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Published in:
Journal of cleaner production

Link to article, DOI:
[10.1016/j.jclepro.2019.118816](https://doi.org/10.1016/j.jclepro.2019.118816)

Publication date:
2020

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Bonou, A., Colley, T. A., Hauschild, M. Z., Olsen, S. I., & Birkved, M. (2020). Life cycle assessment of Danish pork exports using different cooling technologies and comparison of upstream supply chain efficiencies between Denmark, China and Australia. *Journal of cleaner production*, 244, [118816].
<https://doi.org/10.1016/j.jclepro.2019.118816>

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Please cite this article as: Alexandra Bonou, Tracey Colley, Michael Z. Hauschild, Stig Olsen, Morten Birkved (2020) Life cycle assessment of Danish pork exports using different cooling technologies and comparison of upstream supply chain efficiencies between Denmark, China and Australia. *Journal of Cleaner Production* 244, <https://doi.org/10.1016/j.jclepro.2019.118816>.

Life cycle assessment of Danish pork exports using different cooling technologies and comparison of upstream supply chain efficiencies between Denmark, China and Australia

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Abstract:

This study completed a cradle-to-retailer life cycle assessment of Danish export pork and provided a comparative assessment of six after cooling technologies for the supply of pork meat to three markets, Denmark, China and Australia. Nine different pork products delivered to retailers were assessed for fourteen midpoint impact categories. Given the higher efficiency of the Danish pork production system, the relatively small impact of transportation, the relatively large contribution of feed production, and the higher yield of crop production in Denmark, Danish pork production could provide a more sustainable pork supply if issues relating to consumer acceptance of superchilled products and cold chain integrity can be addressed. The human edible protein required (HEPR) in feed to produce one kilogram of human edible protein was over 4 for all supply chains, Denmark had the lowest value of 4.17, 4.27 for Australia and 4.56-5.52 for China, largely due to differences in feed conversion efficiencies. The amount of arable land required to produce one kilogram of human edible pork protein ranged from 38 m² in Denmark, to 44-51 m² in China and 161 m² in Australia, due to large differences in crop yields of the feed ingredients. Pork production is therefore a net consumer of human edible protein and HEPR and arable land use are useful metrics by which to assess food supply chains. The life cycle assessment study was undertaken as part of an industry research project into new superchilling technologies, and the HEPR and arable land study was undertaken as part of a PhD on the sustainability of agribusiness value chains.

Keywords² (6 max): pork production, supply chain, life cycle assessment, super-chilling, arable land use, human edible protein required

Highlights (submit as separate document):

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² Human Edible Protein Required (HEPR) is the ratio of human edible protein consumed in the feed material per kilogram of human edible protein produced.

- Superchilling extends the shelf life of “fresh” product and enables exports to distant markets
- Superchilling and transport of pork from Denmark has insignificant impacts, relative to farming
- Human Edible Protein Required (HEPR) was over four for each pork supply chain
- Arable land use ranged from 38 (Denmark) to 161 m² (Australia) per kilogram of human edible protein
- HEPR and arable land use are useful metrics with which to assess food supply chains

1. Introduction

Global demand for meat has been increasing steadily, in line with increases in both the world population and the average standard of living (Dalgaard, 2007; Reckmann et al., 2013; Verge et al., 2012). Denmark has a population of 5.7 million people (Statistics Denmark, 2016) and processes 28 million pigs annually. Pork production in Denmark contributed approximately 1% of the 2017 world production of 82,482 M tonnes, which equated to 6% of EU-28 production (Danish Agriculture & Food Council, 2018). Nearly 90% of Danish pork production is exported, with approximately 70% of the exported meat to countries within the European Union (EU). The remaining percentage is exported to non-EU destinations, with an increasing market share to countries such as Japan, China and other South East Asia nations (Danish Agriculture & Food Council, 2017; Hamann, 2006). The growing export trend raises sustainability related questions such as: when it comes to arable land use and the efficiency of protein production, how does meat produced in Denmark and exported overseas compare to local production in the final markets? Danish Crown (DC) is a farmer-owned co-operative in Denmark which processed 81% of the total number of pigs in Denmark in 2017 (Danish Agriculture & Food Council, 2018), so given the company’s market share, production-related technology choices call for an in-depth environmental investigation using a comprehensive methodology such as a life cycle assessment (LCA). There have been a number of LCAs on European pork production (Basset-Mens and van der Werf, 2005; Cederberg et al., 2005; Dalgaard et al., 2007; Nguyen et al., 2011; Noya et al., 2017; Reckmann et al., 2013). These previous LCAs have consistently identified the on-farm (upstream) pig production, particularly the production of pig feed (60% of total climate impact in Nguyen et al. 2011), as the life cycle stage which contributes the most to the environmental impacts. According to a recent review of pork LCAs (McAuliffe et al., 2016), most existing LCA studies included a limited range of mid point impact categories (MPIC), such as climate change, eutrophication and acidification, but did not include water use, land use or a measure of supply chain efficiency, such as human edible protein required. Similarly, most earlier LCAs on pork did not assess impacts from exporting to distant markets, but instead system boundaries included farm to processor gate (Reckmann et al., 2013) or farm to local or regional markets, such as Danish pork to England (Dalgaard et al., 2007). For LCA studies that did include the core meat processing life cycle stage, all report inputs for the stage as a whole and do not provide detail on the breakdown between sub processes to enable differential allocation to different pork products, meaning that results are reported for a generic weight of meat, rather than specific pork products. Laboratory scale data was available on immersion, spiral and cryogenic super-chilling technologies as part of the GlobalMeat research project, which had not previously been scaled up to industrial use and assessed in terms of the potential for using the technologies for export to distant markets. Increasing global demand therefore requires filling in existing research gaps related to two key areas: the potential

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for super-chilling technology to increase the export of pork to distant markets as chilled (rather than frozen) product; and pork supply chain efficiencies in different markets. Although it may be technically feasible to export pork to distant markets, it is necessary to assess whether this is environmentally preferable, based on supply chain efficiencies for the respective markets.

This study investigates **the influence of core pork production system efficiencies, in particular the effect of post-processing cooling technologies** up until the products reach the retail markets in adequate quality. There are three target temperature ranges used to preserve meat products for transport: fresh, frozen ($< -12\text{ }^{\circ}\text{C}$) and super chilled. The latter keeps a meat product at a temperature between the initial freezing temperature ($-1.5\text{ }^{\circ}\text{C}$ for fresh lean meat, down to $-6.7\text{ }^{\circ}\text{C}$ for meat with a higher salt content) and the fully frozen temperature ($-12\text{ }^{\circ}\text{C}$). The resulting product temperature is low enough to significantly retard bacterial activity, but not so low that ice crystal growth causes structural damage to all of the meat (James and James, 2011). The process involves an initial surface freezing, after which the product achieves a uniform temperature distribution that is maintained during storage, transport and distribution. This has the potential to increase the shelf life by 1.4-4 times when compared to conventional chilling methods for meat products without adversely affecting product quality (Bogh-Sorensen and Zeuthen, 1984; Duun et al., 2008; Haugland and Aune, E. J. Hemmingsen, 2005; Magnussen et al., 2008). Although the technology had already been described in 1920 and it has commonly been used in seafood (Beaufort et al., 2009; Olafsdottir et al., 2006; Zhou et al., 2010), it is only recently being used more frequently for meat products. However super-chilling is gaining momentum as it fulfils the consumer preference for higher quality fresh products (USDA Foreign Agricultural Service, 2018a). Such improvement of cooling technologies affects the level of energy consumption; the shelf life at the market and therefore the amount of food waste (Lee et al., 2015), and it is thus relevant to investigate the associated environmental benefits. **The research question for this portion of the study was:** can super-chilling be used to export Danish pork products to distant markets safely from a food safety perspective; if super-chilling is technically viable, which of the available technologies are the best from an environmental perspective and how does their performance compare to freezing; and how do the extra stages of super-chilling and export contribute to the overall environmental impact of the pork products. This study was commissioned by the Danish Government.

The study focuses on Danish pork production and sale into three markets: The Danish, due to it being the location of the supply chain which provided the primary data and its share in global exports; the Chinese, due to its share in global pork production and consumption and importance as the third largest export market for Denmark; and the Australian, the seventh largest export market for Denmark, a minor competitor in Asia for Danish exports and to provide a global perspective (Danish Agriculture & Food Council, 2016).

