involved using tallow for biodiesel production, capturing methane generated in the onsite wastewater treatment system for electricity generation, using tallow to generate the remaining electricity needs and using biomass for thermal energy production. Less than 0.5% of the non-arable

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land area required for producing the livestock for the plant was needed for biomass production, and if all supply chain emissions were offset using biomass, the land area required was 12% for life time grass fed beef. The potential for supply chain integration in the red meat sector appears promising, particularly in terms of offsets from biomethane use for electricity production, tallow use for biodiesel production and biomass production for thermal energy use. Life cycle assessment is a useful tool to screen circular economy options and identify the best future scenario, although a wide range of impact categories should be assessed as climate change is not a suitable proxy.

Key words (6): environmental sustainability, agribusiness supply chain integration, circular economy, gate-to-gate Life cycle assessment, biomass, non- arable land

Highlights:

- Optimising use of edible offal is important for reducing impacts of meat production
- Meat processing SMEs may not be adequately represented by current inventory data
- Climate change may not be a suitable proxy for all other mid point impact categories
- Biomass scenario appears to be the best, utilising biogas and tallow for transport biodiesel
- Less than 0.5% of livestock catchment required to grow biomass

1. Introduction

The adverse environmental impacts of meat production, particularly to land-use change, land degradation and climate change, are well documented (Steinfeld et al., 2006). World population growth is expected to increase the amount of food required globally by 70% by 2050 (FAO, 2012) and more than half of that population growth will occur in Africa (United Nations, 2015). A 2010 study (Leahy et al., 2010) found that only 5% of the world's 1,525 million vegetarians were vegetarians by choice, the remainder were vegetarians "of necessity" who would start consuming meat as soon as they were financially capable of doing so. Although there is a decrease in the consumption of meat and a growth in rates of vegetarianism and veganism in middle and high income countries due to a combination of health, environmental and animal welfare concerns, the growth of meat consumption in other countries will offset this, leading to a net increase in livestock related methane emissions (Leahy et al., 2010). Australia is a net exporter of red meat and for the 2016 calendar year exports included 70% of the national beef production (1,018,105 tonnes), 56% of the lamb production (242,285 tonnes), 95% of the mutton production (132,199 tonnes) and almost all of the goat production (26,794 tonnes) (Meat & Livestock Australia, 2018).

Recent Australian data indicates that 52% of the land area of Australia is used for agriculture, and of this land, only 7% is used for growing crops, including hay and silage (Australian Bureau of Statistics, 2017).. Current climate change projections indicate that there will be increases in temperatures

(mean, daily minimum and maximum), potential evapotranspiration, the frequency and severity of hot days and extreme rainfall events, the duration of droughts and the frequency of extreme droughts in southern Australia, and there will be decreases in the amount of winter and spring rainfall in southern Australia (CSIRO and Bureau of Meteorology, 2015). The changes vary by geographic region but are expected to reduce the quality and quantity of agricultural produce (Reyenga, Howden, Meinke, & Hall, 2001), make production less reliable (Stokes et al., 2008), and increase animal and plant heat stress (Australian Government Department of Agriculture and Water Resources, 2018; Nardone et al., 2010). The net impact will be that the suitability of regions to their current agricultural produce will change, as the increasing frequency of soil-moisture based droughts will lead to a net reduction in the availability of arable land as it transitions to non-arable agricultural production (Mpelasoka et al., 2008).

Life cycle assessment (LCA) has been used to analyse the environmental impacts of meat supply chains, usually focusing on a limited number of midpoint impact categories (MIC) such as carbon or water footprints. A comprehensive review of livestock production (Cederberg et al., 2012) found that **almost all** studies analyse the global warming impact category, **most** studies analyse energy use and acidification, eutrophication and land use impact categories and **some** studies analyse toxicity, resource depletion and water use. Land use indicators have generally not included any consideration of land quality, so have not differentiated between prime arable land and non-arable or more marginal land. Most of the studies of climate change do not include changes to soil carbon or land use change (direct or indirect).

A recent review of LCA studies in Australian chicken, pork, lamb and beef meat supply chains (Wiedemann, 2018) highlighted that the system boundary of most LCA studies end at the farm gate, so only a limited number of studies investigate impacts from processing and transport. Midpoint impact categories covered in all studies relate to the issues most relevant to the Australian context, namely climate change (but often omitting emissions relating to land use, direct land use change and soil carbon), energy use, water use (consumptive and stressed) and in more recent studies, land use (total, arable and non-arable). Nutrient cycles or biodiversity have not been directly addressed even though recent research (Rockström et al., 2009) indicated that their planetary boundaries have been or are close to exceedance. Foreground data used in the life cycle inventories included primary data from SME farms and meat processing plants, as well as more generic industry survey data. Studies used a variety of different methods to handle coproducts and byproducts, ranging from system expansion (tallow replaced by rape seed oil or palm oil, meal replaced by soymeal or sorghum) to allocation, both economic and physical (both mass and biophysical based on energy and protein

content). A detailed review of LCA studies which include meat processing is included in Supplementary Material 1 (SM1) and emissions and consumption relating to the meat processing stage for Australian LCAs indicate that fossil fuel energy use in meat processing ranges from 14% in the pork case through to 67% in a beef study (Gregory M. Peters et al., 2010) for the full life cycle, with higher overall consumption in grain fed beef compared to lifetime grass fed. Only a small portion of total supply chain fresh water consumption (2-6%) and greenhouse gas emissions (4-14%) occurs at the meat processing stage.

Recent European Environmental Product Declarations (COOP, 2016a, 2016b; Inalca, 2018; INALCA, 2018) indicate that core processes (meat processing plant and transport of all raw materials to the plant) contribute a small amount of the total environmental impact per kilogram of boneless meat, ranging from 8-12% for greenhouse gas potential (1.7-2.7 kg CO_{2-e}), 9-12% for eutrophication potential (0.5-0.7 g PO₄^{3--e}), 1-2% for ozone creating potential (5.3-7.5 g C₂H_{4-e}) and 1% for acidification potential (g SO_{2-e}).

LCA and other studies aimed at identifying improvements in the sustainability of meat supply chains have focused on single life cycle stages, then aggregated the opportunities from individual stages to propose a whole of supply chain approach (i.e. an additive approach) (Mayberry et al., 2018; Peters et al., 2009; Wiedemann et al., 2014). Only more recently have LCA studies taken a whole of supply chain approach (Hessle et al., 2017; Notarnicola et al., 2017; Paolotti et al., 2016; Sonesson et al., 2016), identifying opportunities within and between life cycle stages and interconnected supply chains, to optimise the whole supply chain, rather than just individual portions of it (i.e. a synergistic approach). This is more in line with circular economy principles, which are: Principle 1 - the value of products, coproducts and byproducts are to be maximised at all stages in the supply chain and between supply chains, with the overall aim of maintaining inputs and products at their highest utility at all times; Principal 2 - Natural capital is to be preserved and enhanced by replacing finite stocks with renewable resources; and Principle 3 - system effectiveness is to be fostered by identifying and eliminating negative externalities such as waste and pollution (Ellen MacArthur Foundation, 2015; Stahel, 2016). At present the circular economy is depicted as being very consumer-centric, but this study will investigate the potential between the core processing stage in the supply chain (meat processing) with the upstream on-farm production, and the linking transport stages, as indicated by the red arrows in Figure 1.

Figure 1: Circular economy of this study (adapted from (Ellen MacArthur Foundation et al., 2015)).

Q fever, caused by the bacteria *Coxiella burnetii*, is one potential constraint on applying circular economy principles within meat supply chains since if it is present in animals entering the plant it may survive the wastewater treatment system and may then be present in treated wastewater which is available for nutrient recycling. The bacteria is extremely resistant to heat, drying and chemical agents (such as disinfectants), can survive in the environment for long periods of time (Shishido et al., 2016) and is highly infectious, requiring less than 10 bacteria to cause an infection (Center For Disease Control, 2012). It causes cases of illness in the meat industry (Gidding et al., 2009; Lowbridge et al., 2012; Tissot-Dupont et al., 2004) and the wider population (Dahlgren et al., 2015b; Eastwood et al., 2018; O'CONNOR et al., 2015; Sivabalan et al., 2017; Tozer et al., 2011; Whitney et al., 2009), with symptoms similar to influenza even though a small percentage have more severe symptoms (Anderson et al., 2005; Dahlgren et al., 2015a; Nourse et al., 2004).

The definition of a small and medium-sized enterprise varies, but in this study a SME is defined as having less than 250 employees, to be consistent with the OECD definition (OECD, 2005). The study site is representative of SMEs in the meat processing sector in regional Australia. In a recent environmental benchmarking report (Ridoutt et al., 2015) 14 red meat processing facilities, which did not include the current study site, were assessed of the 150 plants operating in Australia (i.e. 9%) and the assessed plants produced 34% of the total production for the year of the study (2012/2014), meaning that the study was dominated by non-SME plants. This study was intended to assist the site, a SME, with identifying where it could most significantly improve its environmental performance while simultaneously addressing business costs and risk issues. The **research questions**

therefore were: 1) do current life cycle inventories and LCA studies adequately represent SMEs in this sector such as this plant; 2) what are the circular economy opportunities for SME regional meat processors to reduce their environmental impacts, using LCA as the analytical tool to prevent burden shifting; and 3) is climate change a suitable proxy for other impact categories.

2. Material and Methods

2.1 System Description

This study focuses on a **gate-to-gate life cycle assessment** of a domestic meat processing plant which processes lamb, sheep, veal, beef, pork and goats and is representative of smaller plant with rendering serving the domestic “kill and chill” market in regional areas, using a more comprehensive inventory than previous studies. The site does not include freezing, so the onsite heating ventilation and air conditioning services (HVAC) are provided by individual packaged refrigeration units using hydrofluorocarbon and hydrochlorofluorocarbons, rather than the centralised ammonia systems. The functional unit was 1 tonne of hot standard carcass weight (HSCW) at the retailer, as the plant sells whole carcasses, sides, primal cuts and has its own retail ready product lines (New England Lamb and Macleay River Veal). The system boundaries cover the core processes at the processing plant, including onsite activities and wastewater treatment, transport of inputs to the processing plant and the transport of products to market, which is controlled by the processing plant owner, as outlined in Figure 2.

Figure 2: System boundaries for current study - livestock production system for cattle, sheep, goats and pigs

The SME study site was located in the Mid North Coast region of New South Wales, an area of 18,851 square kilometres, 52% of which is agricultural land including 27% which is used for grazing on modified pastures (Department of Agriculture and Water Resources, 2017). Beef cattle and dairy farms account for 59% and 16% of all farms respectively (Australian Bureau of Statistics, 2018). A recent Australia wide review of native vegetation management on agricultural land found that the percentage of native vegetation on farms ranged from a low of 3% on dairy farms, to 11% for specialised sheep and mixed cropping-livestock farm, 14% on sheep-beef farms and 30% on specialised beef farms (Harris-Adams et al., 2012). Linear easements, such as rail, road and

powerline corridors, occupy 6.5% of the land area of New South Wales, which is not insignificant when compared to the 8% of land area preserved within National Parks and Nature Reserves (Dufty, 2010).

2.2 Inventory data, benchmarking, risks and opportunities

Primary data was collected from the processing site for the 2015-2016 financial year for **inputs** such as livestock, energy (electricity, boiler fuels, transport fuels), water, chemicals (boiler, pest control, skins treating), **products** (meat), **coproducts** (edible offal), **byproducts** (not edible for humans but have a current use, such as tallow, meal, skins, paunch, manure, boiler ash, treated effluent) and **wastes** (no current economic use such as wastewater methane). Production data for meat, tallow and meal was obtained and based on the mix of species entering the plant, it was calculated that the average yield from live weight to HSCW was 50%. As the study site is an integrated plant, an onsite rendering plant converts byproducts from meat processing and waste from local butchers and boning rooms into tallow and meal. A detailed inventory is provided in SM2.1.

