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Decarbonising meat: exploring greenhouse gas emissions in the meat sector

S.I. aan den Toorn[a]*, M.A. van den Broek[a], E. Worrell[a]

[a]*Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3508 CT Utrecht, The Netherlands*

Abstract

Consumption of meat is an important source of global greenhouse gas (GHG) emission and deep decarbonisation of the whole meat production chain is required to be able to meet global climate change (CC) mitigation goals. Emissions happen in different stages of meat production ranging from agricultural input production, feed production, livestock production to slaughtering, meat processing, and retail. An overview of direct emissions from processes in the meat sector themselves and indirect emissions from energy consumptions would provide a clearer picture for potential CC impact reduction. This paper explores the total GHG emissions and data availability within the meat sector of the pig, chicken, and cattle meat product system. Through statistical data provided by FAOSTAT and supplementary data from literature, the CC impacts of energy use and process GHG emissions in the pig, chicken and cattle meat life cycle are estimated. Cattle dominates, but pig and chicken meat have a sizable amount of GHG emissions with a relatively high contribution from agricultural inputs and post-farm processes. However, uncertainty and unavailability of data are large for the energy consumption, direct GHG emissions, and product flows of post-farm and agricultural input processes. In order to gain a more complete understanding of the total CC impacts of the meat sector, further research is necessary to reduce the uncertainty in the considered life cycle stages and to quantify the processes and meat products that have been excluded from this study.

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Keywords: Meat sector; decarbonisation; climate change; greenhouse gases; energy use

* Corresponding author. Tel.: +31-30-253-3145.
E-mail address: s.i.aandentoorn@uu.nl

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1. Introduction

Consumption of meat is an important source of global greenhouse gas (GHG) emission. Therefore, deep decarbonisation of the whole meat product system is required to meet global climate change (CC) mitigation goals. The global livestock production chain was estimated to be about 7 Gt CO2-eq [1] in 2005 with an update in process estimating emissions in 2010. However, the calculations and sources are not always transparent and it is clear that updates require significant time.

Instead, basing calculations on global statistical data could improve transparency and reduce data gathering efforts. This improvement is limited by aggregated statistical data for pre- and post-agricultural emissions into different industry categories or a lack of data, though literature may be used to estimate these based on statistical data.

This paper explores the data availability of total process GHG emissions and energy consumption of the pork, chicken, and beef. The results are an initial estimation of total global GHG emissions of the meat sector and an overview of the data availability within the product system.

2. Methods

The global CC of the meat sector from a life cycle perspective was quantified using statistical data and literature data (fig. 1). This study includes GHG emissions resulting from processes in the life cycle stages and from energy consumption, though it excludes emissions and energy for the production of other material inputs. Statistical data from FAOSTAT [6] and IEA were used to determine global energy use, CO_2, CH_4, and N_2O emissions when available. Literature was used to estimate values where statistical data gaps exist.

The calculation of CC impact requires the conversion of GHG emissions into CO_2-eq using the GWP_{100} factors defined by IPCC AR5 [2]. To convert energy data into CO_2 emissions, IEA [3,4] data on GHG emissions were linked to data on total primary energy, fuel, oil, natural gas, and electricity consumption (table 1). When the energy source for energy consumption is explicitly given, or can be inferred, the corresponding emissions per energy unit are assigned to calculate GHG emissions. For unspecified energy sources, the total fuel consumption values are taken instead, as it represents the total energy and emissions of all fossil fuel combustion combined.