The study then investigated **the influence of upstream pork production system efficiencies** and how they vary between geographic locations and production systems. Comprehensive details on Danish pork production are published annually providing mostly “bottom up” or **micro** metrics that analyse farm performance (Agriculture and Horticulture Development Board, 2018; Danish Agriculture & Food Council, 2018). Danish pork production has three categories of farms: sow herds, which produce weaned piglets (about 30 kg); finisher herds, where weaned piglets are grown to the slaughter weight (100-110 kg); and integrated farms, which have sows for piglet production and grow piglets to the slaughter weight (Danish Pig Research Centre (SEGES), 2016). One of the

efficiency metrics used is the feed conversion ratio (FCR), which are the kilograms of feed required for each kilogram of weight gain. The 2016 feed conversion ratio of Danish production was **2.69** for finishers, compared to the European average of **2.84** for finishers and 1.8 for rearing (i.e. piglets growing from the average weaning weight of 7.2 kg to 29.5 kg, the average weight for transfer from rearing to finishing) (Agriculture and Horticulture Development Board, 2018). Denmark has been regulating the emissions of nitrogen and phosphorus from agriculture, such as the application of pig waste to pastures, since 1987, when the Action Plan on the Aquatic Environment (APEA I) was adopted (Environmental Protection Agency, 2017). Farmers must submit an annual fertilization account, which includes information on the total application area, catch crops and nitrogen and phosphorus load and the net effect of the Danish laws was that upstream pork production was limited by the availability of land to recycle the pig effluent. Australian pork production systems are similar to those in Denmark, and similarly, management of manure and effluent is regulated by State-based laws aimed at protecting the surrounding environment from nutrient runoff and organic loads. China is the global leader with more than 50% of global pork production (FAO, 2017). Pork production has changed significantly in the last 50 years, from backyard (0 - 2 pigs per farm) and traditional (3 - 49 pigs per farm) systems to “landless” medium (50 - 3000 pigs per farm) and industrial (over 3000 pigs per farm) systems (Bai et al., 2014). The growth in Chinese landless pig production systems has led to reduced nutrient use efficiencies and increased environmental pollution (Bai et al., 2014). However, new regulations, including the Environmental Protection Tax program which came into effect on 1 January 2018, are designed to reduce nutrient emissions from intensive livestock farming including cattle, pig, chicken and duck operations (USDA Foreign Agricultural Service, 2018a). Less data is available on Chinese pork production efficiencies and there are some discrepancies in data available (Gale, 2017). The values for finisher FCRs in Chinese industrial systems range from **2.68** (Zhou et al., 2018) for large-scale production in northern China to **3.0-3.1** for industrial farms during the period 2006-2015 and **3.1** in 2015 for backyard farms (Gale, 2017). The latter numbers equate to 8% less efficient than the EU average and 15% less efficient than the Danish average for 2015) (Agriculture and Horticulture Development Board, 2018).

However, the finisher FCR metric only looks at part of the upstream pork production system. The Danish farm inventory data used for this assessment (Nguyen et al., 2011) has a whole herd FCR of **2.805**, which includes all production stages (sows and finishers herds) and measures the amount of feed required to produce 1 kilogram of live weight (LW). Australian research (Wiedemann et al., 2018) documented a whole herd FCR (kg feed/ kg LW) of **3.1** for Australia using 2010-2011 data. Whole herd FCR reported per kilograms of LW still need to be corrected for the live weight to carcass weight (CW) yield (LW: CW), as these values can vary between species and production systems. The whole herd FCR (kg feed/kg LW or kg feed/kg CW) is an example of a meso level metric.

“Top down” or macro level metrics could be used to compare the efficiency of supply chains in different geographic locations within the same agricultural sector, or supply chains in different sectors, such as pork and beef, and as such could potentially be of interest to external stakeholders such as consumers and policy makers. Metrics have been proposed such as the tonnes of people nourished per hectare (Cassidy et al., 2013), human digestible protein yield converted into land use ratios (Van Zanten et al., 2016) or simpler metrics such as human edible protein required (HEPR) (Wiedemann, 2018). HEPR is the mass of human edible proteins in the feed material divided by the mass of human edible protein in the final product, so a value greater than 1 indicates the product is reducing the amount of human edible protein, whereas a number below value indicates the produce

is increasing the amount of human edible protein. Given the limited amount of arable land available in countries like China and Australia (Cheng et al., 2011; Wiedemann et al., 2017), it is useful to investigate the amount of arable land required to produce each kilogram of human edible protein. Values for these two metrics were recently reported in (Wiedemann, 2018) for Australia, the HEPR ratio was 4.27 (kg HEPR in feed to produce 1 kg HEPR in pork meat) and the arable land occupation for the national herd was 16.1 +/- 3.6 m² per kg LW. In combination, these metrics incorporate pork production efficiency with feed production efficiency in metrics that encapsulate the whole upstream section of the pork production system. The authors are not aware of any previous studies looking at HEPR or arable land use for the Chinese or Danish pork production supply chains.

The research questions for this part of the study was: what are the upstream supply chain efficiencies of the chosen markets, as measured by the HEPR and arable land required per kilogram of human edible protein produced.

2. Methods

2.1 Life Cycle Assessment of 9 pork products

This study investigated the potential improvement to the shelf life for fresh pork meat exported to foreign markets by using different cooling technologies and the resulting potential environmental benefits. It was commissioned by the GlobalMeat project, which was funded by the Ministry of Environment and Food of Denmark and The Danish AgriFish Agency, and was not intended for comparative purposes.

2.1.1 Technology definition

The technologies assessed in this LCA included three that are already available on an industrial scale (spirals, chilling rooms and impingement), two that are currently under development (immersion and contact) and one (cryogenic) which is currently used in limited, special applications (GlobalMeat 2013). The technologies were compared with each other and with freezing, which is the current cooling technology used and comprehensive details on each technology are available in the GlobalMeat project report (Bonou and Birkved, 2016). Nine pork products were considered (see Table 1) and for each of them, the heat capacity above and below zero was calculated using composition data from two online databases (DTU, 2016; USDA, 2016) and commonly used methods (ASHRAE, 2006) (results are provided in Appendix A, Table A.1). For the heat capacity below zero, the sensible heat from the temperate change and the latent heat of water fusion, including the mass fraction of bound water in protein (40% by mass) are included (ASHRAE, 2006). The temperature range of the analysis is 5 to -1 °C i.e. 6 K. For freezing, the final product temperature is assumed to be -20 °C. The amount of energy required to achieve the required temperature reduction is indicated by a coefficient of performance (COP) for each technology type, which is included in Appendix A, Table A.2. When combined with the heat capacities of the nine different pork products under assessment, the COP of each technology allows the amount of electricity required for each kilogram of product to be calculated for each technology and product type as presented in Table 1. This indicates that freezing requires between two to three times the amount of energy compared to the super-chilling technologies under assessment.

Table 1: Electricity requirements for the technologies under assessment for nine pork products (kJ/kg)

Pork products ¹	Cooling method		
	Impingement // Spiral (COP 2.6)	Immersion // Contact // Chilling room (COP 3.7)	Freezing (COP 3.7)
Tender Loin	8.2	5.8	20.1
Neck bone	7.4	5.2	16.0
Rib bones	7.4	5.2	16.0
Minced meat	8.0	5.6	17.4
Whole ham	6.9	4.8	16.2
Belly (for Bacon)	6.4	4.5	12.8
Tongue	7.9	5.6	17.3
Heart	8.5	6.0	18.9
Front feet	7.9	5.5	16.8

Note: 1) pork products of differing composition were assessed using product weights provided by the Danish Meat Research Institute (DMRI) (Nersting, 2016; Scheller Andersen, 2016) and Danish Crown (Heddal Hofer, 2016; Thy, 2016).

A model developed by DMRI (DMRI, 2016) to predict the shelf life of fresh meat was used to check that the shelf life of the assessed products exceeded the duration of the transport to market. The model is based on storage trials performed under controlled conditions with different meat products from different plants in several European countries but does not currently include freezing.

One of the weakest links in the cold chain for pork supply is the transport between the retailer and the home of the consumer, which can vary in duration and temperature, with subsequent adverse impacts on product quality and safety. Due to the difficulties in quantifying this factor and the fact that it is a larger challenge for fresh meat than for super-chilled meat, it has not been included in the current study.

2.1.2 Product definition

An average slaughter weight of 104 kg was used, based on actual plant data provided by Danish Crown, as outlined in Table 2. Water loss can range from 5.5 - 7% between slaughter and retail for meat (James, 2002) and drip loss of 1.6% for super-chilling is possible (Heddal Hofer, 2016), so 5.9% of the live weight was assumed to be lost as water prior to super-chilling.

Table 2: Weight specification of Danish pork products included in study (Thy, 2016)

	% of live weight	Weight (kg/pig)	Comment
Live weight	100	104	Primary data from Danish Crown
For human use	84	87.36	Fit for human consumption
Water/ drip loss	5.9%	6.1	From slaughter to retail sale (James, 2002)
Assessed products	39% total 32.74% excluding water	34.05	
Tender Loin		1.275	Primary data from Danish Crown
Neck bone		1.185	
Rib bones		0.573	
Minced meat		6.000	
Whole ham		15.740	
Belly (for bacon)		7.871	
Tongue		0.243	
Heart		0.324	

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	% of live weight	Weight (kg/pig)	Comment
Front feet		0.842	
Byproducts	16		Not fit for human consumption

Note: Green shading indicates data from literature, blue shading indicates primary data provided by industry (number of digits as in original source), yellow shading indicates calculated figures.

2.1.3 Goal, scope and system boundaries

The goal of the LCA was to assess the environmental impact of the use of six alternative super-chilling technologies on nine different pork products and the subsequent export of pork relative to the entire pork supply chain. The LCA was conducted in accordance with the International Reference Life Cycle Data System (ILCD) Handbook for LCA (EC-JRC, 2010), using an attributional approach, which is consistent with the goal situation A “micro-level decision support”. The scope is reflected in the functional unit, which was “1 kg of pork product delivered to the retailer”, so the system boundary extended from the farm to the retailer, as outlined in Figure 1. Potential stakeholders include pork producers, retailers, policy makers, researchers and other stakeholders wanting to understand the potential contribution of super-chilling to supply chain augmentation for exporting products.

Figure 1: System boundaries for this study (indicated by the large box).