This primary life cycle inventory data was benchmarked against existing metrics for the red meat processing industry and the relative energy costs were ranked, to assist with identifying priorities for substitution. An energy balance of the site was undertaken to identify the current consumption and production of energy and to identify the reuse potential of coproducts, byproducts or wastes.

Secondary data from literature was used for inputs sourced from multiple suppliers such as packaging and chemicals (lube oil, cleaning, wastewater treatment) (Pagan et al., 2002). The site refrigeration system uses individual packaged units rather than a centralised ammonia or glycol system, so estimates of refrigerant losses were included based on the installed capacity, estimated refrigerant charge of 1.5 kg/kW load and an estimated annual leakage rate of 10% for a medium temperature distributed system (Emerson Climate Technologies, 2010a). The theoretical maximum pond methane emissions were calculated using production data and the default values for meat processing in the methodology specified by the Australian Federal Government (Department of the Environment and Energy, 2016a). Transport fuel consumption for most site inputs was estimated based on the weight and transport distances (450 km from the port of Brisbane to the regional hub at Coffs Harbour and 150 km from the regional hub to the site for most inputs, with 1,800 km for salt for skins treating, 900 km for skin preservative and 450 km for boiler coal). A commercial database (Ecoinvent 3.2) was used for background processes and some processes, such as the average diesel consumption in truck transport, were modified for Australian fleet averages (0.028 L/ tkm for articulated trucks and 0.076 L/ tkm for rigid/other trucks (Australian Bureau of Statistics, 2015). The

fuel consumption in the site-owned transport fleet that delivers products to customers was converted to a tkm equivalent by dividing the litres of diesel consumed per functional unit by the average fuel consumption per tkm, assuming that 50% of the product was delivered by rigid trucks and 50% by articulated trucks, then modelled using a modified Ecoinvent processes. Previous LCA studies were used to provide information on the area of arable and non-arable land used for upstream sheep and beef production (Wiedemann et al., 2016, 2015a) for biomass production.

A qualitative review of risks and opportunities in the supply chain was undertaken, with a particular focus on **risks** with catastrophic consequences (SAI Global, 1999), which could lead to an offsite impact such as the death of a member of the public, a toxic release with detrimental effects or significant financial loss. Information on risks was obtained from site specific data (NSW Environment Protection Authority, 2015), generic industry data (Dames & Moore Pty Ltd, 1999; Office of Environment & Heritage, 2011; Sloan-Gardner et al., 2017; URS Australia Pty Ltd, 2006) and compliance review information from the regulator (NSW Environment Protection Authority, 2010, 2009, 2003). The review of **opportunities** focused on the potential for supply chain integration in the surrounding geographic area and the potential to contribute positively to issues such as biodiversity, animal welfare and local employment, using the three circular economy principles. Opportunities were limited to widely available, proven technologies, due to the regional location of the plant (and subsequent limitation on the availability of skilled specialists) and the risk averse nature of the industry.

The locational benefits of the site (i.e. regional location and surrounding land use) and current operation were assessed in a qualitative fashion, to match potential synergies with identified risks, such as the beneficial reuse of treated effluent.

2.3 Life Cycle Impact Assessment – methods and modelling

Given that the goal was consistent with situation A “micro-level decision support” with no change in production levels, attributional datasets were used (EC-JRC, 2010). Previous LCAs had used a hybrid approach for handling coproducts and byproducts, using a combination of system expansion and by allocation (economic, physical or both). For this study, system expansion was used for handling all coproducts and byproducts. The main substituted products for tallow were palm oil and rape seed oil (on a mass basis), polyester for hides (on a mass basis), rape meal for meal (on a mass basis) and an upstream substitution of market for edible offal (upstream substitution of market for cattle for slaughtering on a mass basis). Other system expansions included natural aggregate for boiler ash on a mass basis, market for soil conditioner for manure and paunch on a mass basis, and the market for

irrigation for wastewater irrigation volumes on a volume basis. For the biomass case, the nutrient content of the wastewater was assumed to replace commercial fertilisers.

The life cycle impact assessment methods and 12 midpoint impact categories (MIC) recommended in the Best Practice Guide by the Australian Life Cycle Assessment Society (ALCAS) were used (Renouf et al., 2016), namely: climate change (kg CO_{2-eq}); minerals resource depletion (Sb_{-eq}); fossil fuels resource depletion (MJ); consumptive water use (m³ H₂O_{-eq}); eutrophication (kg PO₄^{3--eq}); acidification (kg SO_{2-eq}); human toxicity (CTU_h); ecotoxicity (CTU_e); photochemical ozone formation (C₂H_{4-eq}); particulate matter formation (kg PM_{2.5-eq}); ozone depletion (kg CFC-11_{-eq}); and ionizing radiation (kBq U235_{-eq}). The characterisation factors used were from version 2 of the best practice guide (Renouf et al., 2016) except for human toxicity and ecotoxicity, which used USEtox, the default method in openLCA. Three ReCiPe (H) endpoint (damage) impact categories (EIC) (human health, ecosystems and resources) were also used, as was agricultural land use using the ReCiPe (H) method. LCA modelling used openLCA software (version 1.7).

2.4 Scenarios – LCA modelling, land use balance

The reference scenario (REF) was based on the current operation. A number of electricity efficiency projects had been identified at the site and it is assumed that these were implemented, thus reducing the baseline energy consumption compared to the collected data for the REF case in the efficiency scenario (EFF). The efficiency projects were combined with electricity from solar photovoltaics and a small wind turbine.

Alternative energy supply scenarios were developed, particularly opportunities to integrate with upstream (farming) and downstream (retail/consumer). Options considered were the use of tallow (TAL), the use of biogas from anaerobic wastewater treatment ponds (BGS) and the use of biomass (BMS). When tallow was converted to biodiesel, it was assumed that the glycerine produced was discharged into the onsite wastewater treatment pond system in the BGS and BMS scenarios to increase methane generation, whereas in the TAL scenario it was handled via system expansion. Inventory data for tallow biodiesel production was taken from (Dufour and Iribarren, 2012), from (Poeschl et al., 2012) for biogas upgrading and from (Yanagida et al., 2011) for biomass production. The details of these scenarios are outlined in Table 1. The results for the scenarios were internally normalised by dividing by the “best” result in each impact category, so the value 1 represents the best environmental outcome.

Table 1: Scenarios – current and potential future energy supply options for plant

Scenario	Details
Reference (REF)	Current operation
Efficiency (EFF)	(14% reduction in electricity consumption) + (15kW of solar photovoltaics electricity generation) + (25 kW of wind electricity generation)
Tallow (TAL)	EFF + (tallow used for electricity generation, site transport fleet (biodiesel) and part of thermal energy) + (residual of thermal energy from current fuel source)
Biogas (BGS)	EFF + (biogas used for electricity generation) + (tallow used for residual electricity generation + biodiesel for site transport fleet + all thermal energy)
Biomass (BMS)	EFF + (biogas for electricity generation) + (residual electricity generation from tallow) + (tallow used for site transport fleet diesel consumption) + (biomass for all thermal energy) + residual tallow sold

273

274 A land use balance was conducted to assess the area of land required for biomass production for 2
275 cases; 1) using non agricultural land and 2) comparing non-arable land required to produce livestock
276 for the plant and the area of land required to produce sufficient biomass for the plant thermal
277 energy requirement. Only non-arable land use associated with livestock production was used, as
278 insufficient data was available on goat and pork production. Biomass production per hectare was
279 assumed to be 30 m³/ha/year (Heathcote, 2002) with a density of 265 kg/m³ (Thomas et al., 2009)
280 and the energy content was assumed to be 10.4 GJ/t (Department of the Environment and Energy,
281 2016a), providing a gross energy production of 83 GJ/ha/year.

282 3. Results and Discussion

283 3.1 Life Cycle Inventory benchmarking, risks & opportunities

284 As indicated in Table 2, the site consumed a significantly lower volume of water compared to the
285 Australian industry benchmarking data, by ratios of 0.28-0.34, and the nitrogen and phosphorus
286 emission levels were lower than industry averages but not as significantly, with average ratios of
287 0.55 and 0.75 respectively. The water consumption values are consistent with Australian industry
288 data, as significant amounts of water are used in the boning room and this plant only processes a
289 small percentage of the carcasses, which highlights the difference between domestic SME and larger
290 export plants (Pagan et al., 2002). The difference between the Australian industry and overseas
291 industry figures from COOP Environmental Product Declarations (EPDs) (e and f) may reflect the
292 importance that has been placed on reducing water consumption in Australia due to scarcity issues.
293 The nutrient levels are consistent with research on the source of nutrients and organic load within

meat processing plants, which indicates that the paunch processing and rendering plants contribute the greatest nutrient load, whereas boning rooms contribute only a very small proportion of the wastewater nutrient load (Jensen and Batstone, 2012).

For electricity consumption, the plant consumed 0.4 of the industry average. This is consistent with SME “kill and chill” domestic plants, which chill but do not freeze product. Thermal energy use and total energy use were about the same as the average industry consumption in terms of the total amount. This is consistent with industry data, as thermal energy use is normally over 70% of total site stationery energy use, and the rendering plant is normally the largest thermal energy consumer (Hydro Tasmania Consulting, 2009). It may also indicate inefficiency in the thermal energy system, ranging from generation, distribution or end use efficiency.

Table 2: Life Cycle Inventory data benchmarked against published meat processing industry data

Parameter	Site value	Industry	Site: Industry ratio
Water use (kL/t HSCW)	3.0	6-9 ^a	0.33-0.5
		8.9 ^b	0.34
		9.4 ^b	0.32
		10.6 ^d	0.28
		43 ^e	0.07
		33 ^f	0.09
Wastewater Nitrogen release (kg N/ t HSCW)	0.95	1.5 ^c	0.6
		2.1 ^d	0.5
Wastewater Phosphorus release (kg P/ t HSCW)	0.20	0.25 ^c	0.8
		0.3 ^d	0.7
Electricity use (kWh/ t HSCW)	105	271 ^g	0.4
		280 ^h	0.4
Thermal energy use (MJ/t HSCW)	2,739	2,391 ^f	1.1
Total energy use (MJ/t HSCW) (note – excludes transport)	3,117	3,005 ^b	1.0
		4,108 ^c	0.8
		3,389 ^d	0.9
		3,368 ^g	0.9

Notes – a - refer to table 1, b - (Ridoutt et al., 2015), c - (GHD, 2011), d - (URS Australia Pty Ltd, 2005), e - (COOP, 2016b) core processes for veal only, corrected for 75% boneless meat yield, f -

(COOP, 2016a), core processes for beef only, corrected for 80% boneless meat yield, **g** - (Hydro Tasmania Consulting, 2009), **h** - (Rowlands et al., 2007).

Transport energy consumption added over 30% to the total site total energy use, bringing it up to 4,701 MJ per tonne of HSCW, as indicated in Table 3. Significant energy is available from coproducts and waste, with nearly 5,000 MJ/ t HSCW from tallow and 1,000 MJ/ t HSCW from biogas from the onsite anaerobic wastewater treatment ponds. If the efficiency of generation (assumed to be 39% (GE Power, 2016)) was factored into the electricity consumption figure, this would give energy consumption of 969 MJ for the electricity generation and a total site consumption of 5,293 MJ/ t HSCW.

In terms of costs per MJ, if electricity is ranked as a value of 1, then diesel is 0.5 (or 50% of the cost of electricity) and coal (the main boiler fuel) is 0.1 (or 10% of the cost of electricity). This is consistent with industry data (Hydro Tasmania Consulting, 2009).