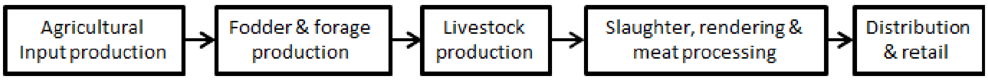

Fig 1: Life cycle stages of the meat sector product system

Table 1: Total primary energy and total fuel, oil and electricity consumption with related GHG emissions from combustion in 2014

Energy type	Energy [a]	GHG emissions [b]	Emissions per energy unit
	PJ	Mt CO2-eq	Mt CO2-eq per PJ
Total primary energy	573,550	32,381	0.06
Total fuel	394,606	32,381	0.08
Oil	157,448	10,973	0.07
Natural gas	59,585	6,363	0.11
Electricity and heat	99483	13,625	0.14

[a] Data from [3], [b] Data from [4]

3. Results and Discussion

3.1. Synthetic fertilizer and pesticide production

Synthetic fertilizers are dominated by nitrogen, phosphorus and potassium fertilizers, either as a single substance or in various combinations. The main source of nitrogen is the Haber-Bosch process producing NH_3 which can be further processed into other nitrogen-containing compounds [5]. The dominant sources of phosphorus and potassium are rocks containing these elements which are further processed by chemical and physical means (Aguilera et al 2015).

Quantitative data on the production and consumption of synthetic fertilizers for the agricultural sector is available from FAOSTAT [6]. In 2014, the consumption of each major fertilizer nutrient was 109 Mt N, 47 Mt P205, and 38 Mt K20. The specific energy in literature did not specify the energy source besides natural gas for nitrogen production [7,8]. Process CO_2 emissions occur through the use of natural gas in NH_3 production and the conversion of ammonium nitrate to calcium ammonium nitrate, but the energy intensive processes also results in GHG emissions. The total GHG emissions for total fertilizer production have been estimated (table 2).

Table 2: Global energy use and related GHG emissions of fertilizer production in 2014 [a]

Fertilizer	Specific energy		Amount [b]	Energy	GHG emissions
	Natural gas	Unspecified			
	MJ/kg	MJ/kg	Mt	PJ	Mt CO2-eq
Nitrogen (N)	49-118 (69.5)		109	5338-12855 (7571)	570.0-1372.7 (808.5)
Phosphorus (P205)		0.3-4.6 (7.7)	47	14-215 (360)	1.1-17.6 (29.5)
Potassium (K20)		6.5 (6.4)	38	245 (241)	20.1 (19.8)

[a] Values within parenthesis from [7], outside from [8], [b] Amounts taken from [6]

The wide variety of pesticides and commercial confidentiality inhibits generalizing production processes [9]. Pesticides are classified into eight groups [6]: herbicides, fungicides and bactericides, insecticides, mineral oils, disinfectants, rodenticides, plant growth regulators, and other pesticides.

FAOSTAT [6] includes quantitative data on a variety of pesticides, but the data only covers 72-74 countries for 2014. Existing quantifications of specific energy consumption herbicides, fungicides, and insecticides date from studies in 1987 and older [9]. Though the information is outdated and does not cover all pesticide product groups, a rough estimate of the GHG emissions from pesticides can be calculated (table 3). The result is a total of 15.9 Mt CO_2-eq which is likely to be an underestimation because the total active ingredients do not cover all countries.

Table 3: Global energy use and related GHG emissions of pesticides in 2014[a]

Pesticide	Specific energy			Amount ai [b]	Energy			GHG emissions
	Oil	Electricity	Steam (unspecified)		Oil	Electricity	Steam (unspecified)	
	MJ/kg ai	MJ/kg ai	MJ/kg ai	Kt ai	PJ	PJ	PJ	Mt CO^2-eq
Herbicide	9.4	80.6	56.7	575	5	46	33	9.4
Fungicide	5.8	52.8	36.2	370	2	20	13	3.9
Insecticide	7.5	79.1	41.3	177	1	14	7	2.6

[a] Specific energy values [9], total amount of ai [6], [b] Active ingredient

3.2. Water production

Water extraction and usage data is often outdated and limited, but [10] estimates 70% of all freshwater is used for irrigation. The production of irrigation and drinking water for agriculture requires extraction from ground or surface sources. This water can either be transported to storage facilities for direct use or to water treatment plants after which the water is kept in separate storage for distribution and usage.