2.1.4 Inventory and data collection

Foreground data was used for processes relating to meat processing plants, cooling, packaging and transport, and data for the new after-cooling technologies was based on primary lab-scale data which had been scaled up to the equivalent final industrial usage using DMRI models. Background data was obtained from the Ecoinvent database v3.01 and literature. SimaPro v8.1 software was used for the modelling, to maintain consistency with the two previous LCA studies of Danish pork. The life cycle impact assessment (LCIA) methods used were ILCD 2001 midpoint, v1.07, EU27 2010, to be consistent with the Product Environmental Footprint - Product Category Rules (PEFPCR) recommendation for the assessment of meat products (TS 2016). Midpoint impact categories outlined in the PEFPCR (climate change, acidification, terrestrial eutrophication, marine eutrophication, freshwater eutrophication and land use) are reported in this paper, along with water resource depletion.

For the upstream (farm) life cycle stage, life cycle inventory data was taken from (Nguyen et al., 2011), as this is the most recent, comprehensive LCA of Danish pork production. For the meat processing life cycle stage, primary data on resource and energy consumption was provided by

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Danish Crown (Thy 2016) and DMRI (Scheller Andersen 2016) and is summarised Table 3. Details on specific process areas are provided in Appendix A, Table A.3.

Table 3: Resource and energy consumption per live pig (104 kg live weight) allocated to specific process areas (Danish Crown and DMRI)

	Electricity	Natural gas ¹	Water	Liquid CO ₂ ²
Total usage/ live pig	13.67 kWh	54.88 MJ	197 L	0.56 kg
Washing area		1%	7.52%	
Black slaughter line	20%	23%	25.7%	50%
Cleaning	14%		16.61%	
Boiler (process and space heating)		71%		
Ventilation	2%			
Evaporative cooling			3.5%	
Others	3%		8.04%	
Smoking oven		4%		
Energy recovery	0.83 kWh	0.58 kWh		
Clean slaughter line			24.36%	
Chilling	40%			
Cutting	5%		4.61%	
Deboning	10%			
Organ processing/by-product production	6%		9.65%	

Notes: 1) based on conversion from Nm³ using natural gas density of 0.0008 kg/L and heating value of 49 MJ/kg, 2) the remaining 50% is used for generic cooling purposes

Primary data on packaging was provided by Danish Crown, who indicated that 20 g of plastic materials were used per kilogram of meat product. It was assumed that this mass was comprised of an equal proportion of high and low density polyethylene (HDPE and LDPE), polyamide (PA), ethylene vinyl acetate, polyethylene terephthalate (PET), polystyrene (PS) and polyvinylchloride (PVC) (McMillin and Belcher, 2012). Packaged products are then put into cardboard boxes for transport and 0.055 kg of cardboard per kilogram of meat is used (Hededal Hofer, 2016).

For modelling product transportation to markets, a distance of 52 km from the Danish Crown Horsens plant to the export port of Aarhus was used and the distance by road in each country from the port to the retailer was assumed to be the same as the distance from the Horsens plant to Copenhagen (267 km). The distance by ship to China was representative of the distance to Australia, and assuming an average boat speed of 23 knots (Notteboom and Cariou, 2009; Sea-distances.org, 2016; Worldshipping.org, 2016), the duration of the sea voyage was calculated (Table 4).

Table 4: Distances and travel times to different markets

Country	Distance by truck (km)	Distance by ship (km)	Time by ship (days)
Denmark	267	-	-
China/ Japan/ Australia	267 + 52	14,413 (average)	20-32

Regarding energy use during container transport by sea, primary data was provided by DMRI (Scheller Andersen, 2016) and is outlined in Table 5. It was assumed that the cooling was provided by liquid carbon dioxide (573 kJ/kg) for transport to Japan. Given the similarity in distance, this data was used for the China and Australia modelling.

Table 5: Energy consumption during transport to Japan (Scheller Andersen, 2016)

Sea voyage time	24.5 days	
Container load	22,000 kilograms	
Energy consumption per container		
	kWh container/day	kg CO ₂ used/kg product for sea voyage
Fresh product	22.6	0.16
Frozen product	34.2	0.23

2.1.5 Impact allocation and handling Multifunctionality (coproducts and byproducts)

The mass based allocation factors and comprehensive details for different production stages within the meat processing life cycle stage are outlined in Appendix A, Table A.4.

“Other inedible” byproducts (European Commission, 2005) can be further categorised using the details provided in Table 6:. Byproducts can be sent to rendering, where they are converted into meal and tallow. Some of the byproducts are suitable for producing pet food or food for animals in the fur industry, while other byproducts can be used to produce pharmaceutical products such as collagen, gelatine, peptides and proteins. Wastes with an organic content (such as the contents of the pig’s digestive system, sawdust from road transport, slurry from holding pens and wastewater) can be used to produce biogas via anaerobic digestion. The biogas can then be used in a cogeneration plant to produce electricity and thermal energy, while the digestate from the anaerobic digestion can be returned to farms, offsetting the use of industrial fertilisers.

System expansion and mass allocation were used to address the multifunctionality of coproducts for human consumption and byproducts for animal feed and industrial applications, which is consistent with both the ILCD Handbook and previous studies (Dalgaard et al., 2007, 2006; Dalgaard, 2007; Nguyen et al., 2011). Primary data relating to mass yields of byproducts relative to live pig weights was provided by Danish Crown, is provided in Table 6 and comprehensive details of the allocation are provided in Appendix A, Table A.4.

Table 6: Average Danish pork products and byproducts by weight (primary data from Danish Crown, kg product/ tonne live pig) (Thy, 2016)

			Product	Byproduct	Byproduct	Byproduct	Byproduct	Byproduct
Product	Total	%	Human food	Pet food	Fur ¹	Rendering	Pharma	Biogas
Muscle	640	63	640	0	0	0	0	0
Bone	132	13	114	0	2	16	0	0
Fat	75	7	52	6	1	0	0	16
Blood	33	3	12	10	11	0	0	0
Liver, heart	26	3	11	11	4	0	0	0
Other byproducts	31	3	11	10	6	4	0	0
Intestines	19	2	1	6	5	1	2	4
Destruction	54	5	0	0	3	51	0	0
			840	43	32	72	2	20

Note: 1) included in food for animals in the fur trade

Rather than modelling substitutes for final byproducts (downstream substitution) as part of the system expansion, such as the district heating and barley used in the most recent Danish LCA (Nguyen et al., 2011), the modelling replaced pork with a suitable upstream meat input based on the

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current market share of meat consumption. The meat products to provide the upstream replacement for pork were estimated using 2014 data for slaughtered livestock weights in Denmark (EUROSTAT, 2014), which indicated that 46% was beef, 53% chicken and 1% sheep, as outlined in Appendix A, Table A.5.

The credits from pet food, fur, rendering and pharma byproducts were calculated by multiplying the mass fraction of the byproduct by the market contribution of a substitute meat product, as indicated in Appendix A, Table A.6. For biogas, it was assumed that an equivalent of 2% of the live weight as fat (38 MJ/kg) was converted to biogas and then used to substitute natural gas (49 MJ/kg).

2.2 Upstream (feed and pork) production system efficiencies

2.2.1 Data collection for both mid point impact categories

Whole herd FCR for Denmark and Australia were taken from literature ((Nguyen et al., 2011; Wiedemann et al., 2017). Two values were calculated for Chinese whole herd FCR based on the ratio of two reported finisher FCRs (3.1 in Gale, 2017; 2.68 in Zhou *et al.*, 2018) to Danish finisher FCR (2.69 in AHDB Market Intelligence, 2018) for 2015, representing the best and worst cases. Australian values for HEPR and arable land use have recently been reported (Wiedemann, 2018). The quantities of different feed ingredients used in Denmark were taken from the most recent Life Cycle Assessment of Danish pork (Nguyen et al 2011) and in China from (Zhou et al., 2018) for the lower finisher FCR, and (USDA Foreign Agricultural Service, 2018b) for the higher finisher FCR. The mass of “other” in the Chinese feed ingredients was calculated using two cases, one as sprouted wheat (100% allocation to wheat) and one as a non-grain product without land use such as fish meal.

2.2.2 Arable land use calculation

The origins of the feed ingredients for Denmark (Mogensen et al., 2018) and for China (USDA Foreign Agricultural Service, 2018c, 2018d) are included in Appendix B, in Table B.2 for Denmark and Tables B.3 and B.4 for China. Yield data for all crops was taken from the FAO online statistical database for the year 2016. To be consistent with the Australian analysis, economic allocation was used for allocating land use to coproducts, so the land area allocations were 62% to soymeal and 28% to rapeseed cake (Wiedemann, McGahan and Murphy, 2016). Recent Danish values (Mogensen et al., 2018) were used for the remaining Danish and Chinese feed components, namely 6% and 84% to wheat bran and wheat respectively, 28% to sunflower cake, 95% to palm oil and 5% to beet molasses. It was assumed that rice bran had the same economic allocation as wheat bran (6%). This data was used to calculate the arable land required to produce one kilogram of LW and the average protein content of the feed for Denmark and China, while the Australian value was taken from literature (Wiedemann, 2018).

To provide an indication of the impact of yield on the results, the arable land area required for China and Denmark were recalculated using the worst yield within a 10 year period (2008-2017) for each feed component from all current geographic feed sources. Comprehensive details are included in Appendix B.