Table 3: Site Energy Balance and Cost Ratios

Site Energy Balance	Use (MJ/ t HSCW)	Availability (MJ/ t HSCW)	Cost ratio
Electricity	378		1
Thermal Energy (boiler etc.)	2,739		Coal: 0.1
Transport Energy	1,585		Diesel: 0.5
Total usage	4,701		
Total usage (corrected for efficiency of electricity production)	5,293		
Tallow ^a		4,793	
Biomethane from anaerobic ponds ^b		926	
Total availability		5,720	

Notes – a) based on 0.12 t tallow produced per 1 t HSCW (site primary data) and calorific value of 40 MJ/kg (CSIRO, 2002), b) maximum theoretical amount based on NGER default values of 13.7 kL wastewater/t HSCW, 6.1 kg COD/kL wastewater, 0.8 fraction conversion of COD to methane, 6.3 t CO₂-eq biomethane/t COD removed, 25 t CO₂-eq/t methane, 0.6784 kg methane/m³ methane and 37.3 MJ/m³ biomethane (Australian Government Clean Energy Regulator, 2018; Department of the Environment and Energy, 2016b).

As indicated in Table 4, the two major risks relate to the interruption to electricity supply to the site and the potential risk that Q fever may be entering the plant, surviving through the wastewater treatment system and therefore be present in the treated effluent. The major opportunities relate to

converting tallow into biodiesel to replace fossil diesel in the company transport fleet, capturing and using biogas from the anaerobic wastewater treatment pond and engaging with upstream farmers in the local area for on-farm coproduction of biomass.

Table 4: Summary of risks, opportunities and circular economy opportunities.

	Upstream (on-farm primary production)	Core (processing)	Downstream (use & end of life)
Risk	Q fever in animals	Q fever in wastewater	
		Interruption to electricity supply	
Opportunity		Energy content in biomethane ^{1, 2, 3} and tallow ²	
	Fertiliser use on farm	Nutrient content in treated effluent ^{1, 2}	
	Transport fuel use	Tallow conversion to biodiesel ^{1, 2}	Transport fuel use
	Biomass production	Biomass use for electrical/thermal energy ²	

Notes: 1 - Circular economy principle 1 – value maximised at all times; 2 – Circular economy principle 2 – preserve natural capital and replace with renewables; Circular economy principles 3 – eliminate waste and pollution.

Given the alignment between the cost ratios and identified risks, finding an alternative source of electricity is the most significant opportunity. From a cost and opportunity perspective, replacing purchased diesel in the site transport fleet with biodiesel produced from tallow should be the next highest priority, with replacement of thermal fuel as a lower priority. Although the treated effluent contains valuable nutrients which could be recycled to on-farm primary production, care should be taken to ensure that it is used in applications which will not cause a risk to animals, so use in dairy farming applications such as pasture fertilisation should be avoided in favour of using the treated effluent for biomass production.

3.2 LCA of Current site operation

LCA results for the reference scenario and previous LCA and EPD studies are presented in Table 5 for the MIC assessed. Compared to the values reported in existing LCA studies from Australia, the climate change value is consistent with previous LCA studies (Gregory M. Peters et al., 2010; Wiedemann et al., 2015a). The fossil fuel use is substantially lower, which is significant given that in previous LCA studies, this life cycle stage contributed from 14-67% of total fossil fuel use. This is consistent with the life cycle inventory, where the electricity use was significantly lower than published industry averages. The difference between the fossil fuel use and climate change values may be due to non-fossil sources, such as wastewater methane emissions, which are currently under-reported in published industry data. For example, the most recent environmental

performance review of the red meat processing sector (Ridoutt et al., 2015) reported a greenhouse gas emission of 0.43 t CO₂-eq/ t HSCW, with 44% of emissions from Scope 1 (onsite) sources and 39% of Scope 1 emissions from wastewater treatment, which equates to 0.07 t CO₂-eq/ t HSCW from wastewater. This is significantly lower than the value obtained when using the default NGER value of 0.42 t CO₂-eq/ t HSCW. The industry average figure includes an unknown number of sites that have installed covers on their anaerobic ponds, and capture and utilise the wastewater biomethane in onsite boilers, which would have a significant impact on the net greenhouse gas emissions.

Compared to the values reported in EPD studies (COOP 2016b; COOP 2016a) assuming a 3% chiller loss, the climate change value is consistent, the fossil fuel use is significantly lower, the acidification and eutrophication potentials are significantly higher and the photochemical ozone formation potential is in the lower end of the range. This is most likely attributable to the use of coal for thermal energy at the plant, and the dominance of coal as a fuel in electricity generation in Australia.

Table 5: Current results for reference scenario (current operation, before system expansion, with transport removed) per kg HSCW, compared to published data using same system boundaries (LCA, current industry benchmarks and EPD), with percentage contributed by meat processing stage in parenthesis

Species	Climate change kg CO ₂ -eq	Fossil fuel use MJ	Acidification potential kg SO ₂ -eq	Eutrophication potential kg PO ₄ ³⁻ -eq	Photochemical ozone creating potential kg C ₂ H ₄ -eq
Multi (current study)	1.1	3.2	4.4	1.4	0.3
Beef ¹	1.4 (14%)	18.2 (67%)	Not assessed		
Beef, lifetime grass fed ²	0.7 (3.7%)	5.2 (30%)			
Beef, long fed grain finishing ²	0.7 (4.0%)	5.2 (19%)			
Sheep ¹	1.0 (14%)	13.6 (50%)			
Lamb ²	0.8 (6%)	7.5 (41%)			
Pork ³	0.4 (8%)	3.1 (14%)			
Industry benchmark (red meat) ⁴	0.43 (n/a)	3.0 (n/a)			
Veal ⁵	2.0 (12%)	18.2 (26%)	1.0 (1%)	0.5 (12%)	5.5 (2%)
Beef ⁶	1.3 (8%)	15.1 (30%)	0.1 (0.1%)	0.4 (9%)	4.1 (1%)
Frozen hamburger ⁷	0.5 (15%)	14.2 (37%)	1.3 (2%)	0.2 (1%)	0.1 (10%)

Notes: 1) - (Gregory M Peters et al., 2010), 2) - (Wiedemann et al., 2015a), long fed is 330 days in the feedlot, 3) - (Wiedemann et al., 2018), 4) - (Ridoutt et al., 2015), **only covers Scope 1 and 2 emissions**, 5) - (COOP, 2016b), 6) - (COOP, 2016a), 8) - (INALCA, 2018), 5-7 use energy contents of 27 kJ/kg for coal, 42 kJ/kg for natural gas, 35.7 kJ/kg for oil and 39.7 GJ/kL for fuel oil with 0.9 kg/L density.

The full LCA results for the reference scenario are in Table 6, with separate values for before and after the inclusion of system expansion to handle the main coproducts and byproducts. Before system expansion all impact categories are emission sources. Two system expansions for replacing tallow production were analysed - palm oil (the marginal product for tallow export) and rape seed oil (the marginal product for tallow use in the domestic market).

Table 6: LCA results for reference scenario (current operation), with and without system expansion (per t HSCW)

Mid point impact categories (MIC)	Unit	Before system expansion	After system expansion ^a	
			Palm oil	Rape seed oil
Climate change	kg CO ₂ -eq	1,394	-2,236	-1,996
Resource depletion – mineral	kg Sb _{-eq}	0.000023	-0.00010	-0.00011
Resource Depletion - fossil fuels	MJ	3,326	-10,400	-10,900
Consumptive water use	m ³ H ₂ O _{-eq}	847	-2,316	-2,599
Eutrophication	kg PO ₄ ³⁻ -eq	1.58	-9.95	-11.46
Acidification potential	kg SO ₂ -eq	5.53	-12.37	-14.59
USEtox human	CTU _h	0.00017	-0.00182	-0.00183
USEtox eco-toxicity (freshwater)	CTU _e	3,409	-45,614	-45,876
Photochemical ozone formation	kg C ₂ H ₄ -eq	0.28	-0.53	-0.35
Particulate matter formation	kg PM _{2.5} -eq	0.55	-1.68	-1.62
Ozone layer depletion	kg CFC-11 _{-eq}	0.00046	0.00034	0.00032
Ionizing radiation	kg U235 _{-eq}	36.56	-74.55	-86.28
Ag Land occupation	m ² *a	52	-2,423	-2,962
Endpoint impact categories (EIC)				
Ecosystems - ReCiPe (H)	species.yr	0.000019	-0.00032	-0.00016
Human health - ReCiPe (H)	DALY	0.0027	-0.0046	-0.0044
Resources - ReCiPe (H)	\$	56.18	-39.31	-44.00

Notes – a) – includes boiler ash (modelled as negative input of natural aggregate), manure (market for soil conditioner), irrigation wastewater (market for irrigation), edible offal (market for cattle for slaughtering), hides (polyethylene), meal (protein feed, rape meal), and tallow (palm oil or rape seed oil)

After system expansion, every category of impacts except ozone layer depletion becomes a sink (negative emission), as the avoided products had higher environmental impacts. It should be noted that the avoided products include the entire supply chain, whereas this gate-to-gate LCA only included the core and transport sections of the supply chain, not the on-farm contributions. Edible offal, which was modelled as market for cattle for slaughtering, provided the largest credit, ranging

from 67% for the mineral resource depletion MIC to 120% for the acidification potential MIC, and 47% for the ecosystems EIC to 121% for the human health EIC. Tallow, which was initially modelled as palm oil, was the second largest contributor in most MIC and EIC, except several categories (mineral and fossil fuel depletion, consumptive water use, acidification potential and ionizing radiation MIC, and resources EIC) where hides (modelled as polyethylene fleece) was a more significant contributor. In other studies, tallow has been modelled as canola (rape seed) oil, so this was modelled as an alternative system expansion. In the climate change, photochemical ozone formation and particulate matter formation MIC, palm oil performs better, but in every other category, rape seed oil performs better. In terms of end point impact categories, palm oil was better for ecosystems and human health (due to the contribution of climate change to these impact categories) while rape seed oil was better for the resources end point impact category. However, the difference between the two system expansions for tallow was less significant than the difference between before and after system expansion.

3.3 Contribution analysis and circular economy opportunities – reference scenario (current operation)

As indicated in Table 7, the most significant contributing process for climate change before system expansion was the methane emitted from the onsite wastewater treatment ponds (34%), followed by coal use in the boiler (20%), road transport (15% in total, with 6 % from site fuel use) and imported electricity (7%). This is consistent with the literature (GHD, 2011; Hydro Tasmania Consulting, 2009; Ridoutt et al., 2015; Rowlands et al., 2007; URS Australia Pty Ltd, 2005). Climate change contributes significantly to the ecosystems and human health EIC categories, so wastewater methane emissions contribute 16% and 19% respectively to these categories, but not to any other MIC. Other than the wastewater methane emissions, the climate change impact category is similar to the acidification, photochemical ozone formation and particulate matter formation MIC in terms of contributing processes. USEtox human and ecotoxicity have similar contributing processes, as do fossil fuel resource depletion and consumptive water use. Other MIC categories, such as eutrophication, mineral resource depletion, ozone layer depletion and agricultural land occupation, have quite different contributing processes: most of the eutrophication impacts come from the onsite wastewater treatment process; 34% of the mineral depletion comes from the cardboard box use; 73% of the ozone layer depletion comes from the onsite refrigeration system; and 66% of the agricultural land use comes from the cardboard box use. This indicates that climate change may not be a suitable proxy for this stage in the supply chain and further investigation is required.

Coal use in the onsite boiler was the most significant process to the most categories, contributing to acidification (42%), photochemical ozone formation (32%), particulate matter formation (28%) and EIC human health (22%). Other significant processes which contributed to MIC and EIC categories include: electricity use, to fossil fuel resource depletion (44%) and consumptive water use (37%); cardboard box use, to mineral resource depletion (34%) and agricultural land use (66%); manure handling, to USEtox human (33%) and ecotoxicity (37%); wastewater nutrients emissions, to eutrophication (64%); and the refrigeration system, to ozone layer depletion (73%).