Total extraction of groundwater in 2010 is estimated to be 1000 km^3, 67% of which is used for irrigation [11]. No estimation is given of surface water extraction, but in 2000 the total irrigation water was estimated to be around 2500 km^3 [10]. Energy is required for pumping and treatment of water and estimates for the electricity requirement to make water potable are given in the same report. Irrigation water needs either little or no treatment, but the UNESCO electricity inputs fall within the range of energy use for extracting surface and ground water as given by the Plapally and Liendhard [12] case studies in California, Australia, Canada and Spain. To make an initial estimation of the GHG emissions for irrigation water, the total extracted water for irrigation is assumed to be 2500 km^3 with 1830 km^3 being surface water (table 4).

Table 4: Global energy use and related GHG emissions of water extraction in 2014 [a]

Source	Extracted	Specific energy - electricity	Electricity	GHG emissions
	km^3	kWh/m^3	(PJ)	Mt CO^2-eq
Surface	1,830	0.37	2,437.6	333.8
Ground	670	0.48	1,157.8	158.6

[a] Specific energy values [10]

3.3. Fodder and forage production

Fodder crop production requires the application of irrigation water, pesticides, synthetic fertilizers and manure. Pasture systems can also utilize pesticides, synthetic fertilizers and manure, but generally to a lesser extent and in some cases irrigation systems takes place to ensure that forage crops have enough water.

Annual commercial feed production in 2015 is estimated to be around 1000 Mt [13]. This is grown on arable cropland and does not include non-commercial production and forage from the 33 Mkm^2 of permanent pastures. Energy is required to spread agricultural inputs for commercial feed production and specific energy consumption values are given for synthetic fertilizers and the electricity requirement for water irrigation systems (table 5). The energy for applying fertilizers and pesticide is not specified, but is assumed to be oil for equipment and the assumption was made that the specific energy of pesticides is equal to potassium as no values were found for pesticides. Calculating GHG emissions of applying inputs for feed production requires more assumptions. The first is that all agricultural inputs go into croplands as they are more intensively managed than pastures. Livestock is estimated to consume 36% of all cereals [14] which for this calculation is assumed to hold for all crops, so 36% of croplands is assumed to be used for the production of feed.

Another source of GHG emissions is the volatilization of nitrogen from applied synthetic nitrogen fertilizer and manure which results in N_2O emissions. FAOSTAT [6] has quantified these emissions, but not for feed production specifically. As pasture is not suitable for most crops, it is assumed that all pasture is used as grazing land which allows the GHG emissions related to feed to be estimated (table 6).

Table 5: Global energy use and related GHG emissions of applying agricultural inputs for feed production in 2014[a]

Input	Total amount		Amount for feed		Oil requirement	Specific energy	Oil	Electricity	Emissions
	Mt	km3	Mt	km3	MJ/kg	kWh/m3	PJ	PJ	Mt CO2-eq
N fertilizer	102		36.7		1.6		58.8		4.1
P fertilizer	47		16.9		1.5		25.4		1.8
K fertilizer	38		13.7		1.0		13.7		1.0
Pesticide	1		0.4		1.0b		0.4		0.0
Water		2500		900		0.024 - 1.3		77.8 - 4212.0	10.6 - 576.9

[a] Specific energy values of fertilizers [7], water [12], [b] No value, conservative estimate taken from K fertilizer

Table 6: Global GHG emissions of fertilizer application in 2014[a]

Source	Fertilizer consumption total	Fertilizer for feed	N2O emissions	Emissions
	Mt of N-nutrient	Mt of N-nutrient	Mt N2O	Mt CO2-eq
Synthetic fertilizer	102	37	0.8	203.0
Manure on cropland	41	15	0.2	59.0
Manure on pasture	128	128	2.7	722.9

[a] Data from [6]

3.4. Livestock production

Pigs, chicken and cattle together are the source of 88% of all boned meat [6]. Raising livestock requires feed, water, well-ventilated housing at suitable temperatures for the given species, and adequate manure handling which are highly mechanised for intensive livestock systems [15], though cattle is also raised extensively on pastures. The total live weight of animals for slaughtering in 2014 was calculated based on FAOSTAT [6] data of produced pig, chicken and cattle meat defined as fresh, chilled, or frozen meat with bone in it. This was linked to information that relates cold carcass weight to live weight [16] resulting in a total live weight of 159Mt, 146 M and 121 Mt for pig chicken and cattle, respectively.