2.2.3 HEPR calculation

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The protein content of feed ingredients was taken from a variety of sources, as outlined in Appendix B, Table B.1-3. The LW: CW yield of Australia and Denmark were taken from literature (73% and 76% respectively), the LW: CW yield for China was assumed to be the same as Australia. The CW to boneless meat yield was assumed to be 72% in all cases and the protein content of boneless pork was assumed to be 19% in all cases (Agriculture and Horticulture Development Board, 2018; Wiedemann, 2018; Wiedemann and Yan, 2014), as indicated in Table B.5 in Appendix B. The HEPRs for China and Denmark were calculated using the formula below, by dividing the total mass of edible protein in the feed ingredients per kilogram of boneless pork by the mass of edible protein per kilogram of boneless pork. The Australian value was taken from literature (Wiedemann, 2018).

$$HEPR = \sum (P_i \times m_i) / (Y_{LW-CW} * Y_{CW-BM} * P_{BM})$$

Where P_i is the mass percent of human edible protein in each feed component (kg)

m_i is the mass of each feed component (kg) per kg of live weight (from whole herd FCR)

Y_{LW-CW} is the yield of cold carcass weight from live weight, assumed to be 0.73 for Australia and China, 0.76 for Denmark

Y_{CW-BM} is the yield of boneless meat from cold carcass weight, assumed to be 0.72 in all cases

P_{BM} is the human edible protein mass percentage of boneless meat, assumed to be 0.19 in all cases

3 Results & Discussion

3.1 LCA of 9 pork products

3.1.1 Product Shelf Life

As presented in Table 7, the DMRI model indicated that super-chilling more than doubled the shelf life for pork meat when compared to current storage temperatures (row 1 compared to row 3, and row 2 compared to row 4). It also indicated that there was sufficient shelf life available on arrival of the 9 superchilled product types (row 1) in the destination market after the 24.5 day sea voyage to allow for distribution and sale to consumers, ranging from 6.5 days for minced meat to 79.5 days for bacon.

Table 7: Impact of storage temperature on estimated total shelf life (days with acceptable raw meat odour) for different pork products

Storage temperature	Minced Meat ¹	Bacon ²	Fresh cuts ³
-1 °C	31	104	41
-1 °C then 7 days at 5 °C	17	90	22
3.5 °C ⁴	13	38	17
3.5 °C then 7 days at 5 °C	5	30	10

Notes: 1) MAP-packed (70 % O₂ + 30 % CO₂) 2) Vacuum packed, 2) 5.5 % salt in aqueous (% Sodium Chloride in the water phase, w/w), with/without Ascorbate, 60-120 ppm nitrite/nitrate added, no smoke, 3) Shelf life of fresh pork cuts - Vacuum packed and/or MAP-packed (70 % O₂ + 30 % CO₂) and/or stored under aerobic conditions (on "Christmas trees" (multiple hooks), in boxes, wrapped, etc.), 4) 3.5 °C represents conventional cooling for fresh products.

3.1.2 Assessing the whole pork supply chain

The analysis shows that the farming stage is the most intensive, as indicated in Figure 2. Ham exported to China or Australia that has been super-chilled using the immersion method is used, as it represents the worst case for emissions per kilogram due to the extra cooking stage required for ham during production. This is consistent with previous European LCA studies for climate change, acidification and eutrophication, and consistent with non-European LCA studies for the land use and water resource depletion impact categories.

Figure 2: Relative contribution of life cycle stages of pork production for ham super-chilled using the immersion method exported to China or Australia by ship

Impacts from the farming stage ranged from 95% for climate change and freshwater eutrophication to almost 100% for terrestrial eutrophication and land use. The extra inputs that super-chilling (including extra packaging) and transport to China or Australia contributed ranged from 0% for land use to 1% for acidification, with 0.6% for climate change and 0.2% for terrestrial eutrophication respectively. A detailed breakdown is available in Appendix C, Table C.1. This is consistent with climate change impacts from other studies of meat exports over similar distances, such as a carbon footprint study of New Zealand chilled and frozen lamb export to the United Kingdom, where shipping contributed less than 5% of the climate change impacts (Ledgard et al., 2011). A similar study of chilled Australian beef and lamb exports to the USA indicated that international transport by ship contributed less than five per cent of the climate change impacts (Wiedemann et al., 2015).

The use of system expansion for the treatment of byproducts and coproducts as avoided production of meat substitutes on a mass basis results in a net credit for all categories except land use and marine eutrophication as shown in Table 8.

Table 8: System expansion for treatment of byproducts as avoided production of meat substitutes and reallocation to edible portion of pig carcass

	Byproduct	Avoided production	Net impact per carcase	Net impact per kg of edible products
Climate change (kg CO ₂ -eq)	61.42	-111.37	-49.95	-0.61
Acidification (molc H ⁺ _{eq})	1.14	-1.84	-0.70	-0.009
Terrestrial eutrophication (molc N _{eq} /kg)	5.70	-7.49	-1.79	-0.022
Marine eutrophication (kg N _{eq})	0.821	-0.672	0.15	0.002
Freshwater eutrophication (kg P _{eq})	0.013	-0.141	-0.127	-0.002
Water resource depletion (m ³ water)	0.131	-2.206	-2.075	-0.025
Land use (kg C deficit)	6,675.0	-896.3	5,778.7	70.6

3.1.3 Assessment of super-chilling and transport options for assessed products

Table 9 contains the climate change impact of different cuts of meat relative to different super-chilling technologies and markets, after the byproducts and avoided production are credited back into the system. Products with similar results, as would be expected from the mass allocation factors and the relatively similar composition in Appendix A (Tables A.4 and A.1 respectively), are grouped together (loin/belly, neck bone/ribs, tongue/heart). This indicates that the product cut with the highest and lowest impacts are ham and feet respectively, which makes intuitive sense given that ham production involves an extra cooking stage and feet production involves the fewest stages, as they are removed early in the production process. However, uncertainty in the data used, the modelling of energy use and the mass allocation could also contribute to the differences, which highlights the need for plant studies to confirm these modelling results. Similar results were obtained for each of the impact categories and details are provided in Appendix C for the remaining impact categories (Tables C.2 – C.7). These climate change values are consistent with the most recent Danish study, which calculated 3.1 kg and 3.4 CO₂-e per kg of carcass weight using attributional (using economic allocation) and consequential (using system expansion) LCA methods respectively.

In terms of the theoretical difference between the impacts of the super-chilling technologies, immersion is the least efficient technology (due in large part to the extra packaging required to use the technology) and chilling rooms, impingement/spiral, cryogenic and contact are the most efficient super-chilling methods. The actual efficiency of chilling rooms may need to be reviewed, as there is some evidence from energy audits in similar industries in other countries that the product load can contribute as little as 20% of the total chiller load, depending on the chiller design, layout and associated usage issues such as door management (Hydro Tasmania Consulting, 2009). Additionally, contact super-chilling is not suitable for irregularly shaped cuts of pork such as ribs, neck bones and feet.

Unsurprisingly, impacts for the products transported to overseas markets were highest for China and Australia, due to the extra burden associated with transport fuel consumption and refrigeration during transport. However, the increment of impacts relating to market location was not significant.

Table 9: Cradle-to-retailer Climate change impacts (kg CO₂-e/kg cut) after re-allocation of byproducts and avoided production

Market	Technology	Loin/ Belly	Neck bone / Ribs	Ham	Tongue/ Heart	Feet	Minced Meat	Average per tech., all cuts
Denmark	Impingement & spiral	3.424	3.424	3.483	3.393	3.371	3.412	3.416
	Immersion	3.441	3.441	3.500	3.410	3.388	3.428	3.433
	Chilling room	3.424	3.423	3.483	3.393	3.371	3.411	3.416
	Contact	3.424	x	3.483	3.393	x	3.411	3.421
	Cryogenic	3.425	3.424	3.484	3.394	3.372	3.412	3.417
China, Australia	Impingement & spiral	3.716	3.716	3.775	3.685	3.663	3.704	3.708
	Immersion	3.733	3.732	3.792	3.702	3.680	3.720	3.725
	Chilling room	3.715	3.715	3.775	3.685	3.663	3.703	3.708
	Contact	3.715	x	3.775	3.685	x	3.703	3.713
	Cryogenic	3.716	3.716	3.776	3.686	3.664	3.704	3.709

3.2 Comparing upstream pork production efficiencies

As presented in Table 10, HEPR values indicate that all pork production systems require over 4 kilogram of edible protein from arable sources to produce one kilogram of edible human protein in the form of pork meat. Denmark has the lowest HEPR value, 4.17, which reflects the lower whole herd FCR. Australia was next with 4.27, in part due to the lower average protein content of the feed from arable sources in Australia (14.1% for Australia compared to 15.3% for Denmark and 15.9 – 17.0% for China). This is a result of a higher proportion of the protein in the Australian feed mix being sourced from non-plant sources such as blood meal (85% protein), meat and bone meal (50% protein) and other protein meal. Chinese HEPR values range from 4.56 to 5.52, a ratio of 1.09 to 1.32 higher than Danish values, due to the lower feed conversion efficiency and higher protein percentage from arable sources. Unsurprisingly, the two Chinese cases using sprouted wheat, where 100% of the wheat land use is allocated to the pork production, have the highest HEPR values (4.75 for the best case and 5.52 for the worst case). All pork supply chains are net consumer of human edible protein, as the HEPR values are above one.