Table 7 highlights the potential benefits of the opportunities identified in Table 4, namely that replacing grid purchased electricity with a renewable energy supply could potentially provide improvements in line with Principle 2 (reducing fossil fuel resource depletion and consumptive water use) and Principle 3 (reducing USEtox human and ecotoxicity MIC), and using the wastewater methane to provide this electricity in line with Principle 2 would potentially improve the climate change MIC and ecosystems and human health EIC (Principle 3). Replacing coal use in the boiler with a fuel with a lower environmental burden would also provide an opportunity to reduce impacts in the climate change, acidification potential, photochemical ozone formation and particulate matter formation MIC, as well as the ecosystems and human health EIC. Although replacing coal use with biomass in the boiler was not a high priority cost or risk issue (Principle 2), it was identified as an opportunity to optimise the reuse of nutrients in the wastewater (Principle 2 and 3).

435 **Table 7: Percentage contribution of processes to impact categories before system expansion (values less than 1% generally not included)**

Impact category	Unit	Wastewater methane	Coal used in boiler	Electricity use	National road transport	Site road transport	Local road transport	Sea transport	Box (packaging)	Other packaging	Manure	Wastewater nutrients	Refrigeration system	Skins treating / Pest control
Climate change	kg CO ₂ eq	34%	20%	7%	7%	6%	2%	2%	2%	3%	2%		0.4%	
Resource depletion – mineral	kg Sb eq			2%					34%	4%	2%			
Resource depletion – fossil fuel	MJ			44%				3%	12%	13%	3%			
Consumptive water use	m ³ H ₂ O eq			37%				6%	12%	11%	3%			
Eutrophication	kg PO ₄		5%	5%	3%	2%	1%	4%	2%	2%	3%	64%		
Acidification potential	kg SO ₂ eq		42%	7%	3%	3%	1%	12%	3%	3%	2%			
USEtox human	CTUh			31%				2%	5%	3%	33%			
USEtox ecotoxicity	CTUe			29%				1%	5%	3%	37%			1%/0.1%
Photochemical ozone formation	kg C ₂ H ₄ eq		32%	5%	1%	1%		8%	3%	3%	3%			
Particulate matter formation	kg PM _{2.5} eq		28%	5%	1%	1%		9%	6%	6%	2%			
Ozone layer depletion	kg CFC-11 eq							1%	1%	8%			73%	
Ionizing radiation	kg U235 eq							9%	12%	8%	2%			
Agricultural land occupation	m ² *year			3%				1%	66%	17%	4%			
Ecosystems – ReCiPe (H)	species*year	16%	12%	5%	4%	4%	1%	2%	6%	3%	2%		0.3%	
Human health – ReCiPe (H)	DALY	19%	22%	9%	6%	5%	1%	4%	3%	3%	3%		0.3%	
Resources – ReCiPe (H)	\$			8%				3%	3%	3%	1%			

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3.4 Scenarios

As indicated in Figure 3, where the best performance is indicated by the value 1, the biomass scenarios provided the best performance for eleven of the thirteen MIC categories and two of the three EIC categories, although in some categories (mineral resource depletion, USEtox human and ozone layer depletion) the performance was the same as the tallow and biogas scenarios. The remaining categories, particulate matter formation, agricultural land occupation and ecosystems damage, the values for the biomass scenario were 0.94, 0.97 and 0.79 respectively, meaning the biomass scenario had only slightly lower performance than the efficiency scenario (which had a value of 1). The reference scenario was the worst performing in 12 MIC and 2 EIC categories, and the tallow scenario was the worst in the photochemical ozone formation category (0.72) and equal worst with the biogas scenario (0.5) in the ecosystems EIC category. The biomass scenario performed poorly in the ecosystem EIC category due to the reduced credit from the tallow use for biodiesel and electricity production, so if tallow use in electricity production could be reduced, for example by the use of a larger solar photovoltaic system, then this ranking could be improved. However, care should be taken in interpreting the results.

Figure 3: Comparison of scenarios (1 = best performance), with palm oil as the system expansion for tallow (REF is reference scenario, EFF is efficiency scenario, TAL is tallow scenario, BGS is biogas scenario and BM is biomass scenario, as outlined in Table 1)

As Indicated in Figure 4, the avoided products make a significant percentage contribution to the climate change impact category, and are the reason that the category becomes a sink. Edible offal, the main coproduct, is the most significant sink contributor in all MIC and EIC in all scenarios, and although the absolute amount remains unchanged, the relative contribution changes in each scenario. The same holds for meal and hides, but those byproducts have a smaller contribution to the sink. The contribution of tallow varies according to how much is used in each scenario.

Figure 4: Percentage contribution of system expansion to climate change category impacts

The sources of greenhouse gas emissions are shown in Figure 5 for individual processes, with the main system expansion credits from edible offal, hides and meal removed. This is consistent with the numbers in Table 7, and shows the trade-off in the TAL, BGS and BMS cases between reducing emissions from the boiler and the reduction in credit from the tallow system expansion, which accounts for why the BM scenario is the best performing.

Figure 5: Contribution to climate change impact category when main sinks from coproduct byproduct system expansion are removed.

3.5 Biomass production and land area use – sequestration and offsets

The biomass potential production rate of 83 GJ/ha/year was compared to the amount of energy required for the plant (thermal and total), and results indicated that 0.03 ha of land was required per t HSCW to provide the thermal energy needs (2,739 MJ/t HSCW). This was then compared to the hectares of land required to produce each t HSCW of livestock, and the results are presented in Table 8 and indicate that in all cases less than 0.5% of the livestock catchment area is required to provide the thermal requirements and only beef finished in feedlots for more than 300 days (long fed beef) require more than 1% of the catchment area. Lifetime grass fed beef requires the smallest amount of the catchment area, and lamb and mid fed beef (grain fed for 108-164 days) are slightly higher but long fed beef require double the amount. If we assume a worst case supply chain emission of greenhouse gases per t HSCW (25.5 kg CO₂-e, (Gregory M. Peters et al., 2010)) and look at offsetting greenhouse gas emissions by replacing an equivalent greenhouse gas emissions amount of coal with biomass grown on the farm, then lifetime grass fed beef has the best performance, with 12% of the livestock capture area required for offsets, as opposed to long fed beef, which requires 30%. This assessment is conservative, as it does not include any increase in soil carbon due to a change from pasture to biomass production. Given the regional location and surrounding land use at the SME study site, it should be technically feasible within a 150km radius of the plant.

Table 8: Percentage of livestock capture area of plant compared to area required for energy and greenhouse needs (land use data derived from (Wiedemann et al., 2015b))

ha/t HSCW	Beef (lifetime grass fed)	Beef (mid fed grain finished)	Beef (long fed grain finished)	Lamb
Non-arable	29.3	21.8	11.6	21.4
Arable pasture	1.5	1.1	0.6	1.1
Arable crop	0.2	1.2	2.1	0.2
Total	31	24.1	14.3	22.7
% required, thermal energy	0.1%	0.2%	0.3%	0.2%
% required, offset + thermal energy	11.8%	15.8%	29.8%	16.1%

4. Conclusions and recommendations

4.1 Risk and LCA

The use of risk and cost screenings at the life cycle inventory stage to prioritise issues for the site provided a useful introduction to the gate-to-gate LCA. This assisted with identifying the circular economy opportunities with upstream and downstream, which were then investigated as part of the LCA study. Serendipitously, the risk and cost screenings aligned well with each other, and with the impacts identified in the reference case of the current operation.

4.2 Gate to gate LCA of current operation

The analysis indicated that current life cycle inventories and LCA results for MIC climate change and fossil fuel are significantly different to this analysis, so it would appear that SMEs, such as the plant in this study, may not be well represented by current life cycle inventories or LCA studies. There are a number of categories that have not previously been assessed in LCA studies, but given the difference in inventory data, it is likely that the results for other MIC would also be significantly different. Similarly, the current reported levels of wastewater methane emissions in industry benchmarking reports does not appear to reflect current SME operations, which are less likely to have biogas capture and use.

Analysing the results before and after the allocation of the system expansion credits highlighted the contribution of coproducts and byproducts, with edible offal contributing the most significant credit, ranging from 56% for ecosystems EIC to 120% for climate change and acidification MIC. Changing the usage rates of this byproduct is not something an individual SME could necessarily influence, but it would need to be handled on an industry basis.

The individual process contribution highlighted that climate change was different to other MIC but similar to ecosystems and human health EIC, so was possibly not suitable as a representative MIC. Wastewater emissions and boiler coal use were most significant in terms of these three categories.

Eutrophication, acidification potential, photochemical ozone formation and particulate matter formation had similar individual process contributions, as did fossil fuel resource depletion, consumptive water use, USEtox human and ecotoxicity and the resources end point indicator.

4.3 Future scenarios, offsets and sequestration.

The best future energy supply option was the biomass scenario, which captured and used wastewater methane from the onsite wastewater treatment system for onsite power generation, used tallow produced at the plant for biodiesel production for the site transport fleet and residual electricity production and then sourced all thermal energy requirements from biomass production.

The amount of land required to produce biomass to replace the current thermal energy requirements was small (0.03 hectares or <0.5% of non-arable land required to produce red meat livestock). If the worst case emission for beef (25.5 kg CO_{2-e}/ kg HSCW) were offset using biomass to replace coal in addition to replacing all energy use at the plant, the land area required would be 3.6 hectares, which ranged from 12% of non-arable land in the case of lifetime grass fed beef to 31% of non-arable land for long fed grain finished beef. The latter value is not likely to be feasible for economic reasons, but a 12% increase in the amount of biomass on a property while maintaining productivity is possibly feasible, meaning that grass fed beef systems may have the most potential for whole of supply chain greenhouse gas offsets through biomass production on non-arable land and subsequent use for fossil fuel offsets. This assessment is conservative, in that it does not include any sequestration from increases in soil carbon in the analysis.

4.4 Circular economy

This study highlighted the potential for supply chain integration for both energy and nutrients in red meat supply chains. LCA provides a useful means of assessing all the categories of impacts, rather than single categories such as climate change, water or land use, as has been the case with previous LCAs. This study indicates that there is potential for processing plants, which represent the core of the supply chain, to exploit circular economy opportunities, particularly with the upstream on-farm production part of the supply chain.

4.5 Limitations and future work

This study was based on a single SME plant, so further work should be done to confirm whether or not other SME plants have similar issues with life cycle inventory data. Risks and opportunities will vary between sites, as will energy costs and availability. The potential for wastewater recycling and

biomass production should be investigated further to assess the feasibility and supply chain offset potential.