IFIF [13] estimates that of the 1000 Mt of feed 45% goes to poultry, 26% goes to pigs, and 20% goes to cattle and other ruminants. Global estimates of livestock drinking water have not been found and will not be further considered in this study, but a study by Maupin et al [17] showed that in the USA about 1% of fresh water is used for livestock. Keeping livestock also uses energy for heating, ventilation, feeding and other requirements. Pig production is estimated to require 0.42 kWh/kg live weight of which 46% is for heating and 39% for ventilation [18]. Ventilation is assumed to consume electricity, but the energy source of heating and other equipment is unspecified. By assuming that specific energy for pigs holds true for chicken and cattle, an estimation of the GHG emissions resulting from the energy use in livestock production can be given (table 7).

Livestock production also has direct GHG emissions through enteric fermentation and manure waste management (table 8). The impact on CC is dominated by the emissions of cattle enteric fermentation followed, other animals have a sizable impact.

Table 7: Global energy use and related GHG emissions for livestock production in 2014[a]

Livestock	Total live weight	Specific energy - electricity	Specific energy - unspecified	Electricity	Unspecified energy	GHG emissions
	Mt	MJ/kg	MJ/kg	PJ	PJ	Mt CO2-eq
Pig	159	0.6	0.9	93.5	146.2	24.8
Chicken	146	0.6	0.9	85.9	134.4	22.8
Cattle	121	0.6	0.9	71.5	111.8	19.0

[a] Specific energy data [18]

Table 8: Global GHG emissions of enteric fermentation and manure waste management in 2014 [a]

Source	Enteric fermentation	Manure waste management		Total emissions
	Mt CH4	Mt CH4	Mt N2O	Mt CO2-eq
Cattle	72.49	4.01	0.25	2,208.27
Pig	1.13	3.65	0.12	166.01
Chicken	0.00	0.67	0.04	29.99
Other	25.67	1.44	0.06	774.74

[a] Data from [6]

3.5. Slaughtering, Rendering, and Meat processing

When the livestock is ready for slaughtering, the animals are sent to the abattoir where cattle, pork, and chicken each have their specific processing steps [19,20]. The resulting products are meat cuts and edible offal that can undergo further meat processing with by-products for rendering, and other products like hides in the case of cattle.

Global boned meat production is 115 Mt of pork, 100 Mt of chicken, 65 Mt of cattle and 38 Mt of other animals as mentioned before. Different estimations are calculated for the slaughtering outputs (table 9), based on three studies and using the live weights calculated earlier. The outputs have different definitions of the meat output and some other differing outputs. To estimate the GHG emissions from energy use in slaughtering, the primary specific energy values of Ramirez et al [20] are used (table 10).

Table 9: Global slaughtering outputs in 2014

Livestock	Retail cuts	Boned meat	Meat	Rendering material	Hide	Edible offal	Blood	Miscellaneous	Waste
	Mt	Mt	Mt	Mt	Mt	Mt	Mt	Mt	Mt
Pig	88.8a	101.5b		31.7 - 36.0a,b		9.2 - 15.9 a,b	4.8b	4.8b	
Chicken	82.3a			50.5a		2.8a			
Cattle	45.3a	46.1b	43.9c	27.3 - 50.5a,b,c	10.1 - 10.9a,b ,c	3.6 - 5.8 a,b,c	3.6b	7.9b	36.1c

[a] Data from [16], [b] Data from [21], [c] Data from [22]

Table 10: Global energy use and related GHG emissions for slaughtering in 2014[a]

Meat	Amount	Specific energy - primary energy	Energy	GHG emissions
	Mt	MJ/t	PJ	Mt CO2-eq
Pork	115	2097	241.8	13.7
Chicken	100	3096	310.7	17.5
Beef	65	1390	89.9	5.1

[a] Primary specific energy values [20]

The by-products from the slaughterhouse are treated through a variety of rendering processes. Ramirez et al [6] highlight cooking, preheating, pressing, centrifuge, evaporation, drying and sterilization as the main processes. UNEP [21] identifies a different set of processes: crushing, sterilisation and drying, condenser, percolating pan, fat refining, pressing and milling. Ramirez et al [23] describe the steps as rendering material first being ground before going through a disk dryer or cooker with vapor going to a condenser or to a thermal oxidizer. The remaining dry material is pressed to separate solids and fats, the former is ground to create protein meal and the latter is sold as animal fat such as tallow.