More than four times as much arable land is required in Australia to produce an equivalent mass of edible pork protein compared to Denmark, mostly due to the lower yield per hectare of feed ingredients but also partly due to the lower feed conversion efficiency. All the Chinese cases are slightly higher than Denmark (ratios of 1.11 to 1.40), due to the lower crop yields and higher whole herd FCR. Both the non-grain China cases require smaller amounts of arable land than the sprouted wheat cases, which is as expected. As indicated in the last three rows of the table, reduced yields of livestock feed increase the area of arable land required to produce human edible protein by 26-34%, with the greatest increase in Australia (34%), followed by China (29-33%), with Denmark having the smallest but still significant increase in land area required of 26%. The lowest yields in China for corn, soy beans, wheat and sorghum were recorded in 2009, which corresponds with a period of drought from October 2008 through until February 2009 in northern China, the main grain growing area for wheat (USDA Foreign Agricultural Service, 2009). The lowest soybean yield of 0.18 kg/m² was recorded in Argentina in 2009, which coincided with a drought (NASA Earth Observatory, 2009).

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Droughts are predicted to become more frequent, severe and longer in duration with climate change.

Table 10: Whole Herd FCR, HEPR and arable land area required to grow feed to produce 1 kg of human edible pork protein using 2016 FAO yield data (bold text indicates existing values from literature, ratios are in comparison to Danish values).

	Unit	Australia ¹	Denmark ²	China ³	China ⁴	China ³	China ⁴
				Sprouted wheat		Non-grain	
Whole Herd FCR	kg feed/ kg LW	3.14	2.81	2.80	3.24	2.80	3.20
	ratio	1.1	1	1	1.2	1	1.2
Feed Protein (from arable)	%	14.1%	15.3%	16.9%	17.0%	16.3%	15.9%
HEPR	kg HEP in feed / kg HEP produced	4.27	4.17	4.75	5.52	4.56	5.14
	ratio	1.02	1	1.14	1.32	1.09	1.23
Arable land required	m ² / kg HEP	161.22	37.99	44.33	50.99	40.91	44.21
	ratio	4.24	1	1.17	1.34	1.08	1.16
Arable land required (low yield)	m ² / kg HEP	215.47	47.84	57.39	67.14	53.24	58.92
	ratio	4.5	1	1.20	1.40	1.11	1.23
% difference between Arable land required for 2016 vs low yield		34%	26%	29%	32%	30%	33%

Notes: 1) (Wiedemann, McGahan and Murphy, 2016), 2) (Nguyen et al., 2011), 3) (Zhou et al., 2018), 4) (Gale, 2017).

Soy production in Brazil is depleting soil nutrients (Cazemier, 2016), and it is expected that yields will decrease over time, so that soy imports from that geographic location will gradually increase the arable land required for pork production.

The combined impact of climate change and nutrient depletion means that any LCA on a livestock production system is dependant on crop yield data for the feed production system used at the time of the assessment. Crop yield data would therefore need to be revisited on a regular basis to analyse how whole herd FCR, HEPR and arable land requirements are changing with time and how this impacts the LCA results.

3.5 Limitations and Uncertainty in the assessment

In terms of methodological choices, the LCA results are sensitive to the way multifunctionality is handled via system expansion and substitution. Using ham as the example, the magnitude of the impacts from the system expansion and substitution ranged from relatively insignificant reductions (4% and 6% for marine and terrestrial eutrophication respectively) to moderate reductions (16% for climate change and 12% for acidification) as indicated in Figure 3. For freshwater eutrophication and water resource depletion, the net impact was very significant (over 100%) and changed the category from being a positive emission (source) to a negative (sink). This can partly be attributed to a reduction in phosphate emissions to freshwater from and water use in intensive livestock production and grain production but also because both categories went from being very small sources to very small sinks, so the percentage change was large but the actual value of the change was small, as

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indicated in Appendix C, Table C.8. Land use and marine eutrophication were the only two categories where the results were worse after the allocation of coproduct impacts.

Figure 3: Percentage reduction in impact categories after reallocation of credits

Overall this indicates the relative efficiency of pork production compared to other meat alternatives in the impact categories where the results improved after allocation of credits. If the replacement “average” Danish meat had included fish, which provided 35% of all non-pork animal products consumed in 2014 (compared to 30% beef and 34% poultry) (EUROSTAT, 2014) or the weighted average of the “average” meat in the markets receiving exports from Denmark, then the analysis would have yielded different results. However, it is not likely that using a different average meat product would have changed the portion of the supply chain which contributes the most impacts or which technology performs the best at super-chilling.

This analysis does not consider the ultimate sustainability of pork production over other meat products or relative to non-animal protein sources, but rather limits its assessment to how consumer demands for pork can be met with the least environmental impact. Values for HEPR and arable land calculated should enable comparisons with other meat and human edible protein supply chains.

The analysis did not consider consumer preferences in the end markets in terms of fresh, super-chilled or frozen products. Similarly, the analysis did not consider loss rates in the receiving markets at the retailer or once the product was purchased by a consumer from a retailer (ie post purchase consumer behaviour), it only considered delivery of the product to the retailer in the final market. Differences within each market would create different loss rates, which would influence the overall assessment.

4. Conclusion & Further work

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This work used the results for a government-funded LCA study to confirm the technical potential of exporting pork from Denmark to distant markets such as China as super-chilled, rather than frozen, products. Further investigation as part of a PhD project into supply chain efficiencies, and analysed the mid-point impact categories of human edible protein required and arable land required, to compare the efficiency of the pork supply chains in Denmark, Australia and China.

The work found that super-chilling is a feasible technology for exporting pork products to distant markets. Of the available super-chilling technologies, chilling rooms, impingement/spiral, and cryogenic have the lowest environmental impact, although the difference between the technologies is not large as indicated in Table 9. The achievable in-plant efficiency of the technologies should be assessed and confirmed rather than relying on theoretical calculations, particularly for the chilling room option. The pork product with the lowest impact was the feet, while ham has the largest impact, but once again, the difference between the products was not significant and could be due, at least in part, to the uncertainty relating to date, the modelling of energy use and the mass allocation used. Given the small differences between the super-chilling technologies, any optimisation will be based on economic rather than environmental impacts. This result reinforces that the upstream (on farm) and downstream (retail-consumer) life cycle stages are more suitable targets for future optimisation efforts.

Some additional work may be required on the consumer or market preferences in the export markets for super-chilled pork as a “fresh” product. As the functional unit relates to delivering the product to the final market, this assessment does not consider loss rates once the product reaches the retailer or end consumer, so this issue may require further research to understand the export pork markets, particularly any limitations associated with the cold chain once products arrive at a destination port that may result in higher loss rates. For example, immersion was the worst performing super-chilling technology, mostly due to the extra packaging required, but the extra packaging may reduce loss rates in the final market.

Given that the additional life cycle stages relating to export contribute 0 – 1% of the impact and that Denmark has a higher relative efficiency in terms of HEPR and hectares of arable land required to produce one kilogram of pork, it is likely that pork produced in Denmark will be the better environmentally preferable pork alternative for the foreseeable future. HEPR and arable land use are useful metrics with which to assess supply chain efficiencies.

Ideally, data would be available from industry sources on a regular basis to enable a comparison between supply chain efficiencies on the basis of a total supply chain indicator, such as the arable land area required to produce one kilogram of edible human protein and the HEPR. Alternatively, the data required to calculate these values (namely the whole herd FCR, feed composition, feed country of origin, protein content and crop yield) would be available rather than single indicators at sub-system levels, such as finisher feed conversion ratios or nutrient use efficiencies.

Although the efficiency of pork production in Denmark is higher than China and Australia, the supply chain is a net consumer of human edible protein, as the HEPR is greater than one. As competition for arable land increases as the global human population increases, HEPR could be used to compare all sources of human edible protein and inform policy choices relating to food production.

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Acknowledgements: Special thanks to Niels Conradsen from Danish Technological Institute, DMRI for his assistance and endless patience, Jakob Raffn and Teodora Dorca-Preda from Aarhus University and to Dr Rowan O'Hagan and Charles Rikard-Bell at the Australian Pork CRC.

Funding: The LCA portion of the work was supported by the GlobalMeat 2013 project, the arable land/HEPR work was completed as part of a self-funded PhD project at DTU.

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Appendices

Appendix A – Detailed information for LCA modelling

Table A.1: Product specifications and calculated specific heat capacities of the assessed pork products. The energy and content has been based on Danish and U.S. food databases (DTU 2016; USDA 2016).