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References

- Anderson, A.D., Smoak, B., Shuping, E., Ockenhouse, C., Petruccelli, B., 2005. Q fever and the US military. *Emerg. Infect. Dis.* 11, 1320–2. <https://doi.org/10.3201/eid1108.050314>
- Australian Bureau of Statistics, 2018. 7503 - Value of Agricultural Commodities Produced, Australia, 2016-2017 [WWW Document]. URL <http://www.abs.gov.au/ausstats/abs@.nsf/mf/7503.0>
- Australian Bureau of Statistics, 2017. Land Use, Australia, year ended 30 June 2016 [WWW Document]. 7120.0 - Agric. Commod. Aust. 2015-2016. URL [http://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/7121.0Main Features312015-16?opendocument&tabname=Summary&prodno=7121.0&issue=2015-16&num=&view=](http://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/7121.0Main+Features312015-16?opendocument&tabname=Summary&prodno=7121.0&issue=2015-16&num=&view=)
- Australian Bureau of Statistics, 2015. 9208.0 - Survey of Motor Vehicle Use, Australia, 12 months ended 31 October 2014. Canberra.
- Australian Government Clean Energy Regulator, 2018. NGER Wastewater Industrial Calculator 2016-2017 [WWW Document]. XLXS Doc. URL <http://www.cleanenergyregulator.gov.au/DocumentAssets/Pages/NGER-Wastewater-Industrial-Calculator-2016-2017.aspx> (accessed 4.23.19).
- Australian Government Department of Agriculture and Water Resources, 2018. Australia’s Farming Future - Adapting to a changing climate [WWW Document]. *Clim. Chang. Res. Progr.* URL <http://www.agriculture.gov.au/ag-farm-food/climatechange/australias-farming-future/adapting-to-a-changing-climate>
- Cederberg, C., Berglund, M., Gustavsson, J., Wallman, M., 2012. Environmental impacts from livestock production with different animal welfare potentials – a literature review.
- Center For Disease Control, 2012. Q Fever [WWW Document]. 2012 West Nile virus Updat. URL <http://www.cdc.gov/ncidod/dvbid/westnile/index.htm>

- 575 Clean Energy Council, 2017. Guide to installing solar PV for households in New South Wales. Sydney.
- 576 COOP, 2016a. Environmental Product Declaration of Coop Beef Meat.
- 577 COOP, 2016b. Environmental Product declaration of Coop Veal Meat. COOP.
- 578 Coopers and Lybrand Consultants, 1996. Trends and future regulatory issues concerning packaging
579 material used in the Australian meat industry (Technical Report M.713). North Sydney.
- 580 CSIRO, 2002. Tallow as a heating fuel. CSIRO Meat Updat. September, 3.
- 581 CSIRO and Bureau of Meteorology, 2015. Climate Change in Australia - Information for Australia's
582 Natural Resource Management Regions: Technical Report. Australia.
- 583 Dahlgren, F.S., Haberling, D.L., McQuiston, J.H., 2015a. Q fever is underestimated in the United
584 states: A comparison of fatal Q fever cases from two national reporting systems. Am. J. Trop.
585 Med. Hyg. 92, 244–246. <https://doi.org/10.4269/ajtmh.14-0502>
- 586 Dahlgren, F.S., McQuiston, J.H., Massung, R.F., Anderson, A.D., 2015b. Q fever in the United States:
587 Summary of case reports from two national surveillance systems, 2000-2012. Am. J. Trop. Med.
588 Hyg. 92, 247–255. <https://doi.org/10.4269/ajtmh.14-0503>
- 589 Dames & Moore Pty Ltd, 1999. Generic manual for development of environmental management
590 systems at meat processing plants in Australia (RPDA.302). Sydney.
- 591 Department of Agriculture and Water Resources, 2017. Mid North Coast NSW Regional Profile
592 [WWW Document]. ABARES. URL [http://www.agriculture.gov.au/abares/research-](http://www.agriculture.gov.au/abares/research-topics/aboutmyregion/mid-north-coast#agricultural-sector)
593 [topics/aboutmyregion/mid-north-coast#agricultural-sector](http://www.agriculture.gov.au/abares/research-topics/aboutmyregion/mid-north-coast#agricultural-sector)
- 594 Department of the Environment and Energy, 2016a. National Greenhouse Accounts Factors,
595 Australian National Greenhouse Accounts. Canberra, ACT.
- 596 Department of the Environment and Energy, 2016b. National Greenhouse and Energy Reporting
597 Scheme, Technical Guidelines for the estimation of emissions by facilities in Australia, 2015-
598 2016 reporting year. Canberra. <https://doi.org/http://www.environment.gov.au>
- 599 Dufour, J., Iribarren, D., 2012. Life cycle assessment of biodiesel production from free fatty acid-rich
600 wastes. Renew. Energy 38, 155–162. <https://doi.org/10.1016/j.renene.2011.07.016>
- 601 Dufty, N., 2010. Leading practice in the environmental management of New South Wales linear
602 reserves - the role of the NSW Roadside Environment Committee. Australas. Plant Conserv. 19.

- 603 Eastwood, K., Massey, P.D., Hutchinson, P., van den Berg, D., Bosward, K., Graves, S.R., 2018. Q
604 fever: A rural disease with potential urban consequences. *Aust. J. Gen. Pract.* 47, 5555.
- 605 EC-JRC, 2010. (ILCD) Handbook: General guide for Life Cycle Assessment - Detailed guidance.
606 Luxembourg. <https://doi.org/10.2788/38479>
- 607 Ellen MacArthur Foundation, 2015. Circular Economy Overview [WWW Document]. URL
608 <https://www.ellenmacarthurfoundation.org/circular-economy> (accessed 6.17.17).
- 609 Ellen MacArthur Foundation, McKinsey Centre for Business and Environment, Stiftungsfonds für
610 Umweltökonomie und Nachhaltigkeit (SUN), 2015. GROWTH WITHIN: A CIRCULAR ECONOMY
611 VISION FOR A COMPETITIVE EUROPE.
- 612 Emerson Climate Technologies, 2010a. Refrigerant Choices for Commercial Refrigeration. Aachen,
613 Germany.
- 614 Emerson Climate Technologies, 2010b. Refrigerant Choices for Commercial Refrigeration - Finding
615 the Right Balance. Aachen, Germany.
- 616 FAO, 2012. Energy-Smart Food at FAO: An Overview. Rome.
- 617 GE Power, 2016. Jenbacher type 2 fact sheet.
- 618 GHD, 2011. Industry environmental sustainability review 2010 (A.ENV.0086). North Sydney.
- 619 Gidding, H.F., Wallace, C., Lawrence, G.L., McIntyre, P.B., 2009. Australia's national Q fever
620 vaccination program. *Vaccine* 27, 2037–2041. <https://doi.org/10.1016/j.vaccine.2009.02.007>
- 621 Harris-Adams, K., Townsend, P., Lawson, K., 2012. Native vegetation management on agricultural
622 land, ABARES Research Report 12.10. Canberra.
- 623 Heathcote, R., 2002. Case Study on Long Rotation Eucalypt Plantations in New South Wales. Rome.
- 624 Hessle, A., Bertilsson, J., Stenberg, B., Kumm, K.-I., Sonesson, U., 2017. Combining environmentally
625 and economically sustainable dairy and beef production in Sweden. *Agric. Syst.* 156, 105–114.
626 <https://doi.org/10.1016/j.agsy.2017.06.004>
- 627 Hydro Tasmania Consulting, 2009. Red Meat Processing Industry Energy Efficiency Manual
628 (A.ENV.0065). North Sydney.
- 629 Inalca, 2018. Montana Canned Beef Meat EPD.

- 630 INALCA, 2018. Frozen Hamburger (in Italian).
- 631 Jensen, P., Batstone, D., 2012. Energy and Nutrient analysis on Individual Waste Streams (Final
632 Report Project A.ENV.0131).
- 633 Leahy, E., Lyons, S., Tol, R.S.J., 2010. An Estimate of the Number of Vegetarians in the World. ESRI
634 Work. Pap. 340 1–44. <https://doi.org/10.1007/s10273-011-1262-2>
- 635 Lowbridge, C.P., Tobin, S., Seale, H., Ferson, M.J., 2012. Notifications of Q fever in NSW, 2001-2010.
636 NSW Public Heal. Bull. 23, 31–35. <https://doi.org/10.1071/NB11037>
- 637 Mayberry, D., Bartlett, H., Moss, J., Wiedemann, S., Herrero, M., 2018. Greenhouse Gas mitigation
638 potential of the Australian red meat production and processing sectors - Executive Summary.
639 North Sydney.
- 640 Meat & Livestock Australia, 2018. Statistics Database [WWW Document]. Mark. Inf. URL
641 <http://statistics.mla.com.au/Report/List>
- 642 Meat & Livestock Australia, 2017. Sheep numbers - as at June 2017, Natural Resource Management
643 Region [WWW Document]. URL [https://www.mla.com.au/globalassets/mla-corporate/prices--](https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/fast-facts--maps/sheep-numbers-map-2018-as-at-june-2017-data.pdf)
644 [markets/documents/trends--analysis/fast-facts--maps/sheep-numbers-map-2018-as-at-june-](https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/fast-facts--maps/sheep-numbers-map-2018-as-at-june-2017-data.pdf)
645 [2017-data.pdf](https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/trends--analysis/fast-facts--maps/sheep-numbers-map-2018-as-at-june-2017-data.pdf) (accessed 2.26.19).
- 646 Mpelasoka, F., Hennessy, K., Jones, R., Bates, B., 2008. Comparison of suitable drought indices for
647 climate change impacts assessment over Australia towards resource managment. Int. J.
648 Climatol. 28, 1283–1292. <https://doi.org/10.1002/joc.1649>
- 649 Nardone, A., Ronchi, B., Lacetera, N., Ranieri, M.S., Bernabucci, U., 2010. Effects of climate changes
650 on animal production and sustainability of livestock systems. Livest. Sci. 130, 57–69.
651 <https://doi.org/10.1016/j.livsci.2010.02.011>
- 652 Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life
653 cycle assessment in supporting sustainable agri-food systems: A review of the challenges. J.
654 Clean. Prod. 140, 399–409. <https://doi.org/10.1016/j.jclepro.2016.06.071>
- 655 Nourse, C., Allworth, A., Jones, A., Horvath, R., McCormack, J., Bartlett, J., Hayes, D., Robson, J.M.,
656 2004. Three cases of Q fever osteomyelitis in children and a review of the literature. Clin Infect
657 Dis 39, e61-6. <https://doi.org/10.1086/424014>
- 658 NSW Environment Protection Authority, 2015. Licence summary - site 3117 [WWW Document]. URL

- 659 [https://apps.epa.nsw.gov.au/prpoeoapp/Detail.aspx?instid=3117&id=3117&option=licence&se](https://apps.epa.nsw.gov.au/prpoeoapp/Detail.aspx?instid=3117&id=3117&option=licence&searchrange=licence&range=POEO licence&prp=no&status=Issued)
660 [archrange=licence&range=POEO licence&prp=no&status=Issued](https://apps.epa.nsw.gov.au/prpoeoapp/Detail.aspx?instid=3117&id=3117&option=licence&searchrange=licence&range=POEO licence&prp=no&status=Issued)
- 661 NSW Environment Protection Authority, 2010. Strategic environmental compliance and performance
662 review: Effluent Reuse Management. Sydney.
- 663 NSW Environment Protection Authority, 2009. Strategic Environmental Compliance and
664 Performance Review - Industry Monitoring. Sydney.
- 665 NSW Environment Protection Authority, 2003. Industry Sector: Livestock Processing Industries
666 (Animal Slaughter and Rendering), Compliance Performance Report. Sydney.
- 667 O'CONNOR, B.A., TRIBE, I.G., GIVNEY, R., 2015. A windy day in a sheep saleyard: an outbreak of Q
668 fever in rural South Australia. *Epidemiol. Infect.* 143, 391–398.
669 <https://doi.org/10.1017/S0950268814001083>
- 670 OECD, 2005. Small and medium-sized enterprises (SMEs) Definition [WWW Document]. OECD Gloss.
671 Stat. Terms . URL <https://stats.oecd.org/glossary/detail.asp?ID=3123> (accessed 3.19.19).
- 672 Office of Environment & Heritage, 2011. Guide to Climate Change Risk Assessment for NSW Local
673 Government. Sydney.
- 674 Pagan, R., Renouf, M., Prasad, P., 2002. Eco-Efficiency Manual for Meat Processing. Meat & Livestock
675 Australia, North Sydney.
- 676 Paolotti, L., Boggia, A., Castellini, C., Rocchi, L., Rosati, A., 2016. Combining livestock and tree crops
677 to improve sustainability in agriculture: a case study using the Life Cycle Assessment (LCA)
678 approach. *J. Clean. Prod.* 131, 351–363. <https://doi.org/10.1016/j.jclepro.2016.05.024>
- 679 Peters, G.M., Rowley, H., Tucker, R., Wiedemann, S.G., Short, M., Schulz, M., Feitz, A., 2009.
680 Southern Red Meat Production – a Life Cycle Assessment, Final Report Project COMP.094.
681 North Sydney. <https://doi.org/10.1007/s11367-010-0161-x>
- 682 Peters, Gregory M., Rowley, H. V., Wiedemann, S.G., Tucker, R., Short, M.D., Schulz, M., 2010. Red
683 Meat Production in Australia: Life Cycle Assessment and Comparison with Overseas Studies.
684 *Environ. Sci. Technol.* 44, 1327–1332. <https://doi.org/10.1021/es901131e>
- 685 Peters, Gregory M, Rowley, H. V, Wiedemann, S.G., Tucker, R., Short, M.D., Schulz, M., 2010. Red
686 Meat Production in Australia: Life Cycle Assessment and Comparison with Overseas Studies
687 (Supporting information). *Environ. Sci. Technol.* 44, 6.