	Weight kg/pig	kcal/ 100 g	Fat %	Protein %	Ash %	Water %	Specific heat above freezing (kJ/ kg K)	Specific heat below freezing (kJ/ kg K)
Tender Loin	1.275	119	3.8	20.9	1.2	74.1	3.57	2.97
Neck bone	1.185						3.20	2.36
Rib bones	0.573	275	23.4	15.67	0.69	58.43	3.20	2.36
Minced meat	6	173	11.2	18.4	1	69.4	3.47	2.58
Whole ham	15.74	165	2	20.7	0.9	60.8	2.98	2.40
Belly (for Bacon)	7.871	518	53.01	9.34		36.74	2.76	1.90
Tongue	0.243	225	13.27	17.00	0.94	68.30	3.44	2.56
Heart	0.324	118	1.63	17.69	1.1	79.29	3.67	2.79
Front feet	0.842	212	12.59	23.16	0.8**	64.99	3.41	2.49

Table A.2: Electricity requirements for the technologies under assessment (kJ/kg)

	Cooling method			
	Jet-stream (Impingement NH ₃) Spiral (COP 2.6)	Immersion // Contact // Chilling room (COP 3.7)	Cryogenic (COP 1) ¹	Freezing (COP 3.7)
Tender Loin	8.24	5.79	21.42	20.07
Neck bone	7.39	5.19	19.2	15.95
Rib bones	7.39	5.19	19.2	15.95
Minced meat	8.01	5.63	20.82	17.43
Whole ham	6.87	4.83	17.88	16.22
Belly (for Bacon)	6.37	4.48	16.56	12.84
Tongue	7.93	5.57	20.64	17.30
Heart	8.48	5.96	22.02	18.85
Front feet	7.87	5.53	20.46	16.82

Note: 1) based on the sublimation energy of R477

Table A.3: Detailed information relating to specific process areas

Issue	Detail or assumption
Assessment	<ul style="list-style-type: none"> Attributional, mass allocation of impacts, system expansion to handle multi-functionality with upstream substitution Software SimaPro v8.1, Ecoinvent database v3.01 System boundary: from the farm to the consumer Functional unit: 1 kg of pork product unpacked at the consumer
Animal raising	<ul style="list-style-type: none"> Based on average pig raising for the average Danish Landrace pig breed Manure/slurry is digested anaerobically and biogas generated is used to replace fossil fuels Inventory taken from Nguyen et al. 2011, Table 1, Baseline: typical 2010 production, Attributional PAS 2050 data Live weight of fattened pigs sent to meat processing plant is 100kg, but average weight of live animals received at meat processing plant is higher depending on how many surplus breeder sows are received in the given reporting period

Issue	Detail or assumption
Transport to meat processing	<ul style="list-style-type: none"> Assumed to be 240 km from farm to meat processing plant Meat processing plant located at Horsens in Denmark was used
Meat processing	<ul style="list-style-type: none"> Average live weight at start of meat processing is 104 kg The black slaughter line removes blood and hair/bristles/toenails from carcase, weight of carcase leaving line is 99 kg (based on data from DMRI that 4.5% of live weight lost in black slaughter line) The clean slaughter line workers remove intestines, internal organs and front feet and the carcase is split into two. Weight of hot standard carcase leaving line is 79 kg (HSCW) based on 76% yield live weight to hot standard carcase weight (DMRI). Chilling reduces the carcase temperature to 5 °C during a residence time of 110 minutes in a chilling tunnel using air at -16 °C and then 16 hours in an equalisation room at 5 °C. This results in evaporative loss of approximately 1 kg water (EU maximum of 2% weight loss in chillers), weight of dry carcase leaving equalisation room is 78 kg (DCW), assumes 1.3% HSCW water loss in chillers (i.e. 1 kg). Cutting stage involves partial head removal, automated trisection (into shoulders, middle and hams), grading, further automated cutting of middle piece (into loin and streaky bacon), further trimming of hams (and tail removal) and shoulder (removal of remainder of head) and hanging of trimmed shoulders, middle parts (loin and streaky bacon) and trimmed hams onto storage equipment ("Christmas trees"). Combined weight of pork leaving cutting stage for deboning depends on customer requirements. Deboning stage involves removal of bones from streaky bacon and other cuts, depending on customer requirements Packaging of products uses either boxes for the retail sector, or Christmas trees and product bins for cuts being sent for further processing by Danish Crown or external customers. Further processing may involve brine injection/immersion, cooking, smoking, etc., depending on customer requirements Water loss from live weight to retail including drip loss is assumed to be 7% of human edible products
Mass allocation	<ul style="list-style-type: none"> Clean slaughter line/Cleaning/Boiler/Ventilation/Evaporative cooling/ Others/ Energy recovery/ Waste water – uses mass of each product divided by total live weight (104 kg) minus total water loss (6.1 kg) for each of the 9 products under study. Remaining mass is split between other edible and inedible categories based on their respective mass fraction of the total amount (e.g. other edible = remaining mass x 47/(47+16)) Organ processing/byproducts – uses the same mass allocation for tongue and heart as clean slaughter line. Remaining mass is split between minced meat, other edible and inedible based on their respective mass fraction of the total amount Chilling/Cutting/Deboning – for loin, neck bone, ribs, ham and belly, uses same mass allocation as clean slaughter line. Remaining mass is split between minced meat, other edible and inedible based on their respective mass fraction of the total amount

Issue	Detail or assumption
Ham cooking	<ul style="list-style-type: none"> • 7 – 8 kg of whole ham is used for producing processed ham (Nersting, 2016) • Raw ham goes through curing process where brine solution is directly injected into muscle tissue and accounts for 30% of final product weight • Brine composition based on DMRI data (Nersting, 2016) – 80.28% water, 5.63% sodium chloride, 3.9% sodium nitrate, 8.7% dextrose, 0.2% sodium ascorbate (all percentages are weight) • Cured meat cooked at 75 °C, cools to 40 °C using spray chilling (water at 2-3 °C sprayed for 30-90 seconds at 15-30 minute intervals (Sofos, 2005), estimated 10% weight loss (Nersting, 2016). After cooling to 40 °C product is put into chilling room to reduce the temperature to 5 °C
Super-chilling technologies	<p>Existing super-chilling technologies currently used in industry</p> <ul style="list-style-type: none"> • Impingement – an air-based, radiant cooling system, where high velocity air jets are directed at the top and bottom surfaces of the pork product, the boundary layer at the meat surface is disturbed and heat exchange becomes more effective, with the resulting time required to freeze the product being similar to cryogenic freezing • Spiral – an air-based, convection cooling system, where product is on a spiral conveyor, and the movement of chilled air removes heat from the product. • Chilling room – an air-based, convention cooling system, where a continual movement of chilled air removes heat from the product • Cryogenic – a carbon dioxide-based, convection cooling system, where dry carbon-dioxide ice is used to cool the product and the high surface heat transfer coefficients mean that the cooling rates are higher than other systems <p>New super-chilling technologies laboratory tested in this study</p> <ul style="list-style-type: none"> • Immersion – a liquid-based convection cooling system, where wrapped meat is immersed in a tank of cooled liquid. Requires extra packaging material for the meat product. • Contact – a conduction cooling system, where there is physical contact between the meat product and a conducting medium (such as metal plates), and the conducting medium is cooled using a cooling medium such as a fluid or refrigerant. Difficult to apply to irregularly shaped meat cuts such as feet (trotters).
Wastewater emissions	<ul style="list-style-type: none"> • modelled using secondary data from the FAO (Verheijen et al., 1996), which indicates that 2.4 kg BOD and 0.6 kg N_{kj} (Kjeldahl nitrogen) are emitted to the wastewater system per tonne of carcase.
Biogas production	<ul style="list-style-type: none"> • 2% of live weight as fat used in biogas production, fat heating value of 38 MJ/kg and natural gas heating value of 49 MJ/kg, 1 kg of fat corresponds to 0.78 kg natural gas
Transport	<ul style="list-style-type: none"> • By road to market – 267 km from Horsens plant to Copenhagen used as default road transport distance for all markets • By road to port – 52 km from Horsens plant to Aarhus port • By ship to China – 11,052 – 17,773 km • By ship to Australia – 11,638 – 13,888 km

Table A.4: Mass based allocation factors for allocating inputs and impacts to products, coproducts (human edible) and byproducts (human inedible)

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	Processed animal	Loin	Neck bone	Ribs	Ham	Belly	Tongue	Heart	Feet	Minced meat	Others human edible (coproducts)	Others inedible (byproducts)
Cut weight (kg)		1.28	1.19	0.57	15.7	7.78	0.24	0.32	0.84	6.0	47.8	16
	Animal weight	% allocation based on each cut's proportion of the animal weight going through each process										
- Farming - Transport from farm - Washing area - Black slaughter line - Cleaning - Heating - Ventilation - Evaporative cooling - Others - Energy recovery - Wastewater	104	1.3	1.2	0.6	16.1	8	0.2	0.3	0.9	6.1	48.9	16.3
Clean slaughter line	99	1.4	1.3	0.6	16.9	8.5	0.3	0.3	0.9	6.5	47.5	15.9
Chilling	79	1.7	1.6	0.8	21.6	10.8	-	-	-	5.5	43.5	14.5
Cutting/ Deboning	78	1.8	1.6	0.8	21.9	10.9	-	-	-	5.4	43.1	14.4
Organ processing/ by-product production	25	-	-	-	-	-	1	1.3	-	8.4	66.9	22.4

Table A.5: Average meat composition for Denmark, 2014 (EUROSTAT, 2014)

Animal	Total weight slaughtered (1000 tonnes)	Average animal (excluding pigs)
Pork (porcine)	1,587	
Beef (bovine)	126	46%
Chicken (galline)	143	53%
Sheep (ovine)	2	1%

Generic life cycle inventory data for the global market for cattle, chicken and sheep slaughtering from the Ecoinvent database was used for the substituted meat products. So for example, the credit from feed was calculated by multiplying the mass percentage of live weight (7.5%) by the percentage of each of the other meat categories, to give the allocation keys in Table .

Table A.6: Allocations keys for substituting 'average meat' byproducts

Secondary functions	% live weight	Allocation factors for assigning impacts to the corresponding functions of the average meat		
		Bovine	Ovine	Galline
Feed	7.5	3.5%	0.1%	4.0%
Pharma	0.2	0.1%	0.001%	0.1%
Rendering	7.2	3.3%	0.1%	3.8%
Fat for biogas	2	Substitute for natural gas. Assumed heating values for fat: 38 MJ/kg. For natural gas 49 MJ/kg. 1 kg of fat corresponds to 0.78 kg natural gas		

These were then included in the modelling as negative flows, so

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$$\begin{aligned}\text{avoided feed} = & (104 \text{ kg live weight} * -0.035 * \text{market for cattle for slaughtering}) \\ & + (104 \text{ kg live weight} * -0.001 * \text{market for sheep for slaughtering}) \\ & + (104 \text{ kg live weight} * -0.04 * \text{market for chicken slaughtering})\end{aligned}$$

Appendix B – Detailed data used in HEPR and arable land calculations

Table B.1: Detailed information on Australian feed derived from published literature

Ratio component (kg)	National Herd average			Whole herd FCR ¹	Mass %	Average protein	Economic allocation	Feed origin	Yield (kg/m ²) base case-2016/ lowest ⁴
	Breeder ¹	Weaner ¹	Grower- Finisher ¹						
Barley	349.01	105.77	230.73	0.70	22	11%	99% ²	100% Australia, same % per region assumed as pork production	0.16 ¹ / 0.15
Wheat	383.83	628.43	460.06	1.65	53	12%	95% ²		0.16 ¹ / 0.11
Sorghum	85.49	57.39	124.20	0.35	11	11%	60% ³	100% Australian	0.34 ⁴ / 0.24
Lupins	19.10	11.40	22.80	0.07	2	34%	100% ³		0.12 ⁴ / 0.09
Field peas	27.81	16.60	33.20	0.10	3	20.5%	100% ³		0.57 ⁴ / 0.44
Canola meal	39.97	47.34	53.97	0.17	6	34%	28% ⁵		0.13 ⁴ / 0.10
Soymeal	15.10	24.07	10.00	0.05	1	48%	62% ⁵	5% Australian, 18% USA, 39% Brazil, 38% Argentina ⁵	2016 ⁴ - AU = 0.213, USA = 0.3494, Brazil = 0.2905, Argentina = 0.3015 Lowest - 0.18, Argentina, 2009
Veg oil (canola)	10.52	13.54	3.92	0.02	1	0%	72% ⁵		
Crude protein	14.38% ⁵	18.72% ⁵	16.48% ⁵	14.1%	13.8% average protein from (Wiedemann, 2018) 14.1% average protein calculated using data provided				
Total	945.20	923.25	955.36		16.10 m ² arable land from Wiedemann, 2018				
Weight gain (kg per live pig)	7	23	67.4	97.4	16.11 m ² arable land calculated using data provided and assumed economic allocation factors				
Whole herd FCR kg feed / kg LW	0.22	0.73	2.15	3.1					

Notes: 1) breeder/ weaner / grower – finisher national average calculated from (Wiedemann et al., 2016) based on aggregated diets per tonne of ratio for four diets used for the national herd data and land occupation (only wheat and barley data available) multiplied by percentage of production in each geographic area (49% in NSW-Vic, 23% in Qld, 11.4% in WA and 16.6% in SA), when two values were provided for wheat data for each geographic area, the

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lowest was used, 2) (Mogensen et al., 2018), 3) assumed values, 4) FAOSTAT, 5) data taken directly from (Wiedemann et al., 2016), crude protein values include non arable sources, such as blood meal (85% protein), meat and bone meal (50% protein) and other protein meal such as fishmeal

Table B.2: Detailed information on Danish feed

Danish feed per 100kg LW	Mass ¹	Mass %	Average protein % ²	Economic allocation	Feed origin ³	Yield (kg/m ²) ⁵ 2016/lowest (year)
Wheat	111.2	39.5%	9.9%	84% ³	100% Denmark	0.72 / 0.65 (2011)
Barley	85.5	30.4%	9.4%	99% ³	100% Denmark	0.56 / 0.47 (2008)
Soybean meal	34.1	12.1%	45.78%	62% ⁴	64% Argentina, 28% Brazil, 8% USA	2016 - 0.30, 0.29, 0.35 Lowest - 0.18 Argentina (2009)
Sunflower cake	11	3.9%	32.75%	28% ³	14% Estonia, 5% Germany, 4% Lithuania, 42% Russia, 35% Ukraine, (used Russia yield data for Estonia & Lithuania)	2016 - Russia/Estonia/Lithuania – 0.15, Germany – 0.21, Ukraine – 0.22 Lowest - 0.10 Russia (2010)
Rapeseed cake	11	3.9%	34.4%	28% ⁴	100% Denmark	0.31 / 0.31 (2016)
Wheat bran	6.4	2.3%	14.68%	6% ³	100% Denmark	0.72 / 0.65 (2011)
Fish oil	2.2	0.8%	0	n/a	Not required	Not applicable
Palm oil	6	2.1%	0	94% ³	70% Indonesia, 30% Malaysia	2016 - Indon – 0.39 / Malay – 0.37 Lowest – 0.35 Indonesia (2008)
Beet molasses	5.2	1.9%	9.62%	5% ³	10% Denmark, 34% Russia, 16% Ukraine, 4% Egypt, 36% India. nb India used sugar cane yield	2016 - Denmark – 7.10, Russia – 4.70, Ukraine – 4.81, Egypt – 4.77, India – 7.04 Lowest – 2.41, Russia (2010)
Other	8.7	3.1%	Minerals + amino acids + special proteins			
Total	2,812.4	100%				
Whole herd FCR kg feed / kg LW ¹	2.8124	15.5% average protein from arable sources, calculated				

Notes: 1) (Nguyen et al., 2011), 2) (SEGES Svineproduktion, 2018), 2016 average values, 3) (Mogensen et al. 2018), 4) (Wiedemann, McGahan and Murphy, 2016), 5) FAOSTAT

Table B.3: Detailed information on Chinese pig feed

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	Mass % ¹	Mass % ²	Average protein %	Economic allocation	Feed origin	Yield (kg/m ²) ¹¹ 2016 / lowest yield (year)
Corn	55%	63%	9.3% ³	100%	100% China ⁴	0.60 / 0.53 (2009)
Soymeal	20%	18%	48% ⁵	62% ⁵	12% China, 10% Argentina, 42.7% Brazil, 34.7% USA	2016 – China = 0.18, Argentina = 0.30, Brazil = 0.29, USA = 0.27 Lowest – 0.16, China (2009)
Wheat bran	5%	12%	14.68% ⁷	6% ⁸	100% China ⁴	0.54 / 0.47 (2009)
Rice bran	3%	0%	13.4% ⁹	6% ¹⁰	100% China ⁴	0.69 / 0.65 (2010)
Other	12%	7%	9.6% for wheat ⁷	100%	Model as 1) 100% sprouted wheat ⁴ and 2) non-arable crop source	0.54 / 0.47 (2009)
Whole herd FCR (kg feed / kg LW)	3.24	2.80				
Total protein %	17.0% 15.9%	16.9% 16.3%	1) Sprouted wheat case 2) Non-arable crop case			

Notes: 1) (USDA Foreign Agricultural Service, 2018b) finisher FCR 3.1, 2) (Zhou et al., 2018) finisher FCR 2.68, 3) (Ontaria Ministry of Agriculture Food and Rural Affairs, 2012), 4) (USDA Foreign Agricultural Service, 2018d), 5) (Wiedemann, McGahan and Murphy, 2016), 6) (USDA Foreign Agricultural Service, 2018c), 7) (SEGES Svineproduktion, 2018), 8) (Mogensen et al., 2018), 9) (DTU Food (National Food Institute), 2019), 10) assumed value, 11) FAOSTAT.

Table B.4: Detailed information on origin of feed materials in China, based on trade data (derived from (USDA Foreign Agricultural Service, 2018d, 2018c)

	Corn 2016/2017 (1000 tons)	Wheat 2016/2017 (1000 tons)	Soy beans 2016/2017 (1000 tons)	Rice 2016/2017 (1000 tons)
Chinese Imports	4,410	2,464	93,495	4,600
Chinese Exports	748	0	114	368
Chinese Production	133,271	263,613	12,900	147,766
Chinese Consumption	119,000	255,000	102,800	141,761
Ending Stocks	114,929	223,017	20,391	98,500
% used in this report	100% Chinese	100% Chinese	12% Chinese	100% Chinese

Table B.5: Pork Meat Yield Factor Matrix derived from (Wiedemann and Yan, 2014)

	LW	HSCW	CW	RC
Live Weight (LW)	1	1.32	1.37	1.79
Hot Standard Carcass Weight (HSCW)	0.76	1	1.04	1.36
Cold Carcass Weight (CW)	0.73 ¹	0.96	1	1.30
Retail Cuts (RC) wholesale	0.56	0.74	0.77	1
Boneless meat including edible offal	0.53	0.69	0.72	0.94

Note: 1) value for Denmark in 2016 was 0.76 (Agriculture and Horticulture Development Board, 2018)

Appendix C – Detailed results by pork product, super-chilling technology and market destination

Table C.1: Impacts from processing plant by process area (red indicates highest value, green lowest)