- 688 https://doi.org/https://pubs.acs.org/doi/suppl/10.1021/es901131e/suppl_file/es901131e_si_0
689 01.pdf
- 690 Poeschl, M., Ward, S., Owende, P., 2012. Environmental impacts of biogas deployment – Part I: life
691 cycle inventory for evaluation of production process emissions to air. *J. Clean. Prod.* 24, 168–
692 183. <https://doi.org/10.1016/j.jclepro.2011.10.039>
- 693 Renouf, M.A., Grant, T., Sevenster, M., Logie, J., Ridoutt, B., Ximenes, F., Bengtsson, J., Cowie, A.,
694 Lane, J., 2016. Best Practice Guide for Life Cycle Impact Assessment in Australia.
- 695 Reyenga, P.J., Howden, S.M., Meinke, H., Hall, W.B., n.d. Global change impacts on wheat production
696 along an environmental gradient in south Australia.
- 697 Ridoutt, B., Sanguansri, P., Alexander, D., 2015. Environmental Performance Review : Red Meat
698 Processing Sector 2015. North Sydney.
- 699 Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E., Lenton, T.M., Scheffer, M.,
700 Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H.,
701 Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry,
702 V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary
703 boundaries: Exploring the safe operating space for humanity. *Ecol. Soc.* 461, 4.
704 <https://doi.org/10.5751/ES-03180-140232>
- 705 Rowlands, A. (Alliance C., Marlow, J. (ProAnd A., Colley, T. (Colley C.P.L., Georgius, N. (GHD P.L.,
706 Foley, J. (GHD P.L., Hertle, C. (GHD P.L., McPhail, N. (Food S.A., Porter, J. (John R.P.P.L., Schulz,
707 T. (The O.U., Perrens, S. (Evans P.P.L., Christiansen, F. (Evans P.P.L., Sentance, C. (Food S.S.,
708 2007. Environmental Best Practice Guidelines for the Red Meat Processing Industry, 2006th ed.
709 Meat & Livestock Australia, Sydney.
- 710 SAI Global, 1999. Australian/ New Zealand Standard AS/NZS 4360:1999 - Risk Management. AS/NZS
711 4360:1999.
- 712 Shishido, A.A., Letizia, A.G., Hartzell, J.D., 2016. Q fever. *United States Army Med. Dep. J.* Jan-March,
713 68–71. [https://doi.org/10.1016/S0140-6736\(06\)68266-4](https://doi.org/10.1016/S0140-6736(06)68266-4)
- 714 Sivabalan, P., Saboo, A., Yew, J., Norton, R., 2017. Q fever in an endemic region of North
715 Queensland, Australia: A 10 year review. *One Heal.* 3, 51–55.
716 <https://doi.org/10.1016/j.onehlt.2017.03.002>
- 717 Sloan-Gardner, T.S., MASSEY, P.D., HUTCHINSON, P., Knope, K., FEARNLEY, E., 2017. Trends and risk

factors for human Q fever in Australia, 1991–2014. *Epidemiol. Infect.* 145, 787–795.

<https://doi.org/10.1017/S0950268816002843>

Sonesson, U.G., Lorentzon, K., Andersson, A., Barr, U.-K., Bertilsson, J., Borch, E., Brunius, C., Emanuelsson, M., Göransson, L., Gunnarsson, S., Hamberg, L., Hessel, A., Kumm, K.-I., Lundh, Å., Nielsen, T., Östergren, K., Salomon, E., Sindhøj, E., Stenberg, B., Stenberg, M., Sundberg, M., Wall, H., Nemecek, T.J., 2016. Paths to a sustainable food sector: integrated design and LCA of future food supply chains: the case of pork production in Sweden. *Int. J. Life Cycle Assess.* 21, 664–676. <https://doi.org/10.1007/s11367-015-0969-5>

Stahel, W.R., 2016. Circular economy. *Nature* 531, 435–438.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., De Haan, C., 2006. Livestock's long shadow - environmental issues and options, Food and Agriculture Organization of the United Nations. Rome. <https://doi.org/10.1007/s10666-008-9149-3>

Stokes, C.J., Howden, S., Gifford, R., Meinke, H., Bange, M., McRae, D., Roth, G., Gaydon, D., Beecher, H.G., Reinke, R., Crimp, S., Park, S., Inman-Bamber, G., Webb, L., Barlow, E.W.R., Hennessy, K., Whetton, P.H., Booth, T.H., Kirschbaum, M.U.F., Battaglia, M., Stone, G., Cobon, D., Ash, A., McKeon, G., Miller, C.J., Jones, R.N., Hobday, A. J., A., Poloczanska, E.S., Hobday, A., Poloczanska, E.S., 2008. An overview of climate change adaptation in Australian primary industries – impacts , options and priorities.

Thomas, D.S., Henson, M., Joe, B., Boyton, S., Dickson, R., 2009. Review of growth and wood quality of plantation-grown *Eucalyptus dunnii* Maiden. *Aust. For.* 72, 3–11.

Tissot-Dupont, H., Amadei, M.A., Nezri, M., Raoult, D., 2004. Wind in November, Q fever in December. *Emerg. Infect. Dis.* 10, 1264–1269. <https://doi.org/10.3201/eid1007.030724>

Tozer, S.J., Lambert, S.B., Sloots, T.P., Nissen, M.D., 2011. Q fever seroprevalence in metropolitan samples is similar to rural/remote samples in Queensland, Australia. *Eur J Clin Microbiol Infect Dis* 30, 1287–1293. <https://doi.org/10.1007/s10096-011-1225-y>

United Nations, 2015. World Population Prospects: The 2015 Revision, Key Findings and Advance Tables, Department of Economic and Social Affairs, Population Division. <https://doi.org/10.1017/CBO9781107415324.004>

URS Australia Pty Ltd, 2006. Environmental Management System - Integrated Red Meat Supply Chain, Final Report A.SCC.0021.

- 748 URS Australia Pty Ltd, 2005. Industry environmental performance review - Integrated meat
749 processing plants (PRENV.033). North Sydney.
- 750 Whitney, E.A.S., Massung, R.F., Candee, A.J., Ailes, E.C., Myers, L.M., Patterson, N.E., Berkelman, R.L.,
751 2009. Seroepidemiologic and Occupational Risk Survey for *Coxiella burnetii* Antibodies among
752 US Veterinarians. Clin. Infect. Dis. 48, 550–557. <https://doi.org/10.1086/596705>
- 753 Wiedemann, S.G., 2018. Analysis of Resource Use and Greenhouse Gas Emissions from Four
754 Australian Meat production systems, with investigation of mitigation opportunities and trade-
755 offs. Charles Sturt.
- 756 Wiedemann, S.G., McGahan, E., Murphy, C., Yan, M.-J., Henry, B., Thoma, G., Ledgard, S., 2015a.
757 Environmental impacts and resource use of Australian beef and lamb exported to the USA
758 determined using life cycle assessment - Appendix A. Supplementary data. J. Clean. Prod. 94,
759 67–75.
- 760 Wiedemann, S.G., McGahan, E., Murphy, C., Yan, M.-J., Henry, B., Thoma, G., Ledgard, S., 2015b.
761 Environmental impacts and resource use of Australian beef and lamb exported to the USA
762 determined using life cycle assessment. J. Clean. Prod. 94, 67–75.
763 <https://doi.org/10.1016/j.jclepro.2015.01.073>
- 764 Wiedemann, S.G., McGahan, E., Murphy, C., Yan, M., 2016. Resource use and environmental impacts
765 from beef production in eastern Australia investigated using life cycle assessment. Anim. Prod.
766 Sci. 56, 882–894. <https://doi.org/10.1071/AN14687>
- 767 Wiedemann, S.G., McGahan, E.J., Murphy, C.M., 2018. Environmental impacts and resource use
768 from Australian pork production determined using life cycle assessment. 2. Energy, water and
769 land occupation. Anim. Prod. Sci. 58, 1153. <https://doi.org/10.1071/AN16196>
- 770 Wiedemann, S.G., Murphy, C.M., McGahan, E.J., Bonner, S.L., Davis, R.J., 2014. Life Cycle Assessment
771 of four southern beef supply chains - MLA Final Report Project B.FLT.0364. North Sydney.
- 772 Yanagida, T., Maita, H., Fujimoto, S., Minowa, T., 2011. LIFE CYCLE ANALYSIS OF EUCALYPTUS WOOD
773 CHIP PRODUCTION BY SHORT ROTATION COPPICE, in: 19th European Biomass Conference and
774 Exhibition, Berlin, Germany. pp. 6–10. <https://doi.org/10.2478/s11756-009-0109-4.6>

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Supplementary Material 1.1

1.1 Summary of LCA's of meat supply chains which include meat processing.

Table 9: Australian Life Cycle Assessment studies for the beef, sheep or pig supply chains that include meat processing.

Authors	Year	Sector	Details	Results
Gregory M. Peters, Hazel V. Rowley, Stephen Wiedemann, Robyn Tucker, Michael D. Short and Matthias Schulz, Environmental Science Technology Journal, 2010, 44, pp 1327-1332 (funded through MLA Project COMP.094)	2010	Sheep (WA), Beef (organic grass fed (VIC)) Beef (grain lot fed) (NSW)	<ul style="list-style-type: none"> •Attributional LCA •3 case study farms and 1 feedlot over 2 years (2002 and 2004) •System boundary from farm to meat processing plant boundary •Functional unit – 1kg HSCW at exit gate of meat processing plant •Excludes CO₂-e emissions from soil carbon, land use, direct land use change and nitrous oxide emissions from leguminous pastures •Allocation of impacts to coproducts based on mass •Meat processing inventory per t HSCW – 400 kWh electricity, 53 kg coal, 0.8 m³ LPG, 7 kL water consumption 	<ul style="list-style-type: none"> •All report <u>per kg HSCW</u> •Carbon footprint – most emissions from enteric methane from livestock, then nitrous oxide <ul style="list-style-type: none"> Sheep - 7.2 – 8.3 kg CO₂-e, >80% from farm Organic beef – 8.2-12 kg CO₂-e, > 80% from farm Grain fed beef – 9.9-10.2 kg CO₂-e, 65-70% from farm •Primary energy – mostly from processing, due to refrigeration equipment <ul style="list-style-type: none"> Sheep - 27.0 – 28.1 MJ, 50% from farm, 50% from meat processing Organic beef – 24.3-28.8 MJ, 25-40% from farm, 60-75% from meat processing Grain fed beef – 29.5-27.7 MJ, 18-22% from farm, 15% from feedlot, 62-65% from meat processing •Solid waste – mostly from processing