Impact per pig (104 kg)	Climate change (kgCO ₂ -eq)	Acidification (molc H ⁺ _{eq})	Terrestrial eutrophication (molc N _{eq})
Farming total	361.17	6.92	34.76
Transport from farm	4.33	0.019	0.057
Slaughtering total	10.54	0.03	0.045
Washing area	0.04	0.0001	0.0001
Black slaughter line	1.82	0.005	0.006
Clean slaughter line	0.70	0.003	0.004
Organ processing/by-product	0.42	0.002	0.002
Chilling	2.78	0.01	0.015
Cutting	0.35	0.001	0.002
Deboning	0.70	0.002	0.004
Cleaning	0.98	0.003	0.005
Boiler (process/space heating)	2.77	0.005	0.005
Ventilation	0.14	0.0005	0.001
Wastewater	0	0	0
Others	0.21	0.001	0.001
Impact per kg cut			

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Impact per pig (104 kg)	Climate change (kgCO ₂ -eq)	Acidification (molc H ⁺ _{eq})	Terrestrial eutrophication (molc N _{eq})
Cooking (ham only)	0.06	0.001	0.001
Packaging	0.123	0.001	0.001
General cooling	0.002	0.00001	0.00001

Table C.2: Acidification impacts (molc H⁺_{eq} /kg cut) after re-allocation of byproducts and avoided production

Market	Technology	Loin/ Belly	Neck bone / Ribs	Ham	Tongue/ Heart	Feet	Minced Meat	Average per tech., all cuts
Denmark	Impingement & spiral	0.064	0.064	0.065	0.064	0.064	0.064	0.065
	Immersion	0.065	0.065	0.065	0.065	0.064	0.065	0.065
	Chilling room	0.064	0.064	0.065	0.064	0.064	0.064	0.065
	Contact	0.064	x	0.065	0.064	x	0.064	0.065
	Cryogenic	0.064	0.064	0.065	0.064	0.064	0.064	0.065
China/ Australia	Impingement & spiral	0.075	0.075	0.076	0.075	0.075	0.075	0.075
	Immersion	0.075	0.075	0.076	0.075	0.075	0.075	0.075
	Chilling room	0.075	0.075	0.076	0.075	0.075	0.075	0.075
	Contact	0.075	x	0.076	0.075	x	0.075	0.075
	Cryogenic	0.075	0.075	0.076	0.075	0.075	0.075	0.075

Table C.3: Terrestrial eutrophication impacts (molc Neq /kg cut) after re-allocation of byproducts and avoided production

Market	Technology	Loin/ Belly	Neck bone / Ribs	Ham	Tongue/ Heart	Feet	Minced Meat	Average per tech., all cuts
Denmark	Impingement & spiral	0.336	0.336	0.337	0.336	0.336	0.336	0.336
	Immersion	0.336	0.336	0.337	0.336	0.336	0.336	0.336
	Chilling room	0.336	0.336	0.337	0.336	0.336	0.336	0.336
	Contact	0.336	x	0.337	0.336	x	0.336	0.336
	Cryogenic	0.336	0.336	0.337	0.336	0.336	0.336	0.336
China/ Australia	Impingement & spiral	0.346	0.346	0.347	0.346	0.346	0.346	0.346
	Immersion	0.346	0.346	0.347	0.346	0.346	0.346	0.346
	Chilling room	0.346	0.346	0.347	0.346	0.346	0.346	0.346
	Contact	0.346	x	0.347	0.346	x	0.346	0.346
	Cryogenic	0.346	0.346	0.347	0.346	0.346	0.346	0.346

Table C.4: Marine eutrophication impacts (molc Neq /kg cut) after re-allocation of byproducts and avoided production

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Market	Technology	Loin/ Belly	Neck bone / Ribs	Ham	Tongue/ Heart	Feet	Minced Meat	Average per tech., all cuts
Denmark	Impingement & spiral	0.054	0.054	0.054	0.053	0.053	0.054	0.054
	Immersion	0.054	0.054	0.054	0.054	0.053	0.054	0.054
	Chilling room	0.054	0.054	0.054	0.053	0.053	0.054	0.054
	Contact	0.054	x	0.054	0.053	x	0.054	0.054
	Cryogenic	0.054	0.054	0.054	0.053	0.053	0.054	0.054
China/ Australia	Impingement & spiral	0.055	0.055	0.055	0.055	0.055	0.055	0.055
	Immersion	0.055	0.055	0.055	0.055	0.055	0.055	0.055
	Chilling room	0.055	0.055	0.055	0.055	0.055	0.055	0.055
	Contact	0.055	x	0.055	0.055	x	0.055	0.055
	Cryogenic	0.055	0.055	0.055	0.055	0.055	0.055	0.055

Table C.5: Freshwater eutrophication impacts (mol Peq /kg cut) after re-allocation of byproducts and avoided production

Market	Technology	Loin	Neck bone / Ribs	Ham	Tongue/ Heart	Feet	Minced Meat	Average per tech., all cuts
Denmark	Impingement & spiral	-0.00067	-0.00061	-0.00059	-0.00062	-0.00063	-0.00062	-0.00062
	Immersion	-0.00067	-0.00061	-0.00059	-0.00062	-0.00063	-0.00061	-0.00062
	Chilling room	-0.00067	-0.00061	-0.00059	-0.00062	-0.00063	-0.00062	-0.00062
	Contact	-0.00067	x	-0.00059	-0.00062	x	-0.00062	-0.00062
	Cryogenic	-0.00067	-0.00061	-0.00059	-0.00062	-0.00063	-0.00062	-0.00062
China/ Australia	Impingement & spiral	-0.00061	-0.00061	-0.00059	-0.00062	-0.00063	-0.00062	-0.00062
	Immersion	-0.00061	-0.00061	-0.00059	-0.00062	-0.00063	-0.00062	-0.00062
	Chilling room	-0.00061	-0.00061	-0.00059	-0.00063	-0.00063	-0.00062	-0.00062
	Contact	-0.00061	x	-0.00059	-0.00063	x	-0.00062	-0.00061
	Cryogenic	-0.00061	-0.00061	-0.00061	-0.00062	-0.00063	-0.00062	-0.00062

Table C.6: Water resource depletion impacts (m3 water eq/kg cut) after re-allocation of byproducts and avoided production

Market	Technology	Loin/ Belly	Neck bone / Ribs	Ham	Tongue/ Heart	Feet	Minced Meat	Average per tech., all cuts
Denmark	Impingement & spiral	-0.0163	-0.0163	-0.0158	-0.0163	-0.0163	-0.0163	-0.0163
	Immersion	-0.0163	-0.0163	-0.0158	-0.0163	-0.0163	-0.0163	-0.0162
	Chilling room	-0.0163	-0.0163	-0.0158	-0.0163	-0.0163	-0.0163	-0.0163
	Contact	-0.0163	x	-0.0158	-0.0163	x	-0.0163	-0.0162

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Market	Technology	Loin/ Belly	Neck bone / Ribs	Ham	Tongue/ Heart	Feet	Minced Meat	Average per tech., all cuts
	Cryogenic	-0.0163	-0.0163	-0.0158	-0.0163	-0.0163	-0.0163	-0.0163
China / Australia	Impingement & spiral	-0.0161	-0.0161	-0.0157	-0.0161	-0.0162	-0.0161	-0.0161
	Immersion	-0.0161	-0.0161	-0.0156	-0.0161	-0.0161	-0.0161	-0.0161
	Chilling room	-0.0161	-0.0161	-0.0157	-0.0161	-0.0162	-0.0161	-0.0161
	Contact	-0.0161	x	-0.0157	-0.0161	x	-0.0161	-0.0160
	Cryogenic	-0.0161	-0.0161	-0.0161	-0.0161	-0.0161	-0.0161	-0.0161

Table C.7: Land use impacts (kg C deficit/kg cut) after re-allocation of byproducts and avoided production

Market	Technology	Loin/ Belly	Neck bone / Ribs	Ham	Tongue/ Heart	Feet	Minced Meat	Average per tech., all cuts
Denmark	Impingement & spiral	488.29	488.28	488.36	488.25	488.22	488.27	488.28
	Immersion	488.29	488.29	488.37	488.26	488.23	488.28	488.29
	Chilling room	488.28	488.28	488.36	488.25	488.22	488.27	488.28
	Contact	488.28	x	488.36	488.25	x	488.27	488.28
	Cryogenic	488.29	488.29	488.36	488.25	488.22	488.27	488.28
China/ Australia	Impingement & spiral	488.89	488.89	488.97	488.86	488.83	488.88	488.89
	Immersion	488.90	488.90	488.98	488.87	488.84	488.89	488.90
	Chilling room	488.89	488.89	488.97	488.86	488.83	488.88	488.89
	Contact	488.89	x	488.97	488.86	x	488.88	488.89
	Cryogenic	488.90	488.89	488.89	488.86	488.83	488.88	488.88

Table C.8: Impacts for farming and processing per kg of ham, before and after re-allocation of byproducts and avoided production (i.e. without super-chilling and transport to final market).

Indicator per kg	Before	After	% change
Climate change (kg CO ₂ -e)	4.036	3.426	15% better
Acidification (molc H ⁺ eq)	0.073	0.065	12% better
Terrestrial eutrophication (molc N _{eq} /kg)	0.358	0.336	6% better
Marine eutrophication (kg N eq)	0.052	0.054	3% worse
Freshwater eutrophication (kg P eq)	0.001	-0.001	173% better
Water resource depletion (m ³ water)	0.009	-0.016	268% better
Land use (kg C deficit) – before	417	488	17% worse