Authors	Year	Sector	Details	Results
				<p>Sheep – 0.021-0.022 kg, >10% from farm, remainder from meat processing</p> <p>Organic beef – 0.033-0.039 kg, remainder from meat processing</p> <p>Grain fed beef – 0.028-0.029 kg, 7% from feedlot, remainder from meat processing</p>
SG Wiedemann, CM Murphy, EJ McGahan, M Renouf, P Prasad, SL Bonner, EN Zadow, B Henry. Meat & Livestock Australia Project B.CCH.2028 Final Report	2013	Beef (Northern Beef Supply Chain), grass fed bullocks for Japan ox market (NE Qld), grain finished beef for domestic market (SW Qld)	<ul style="list-style-type: none"> • Attributional LCA • 2 case study farms, 1 feedlot and 2 meat processing plants over 24+ months • System boundary from farm to consumer (paddock to plate) • 3 Functional units – kg LW, kg boned beef ready for wholesale/retail at the processor gate, kg beef at consumer in Australia or Japan • CO_{2-e} emissions excludes land use, direct land use change but include soil carbon flux potential • System expansion to handle minor byproducts (pet food, blood, meat and bone meal (soymeal and sorghum on 	<p>All following metrics reported per kg boned beef</p> <p>nb NE = grass, SW = grain</p> <ul style="list-style-type: none"> • Energy demand NE 15.2 MJ, SW 16.8 MJ • Consumptive water use NE 496.3 L, SW 356.2 L • Stress weighted water use NE 77.2 L H₂O_e, SW -4.5 L H₂O_e • Arable land occupation NE -1.9 m², SW 4.9 m² • Non arable land occupation NE 1393.6 m², SW 2180.4 m² • Carbon footprint NE 28.2 kg CO_{2-e}, SW 24.5 kg CO_{2-e}, most (70%) of emissions from enteric methane from livestock, followed by 11% from carbon dioxide from combustion of fossil fuels, then 10% from nitrous oxide from manure (mostly from grain fed beef in feedlots) • Soil carbon flux potential NE 0.03 kg CO_{2-e}, SW 0.26 • Soil depletion potential NE 83.7 kg, SW 10.6 kg

Authors	Year	Sector	Details	Results
			<p>protein and energy equivalent basis), tallow (canola oil on mass basis)), mass allocation for meat and hides (8.8-11% hides by mass)</p> <ul style="list-style-type: none"> • LW to boned retail meat yield was 57.1-60.7% for SW and NE supply chains 	<ul style="list-style-type: none"> • Economic allocation resulted in 7%, 8% and 15% higher burdens being applied to main product (meat) for ghg, energy and water impact categories respectively when compared to system expansion for minor byproducts • Did not specify emissions from meat processing
SG Wiedemann, EJ McGahan, CM Murphy, M-J Yan, B Henry, G. Thoma, S Ledgard. Meat & Livestock Australia Project B.CCH.2072 (Beef), published in "Environmental impacts and resource use of Australian beef	2014	Beef - 2 regions in eastern Australia (southern and central QLD, 25% of Australian beef herd, and north and north western NSW, 10% of Australian beef herd), exported to	<ul style="list-style-type: none"> • Attributional LCA • 15 case study farms and feedlots across 2 regions for the period 2007-2010, augmented with regional survey data for farms from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) (115 beef producers) for the period 2005-2010, regional average farms modelled from the ABARES data, and 2 QLD meat processing plants supplemented by 2011 industry resource survey (GHD, 2011) , including wastewater methane emissions (inventory for t CW of: 318 kWh, 1230 MJ natural gas, 693 MJ coal, 	<ul style="list-style-type: none"> • 7 Impact categories – resource use, consumptive and stress weighted water use, total and arable land occupation, human edible protein efficiency, greenhouse gas emissions, all reported <u>per kg boneless beef</u>. • Resource use – ranged from 24.2 MJ (QLD grass) to 44.3 MJ (NSW LF), approximately 8.6 MJ from meat processing (19 - 35%) • Consumptive water use – ranged from 410.2 L (NSW LF) to 640.3L (QLD grass), approximately 12.6L from meat processing (2 - 3 %) • Stressed water use – ranged from 40 L H₂O_e (NSW grass) to 234 L H₂O_e (QLD grass) • Arable land occupation (cultivated) – ranged from 0 m² (QLD grass) to 28.7 m² (NSW LF), which equates to 0% and 29% of total land use

Authors	Year	Sector	Details	Results
and lamb exported to the USA determined using life cycle assessment”, Journal of Cleaner Production 94 (2015) 67-75.		USA (Philadelphia and Los Angeles), NSW and QLD grass fed, NSW and QLD mid fed grain (MF = 115 days), and NSW long fed grain (LF = 330 days), predominantly Angus and Wagyu for USA restaurant trade	<p>83 MJ LPG, 40 MJ diesel and 7MJ petrol, 8.7 kL water use)</p> <ul style="list-style-type: none"> • System boundary from farm to wholesale distribution (cold-storage warehouse) in USA • Functional units – kg boneless, retail ready beef • CO_{2-e} emissions from land use (LU) and direct land use change (dLUC) estimated from average data) for regional average farms, but excluded for case study farms. Three cases for land use/dLUC associated with feed grain production were included for feedlot. Two cases modelled for net emissions from vegetation clearing and regrowth • System expansion to handle minor byproducts (pet food, blood, meat and bone meal (soymeal and sorghum on protein and energy equivalent basis), tallow (canola oil), biophysical 	<ul style="list-style-type: none"> • Total land occupation – ranged from 94.1 m² (NSW MF) to 684.2 m² (QLD grass) • Human edible protein conversion efficiency (inverse of HEPR) – ranged from 0.4-0.5 (LF grain) and 0.6-0.9 (MF grain), to 1.8 – 12.3 (NSW grass) and 11.0 – 107.8 (QLD grass) • Greenhouse gas emissions – ranged from 19.8 (QLD MF) to 27.2 kg CO_{2-e} (NSW grass), 93% from farm, 4% from meat processing, 3% from transport to USA. Enteric methane contributed 54-84% of total, carbon dioxide 9-13% from fossil fuels and nitrous oxide from manure 6-13%. Herd productivity factors (weaning % and average daily gain) were the major factors contributing to enteric methane and therefore greenhouse gas emissions. • Greenhouse gas emission from LU and dLUC – ranged from 0.4-2.7 kg CO_{2-e} (LF) to 4.1-10.6 kg CO_{2-e} (grass), soil carbon sequestration ranged from 1 kg CO_{2-e} for grass, to 0.6 kg CO_{2-e} for MF and LF. • When using economic allocation at the meat processing stage, greenhouse gas emission were 7-9% higher and consumptive water use 6-9% higher

Authors	Year	Sector	Details	Results
			<p>allocation for meat and hides based on protein content in products</p> <ul style="list-style-type: none"> • Carcase yield of 53% (55% dressing (LW to HSCW), chilling losses of 3% (HSCW to CW)) and retail yield (CW to retail portions) of 70%, edible fraction of retail portions 95% 	
SG Wiedemann, EJ McGahan, CM Murphy, M-J Yan, B Henry, G. Thoma, S Ledgard. Meat & Livestock Australia Project B.CCH.2072 (Lamb), published in "Environmental impacts and resource use of	2015	Lamb - from 3 production regions in south-eastern Australia, Victoria (VIC, 21% of sheep flock), south-eastern South Australia (SA, 16% of sheep flock) and northern and	<ul style="list-style-type: none"> • Attributional LCA • 6 supply chains modelled - 10 case study farms (CSF) in each of the 3 regions over a 1-2+ year period, regional average farms (RAF) from industry survey of specialist lamb producers for each region from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) for the period 2006-2010, one lamb feedlot in VIC, data for 3 meat processing plants from 2011 industry resource survey using data from 2008-09 (GHD, 2011) , including wastewater methane emissions 	<ul style="list-style-type: none"> • 5 Impact categories – fossil fuel energy demand, consumptive and stress weighted water use, land occupation (arable pasture, arable cropping, non-arable rangelands), human-edible protein conversion efficiency (HEP-CE), greenhouse gas emissions, all reported per kg retail ready (bone-in) lamb • Energy demand – ranged from 19.1 MJ to 28.5 MJ, with 43% from on farm, 35% from meat processing (8.6 MJ), 26% from transportation and small credit (-1.2MJ) from system expansion for meat processing coproducts • Consumptive water use – ranged from 125.2 L to 481.1 L, mostly (0-315L) from irrigation and 113L from evaporative losses from drinking water supply. • Stressed water use – ranged from 12.1 L H₂O-e to 280.9 L H₂O-e

Authors	Year	Sector	Details	Results
Australian beef and lamb exported to the USA determined using life cycle assessment”, Journal of Cleaner Production 94 (2015) 67-75.		southern New South Wales (NSW, 37% of Australian flock), mostly pasture fed, 15% of NSW and SA grain finished for 46 days (Meat & Livestock Australia, 2017). Export by ship to USA ports of Philadelphia and Los Angeles.	<p>(assumes inventory for t CW of: 1,185 kWh, 2346 MJ natural gas, 533 MJ LPG, 19 MJ diesel and 14MJ petrol, 6.0 kL water use)</p> <ul style="list-style-type: none"> • System boundary from farm to wholesale distribution (cold-storage warehouse) in USA • Functional units – kg retail ready (bone-in) lamb at the cold-storage warehouse in the USA • CO_{2-e} emissions from land use (LU) and direct land use change (dLUC) estimated for two cases, with and without soil carbon sequestration • Biophysical allocation between wool and meat based on biophysical (protein content), biophysical allocation for meat and skins based on mass of products system expansion to handle minor byproducts (pet food, blood, meat and bone meal (soymeal using economic 	<ul style="list-style-type: none"> • Arable land occupation (cultivated) – averaged 2.1 m² • Total greenhouse gas emissions – ranged from 13.4 to 16.1 kg CO_{2-e}, 90% from farms, 72-79% of which are from enteric methane from sheep. Meat processing (5.5-6.6% of total) and transport were second and third largest contributors. • Greenhouse emissions from land use and land use change was 0.4 if soil carbon sequestration was assumed to be zero, or -0.8 to -4 when soil carbon sequestration from fertilised pastures was included • Note –the 2008/2009 financial year data used in the GDH 2011 report is much higher than the subsequent figures using data from the 2013/2014 financial year (Ridoutt et al., 2015), possibly due to the inclusion of the Fletchers Dubbo wool scour which closed in December 2010. • Sensitivity case using economic allocation for wool/meat and meat/skins increased ghg by 9%, fossil energy by 10% and consumptive water by 8%

Authors	Year	Sector	Details	Results
			<p>allocation, assuming 10% domestic production, 40% import from USA and 50% import from Argentina), tallow (palm oil from Malaysia).</p> <ul style="list-style-type: none"> • Carcass yield 45% (Dressing percentage of 47% (LW to HSCW), chilling losses of 4% (HSCW to CW)), retail yield (bone-in retail cuts from cold carcass weight) of 88% after removal of fat trim 	
S. G. Wiedemann, E. J. McGahan, C. M. Murphy, published as "Environmental impacts and resource use from Australian pork production assessed using life-cycle	2016-2018	Pork (6 case study supply chains and the national herd, 4 major production regions (Queensland (QLD), New South Wales (NSW),	<ul style="list-style-type: none"> • Attributional LCA • Included 14 case study farms in 4 regions, representing 6 case study supply chains for minimum 12 month period in the years 2010-2011 and the national herd (based on national survey for 2010). Six supply chains are QLD small-medium conventional, QLD large conventional, NSW conventional housing for breeding pigs and deep litter housing for grower-finisher pigs, VIC large conventional, WA large conventional 	<ul style="list-style-type: none"> • Impact categories – greenhouse gas emissions (including land use and direct land use change), fossil fuel energy demand, consumptive and stress weighted water use, land occupation (arable pasture, arable cropping, non-arable rangelands), all reported <u>per kg wholesale pork (chilled, bone-in)</u> • Greenhouse gas emissions – 6.36 kg CO_{2-e}, 50% from manure management, 27% from fed production, 8% from meat processing. LU and dLUC only had a minor (6%) impact, mostly due to dLUC soymeal production in South America being higher than sequestration in Australian arable cropland. Capture of methane from manure management and use in cogeneration plant resulted in 31-64% reduction in

Authors	Year	Sector	Details	Results
assessment. 1. Greenhouse gas emissions” in Animal Production Science, 2016, 56, 1418-1431 AND “Environmental impacts and resource use from Australian pork production determined using life cycle assessment. 2. Energy, water and land occupation” in Animal Production		Western Australia (WA) and Victoria (VIC)).	<p>and WA outdoor housing for breeding pigs and deep litter for grower-finisher pigs. Whole herd Feed Conversion Ratio (FCR) ranged from 2.4-3.2, national average 3.1.</p> <ul style="list-style-type: none"> • data for 4 meat processing plants over a 12 month period , including wastewater methane emissions (assumes inventory for t chilled pork of: 252 kWh, 5.9 m³ natural gas, 15.5 L LPG, 11.3 kg coal, 0.49 L diesel and 0.25 L petrol, water use not stated separately • System boundary from farm to cold storage unit where pork is stored prior to wholesale distribution, includes livestock transport from farm to processing plant • 2 Functional units – 1 kg pork liveweight (LW) at the farm gate and 1 kg of wholesale pork (chilled, bone-in) ready for packaging and distribution 	<p>greenhouse emissions. Switching from conventional housing to deep litter resulting in ~30% lower emissions. Higher emissions than European studies due to emissions from manure management. Feed Conversion Ratio accounted for 88% of the variation in ghg intensity between sites.</p> <ul style="list-style-type: none"> • Fossil fuel energy demand – 27 MJ, with 47% from feed production, 23% from piggery energy use (mostly for cooling), 16% from feed milling and 14% from meat processing. Manure use for biogas production could reduce energy demand by 25%. • Consumptive water use – ranged from 184 L, mostly (74%) from irrigation for feed production, followed by farm (animal) consumption (29%) and 6% at meat processing stage. Potential to improve water use efficiency by using piggery effluent for crop production, to reduce fresh water and synthetic fertiliser use • Stressed water use – 172 L H₂O-e, regional water stress has greater impact on results than the actual volume consumed • Arable land occupation – averaged 25.9 m², mostly due to feed production, higher than European values due to lower grain yields

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Science, 2018, 58, 1153-1163. HEPR reported in Wiedemann 2018 PhD thesis (Wiedemann, 2018).			<ul style="list-style-type: none"> • CO₂-e emissions from direct land use change (dLUC) for conversion of forest to crop land and land use (LU) CO₂-e sequestration due to improved cropping were estimated from national inventory data for the period 1990-2010, net result was annualised sequestration of 2 kg CO₂-e /ha • Allocation used with manure, assume 30% of nutrient content is used as cereal crop fertiliser (reducing industrial fertiliser use), economic allocation between meat and pet food, renderable products considered a residue and no impacts allocated to these products ie no allocation to tallow and meal. • Dressing percentage of 76% (LW to HSCW), chilling loss 4% (HSCW to CW), retail yield 77% (CW to retail portions), edible yield/fraction of retail portions 85% 	<ul style="list-style-type: none"> • Sensitivity - feed use was the source of the greatest impacts in most impact categories, diets with lower amounts of soymeal had lower impacts, other Australian grown grains (wheat, barley, sorghum) were relatively similar. Stressed water use is very dependant on irrigation for grain production, and arable land use was very dependent on grain yield, which can vary significantly between years (eg wheat yields were 2.0 and 0.9 t/ha for 2006 and 2007 respectively). Inter annual rainfall variation, and the impact on land and water use, means that benchmarking needs to be updated frequent and/or longer averaging periods used to produce more stable results.

780 Supplementary Material 1.2 - Detailed Life Cycle Inventory & System Expansion per t HSCW (site
781 data unless otherwise specified)

Flow	Unit	Amount	Comment
1. Livestock, consumables & waste			
1.1 Inputs			
Cleaning chemicals ¹	kg	1.3	
Wastewater chemicals	kg	0.2	
Live weight of livestock	t	2	
Oils & lubes ¹	kg	0.18	
Transport – local	tkm	4.75	Includes chemicals to site, waste to landfill
Transport – national	tkm	1000.76	Includes livestock to site, chemicals etc
1.2 Outputs			
Solid waste to landfill	t	0.03	Excludes packaging
N in manure	kg	0.0073	
P in manure	kg	0.0041	
Paunch	t	0.081	Used as soil conditioner
2. Energy systems			
2.1 Inputs			
Boiler ash	t	-0.007	Included as a credit, natural aggregate
Coal	t	0.10	
Electricity	kWh	104.94	
Diesel – backup boiler	MJ	276.19	
LPG	MJ	4.63	Used in water heater, laundry, kitchen etc
Boiler – scale inhibitor	kg	0.00031	Sodium carbonate
Boiler - softener	kg	0.21	Sodium chloride
Boiler – scale inhibitor	kg	0.00008	Sodium hydroxide
Boiler - tannin	kg	0.002	
Transport - local	tkm	5.25	
Transport - national	tkm	61.31	
Diesel – current usage	tkm	63.60	
Petrol – current usage	km	11.84	
2.2 Outputs			
Methane from onsite ponds	t	0.01685	Based on estimate from NGER
Tallow	t	0.12	Included here to enable use in parameterised model
3. Packaging^{1, 2}			
3.1 Inputs			
Cardboard	kg	31	
Vacuum bags	kg	2.56	Assumed to be 50% polyamide, 50% polyethylene, 9% wastage
Polyethylene plastic	kg	2.09	5% wastage
Polypropylene plastic	kg	0.09	Assumed 5% wastage, plastic trays etc
Strapping (polypropylene)	kg	0.84	2% wastage
Paper	kg	0.92	Assumed 5% wastage, used for labels
Other plastics – PVC wrap	kg	0.06	13% wastage
Stockinette - cotton	kg	0.36	Assume 5% wastage
Hessian	kg	0.4	Assumed 5% wastage, modelled as jute
Transport - national			Materials into local depot

Flow	Unit	Amount	Comment
Transport - local			Materials in + waste to landfill
3.2 Outputs – waste to landfill			
Cardboard	kg	0.62	
Plastic mix	kg	0.34	
Plastic - polypropylene	kg	0.02	
4. Pest control			
4.1 Inputs			
Fipronil	kg	0.0000012	All modelled as output flows to agricultural soils
Bifenthrin	kg	0.0005	
Permethrin	kg	0.00000245	
Transport - national	tkm	0.001	
Transport - local	tkm	0.003	
5. Refrigerants			
5.1 Inputs			
R134a equivalent	kg	0.0043	
Transport - national	tkm	0.9	
Transport - local	tkm	0.3	
5.2 Outputs			
R12 (CFC-12)	kg	0.0002	Refrigerant change estimated as 1.5 kg/kW load from wattage on installed equipment list, 10% annual loss rate assumed ³ , modelled as elementary flow to air/ low population density
R22 (HCFC-22)	kg	0.001	
R134a (HFC-134a)	kg	0.0003	
R125 (HFC-125)	kg	0.00008	
R143 (HFC-143)	kg	0.00009	
6. Skins treating			
6.1 Inputs			
5-Chloro-2-methyl-4-isothiazolin-3-one + 2-Methyl-4-isothiazolin-3-one	kg	0.022	benzo[thia]diazole-compound ecoinvent flow used
Boric acid	kg	0.34	
Sodium chloride	kg	29.63	
Sodium fluoride	kg	0.34	
Untreated hides	t	0.18	
Transport – roads – national	tkm	139.65	
Transport - ship	tkm	1,420	
6.2 Outputs			
Etridiazole	kg	0.011	Ecoinvent flow used, 50% to ag soil, rest with effluent
Treated hides	t	0.14	
Hide water	t	0.04	
7. Water use and wastewater treatment			
7.1 Inputs			
Fresh water consumption	m³	3.7	
7.2 Outputs			
Treated effluent	m³	3.0	
Wastewater calcium	kg	0.1	
Wastewater magnesium	kg	0.05	
Wastewater nitrogen	kg	1.0	
Wastewater phosphorus	kg	0.2	

Flow	Unit	Amount	Comment
Wastewater potassium	kg	0.3	
Wastewater sodium chloride	kg	1.3	
Water evaporation	t	0.23	From tallow, meal, chillers losses
8. Whole plant			
8.1 Inputs			
Transport - national	tkm	140	
Transport - sea	tkm	1,438	
8.2 Outputs			
Edible offal	t	0.12	
Meat	t	1	
Meal	t	0.11	

Notes: 1) (Pagan et al., 2002), 2) (Coopers and Lybrand Consultants, 1996), 3) (Emerson Climate

Technologies, 2010b)

- Manure – market for solid cattle manure

Scenario	Details
Efficiency (EFF)	<ul style="list-style-type: none"> • 15 kW solar PV – average daily production assumed to be the same for Coffs Harbour (3.95 kWh/kW.day) (Clean Energy Council, 2017) • Wind – 25 kW
Tallow (TAL)	<ul style="list-style-type: none"> • Life Cycle Inventory data taken from (Dufour and Iribarren, 2012), values for rendered beef tallow, included in all subsequent scenarios • Ecoinvent process modified using emissions data from Australian NGER regulations for <ul style="list-style-type: none"> ○ Biodiesel use in site transport fleet ○ Tallow combustion to produce electricity ○ Tallow combustion to produce thermal energy • No tallow remaining to be sold, some coal still required for thermal energy requirements • Glycerine from biodiesel production assumed to be sold offsite

Scenario	Details																									
Biogas (BGS)	<ul style="list-style-type: none">Life Cycle Inventory data taken from (Poeschl et al., 2012), values for upgrading biogas to biomethane for substituting natural gas (0.38 kWh_{el} / m³ biogas, 0.1 kWh_{th} / m³ biogas).Glycerine assumed to be discharged to the anaerobic pond to increase biogas production, rather than being sold offsite, for this and subsequent process. NGER values used to estimate biogas production, 0.8 fraction degraded anaerobically, density 1.25 kg/L, average COD 1,262,500 mg/L.Ecoinvent process modified using emissions data from Australian NGER regulations for biogas combustion in gas engine																									
Biomass (BM)	<ul style="list-style-type: none">Life Cycle Inventory data taken from (Yanagida et al., 2011), diesel fuel use for transport converted into tkm at given fuel efficiency, included in existing flows. Fertiliser use modelled as credit from all nutrients available from treated effluent from site.Ecoinvent process used for biomass used for thermal energy production, with land use removed from final number for agricultural land use																									
Biomass land area calculations	<ul style="list-style-type: none">Values used – biomass production = 30 m³/ha/year x 265 kg/m³ density x 10.4 GJ/t = 83 GJ biomass/ha/yearPlant thermal energy consumption = 2,739 MJ/ t HSCW → 0.033 ha/yearPlant total energy consumption = 3,326 MJ/ t HSCW at 20% efficiency of conversion = 16,630 MJ/ t HSCW → 0.2 ha/yearLand area for livestock production derived from (Wiedemann et al., 2015b) <table><tr><th>ha/t HSCW</th><th>Beef grass</th><th>Beef MF</th><th>Beef LF</th><th>Lamb</th></tr><tr><td>non arable</td><td>29.3</td><td>21.8</td><td>11.6</td><td>21.4</td></tr><tr><td>arable pasture</td><td>1.5</td><td>1.1</td><td>0.6</td><td>1.1</td></tr><tr><td>arable crop</td><td>0.2</td><td>1.2</td><td>2.1</td><td>0.2</td></tr><tr><td>total</td><td>31</td><td>24.1</td><td>14.3</td><td>22.7</td></tr></table>	ha/t HSCW	Beef grass	Beef MF	Beef LF	Lamb	non arable	29.3	21.8	11.6	21.4	arable pasture	1.5	1.1	0.6	1.1	arable crop	0.2	1.2	2.1	0.2	total	31	24.1	14.3	22.7
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