The materials for rendering have been calculated earlier, but two estimations have been found on the energy input requirements of processing raw rendering materials. These are used together with the Wiedemann and Yan [16] rendering estimates to calculate the related GHG emissions (table 11).

Table 11: Global energy use and related GHG emissions for rendering in 2014[a]

Source	Total rendering material [b]	Specific energy - primary energy	Energy	GHG emissions
	Mt	MJ/t	PJ	Mt CO2-eq
Pig	36	2293 - 3296 (1625)	83.6 - 120.1 (59.2)	4.7 - 6.8 (3.3)
Chicken	50	2294 - 3296 (1625)	115.7 - 166.4 (82.0)	6.5 - 9.4 (4.6)
Cattle	50	2295 - 3296 (1625)	115.8 - 166.4 (82.0)	6.5 - 9.4 (4.6)

[a] Values inside parentheses based on [20], outside [23], [b] Rendering calculations based on Wiedemann and Yan [16]

The carcasses from the slaughterhouse requires further processing before being distributed and sold to customers. Carcasses can be cut into sellable meat pieces or they can be further processed. These processed meat products require different combinations of different processing methods each with energy inputs and some with their own CO_2 emissions. However, no quantitative data and estimates have been found on the quantity of boned meat that is further processed. Without further information, it is not feasible to make an estimation.

3.6. Distribution and retail

To reach customers, the meat products have to be distributed to retailers which can be divided between food stores such as supermarkets and food service providers, for example restaurants and hotels. The key issues in this step are the need for effective storage, which requires packaging and refrigeration, and the attraction of customers by creating a pleasant atmosphere.

Global refrigerated warehouse capacity was 552.5 million m^3 in 2014 [25]. Refrigeration gas leakages are a direct source of GHG emissions, but the main contributor to CC is electricity consumption. This is estimated to be around 1300 TWh of electricity for the global refrigeration capacity [26] (table 12). No information has been found on the total capacity for meat refrigeration, so more specific calculations cannot be made. However, it does give an indication of the significance that refrigeration has for CC.

Table 12: Global energy use and related GHG emissions for refrigeration in 2014[a]

Refrigeration	Total electricity	Specific energy - electricity	GHG emissions per kWh	GHG emissions
	TWh	kWh/m3	kg CO2-eq/kWh	Mt CO2-eq
Chillers		4-250	0.2-13.2	
Freezers		6-240	0.3-12.7	
Mixed		23-157	1.2-8.3	
Total energy	1300			641.0

[a] Data from [26]

3.7. Life cycle

Using the above-mentioned data, an estimation is given of the total GHG emissions and the GHG emissions per kilogram for pig, chicken and cattle meat. The allocation of CC impacts to pig, chicken and cattle meat requires extra assumption to transform the process data into meat sector specific data (table 13):

- 36% of agricultural inputs into commercial feed production, 45% goes to chicken, 26% to pigs and 20% to cattle.
- Manure on cropland is treated as an agricultural input
- All pasture is assumed to be used for cattle grazing, emissions manure on pasture fully in cattle
- The rendering process is either included as a waste treatment with full allocation to meat (high value) or rendering materials are seen as a by-product with slaughter fully allocated to meat (0.0 value)
- Distribution and retail emissions are either not considered at all (0.0 value) or as fully belonging to the meat sector and proportionally divided (e.g. cattle total retail cuts/total retail cuts x 641 Mt CO_2-eq) (high value)

Table 13: Total GHG emissions of meat life cycle stages

	Pigs	Chicken	Cattle	Unit
Agricultural input production	103-180	178-311	79-138	Mt CO2-eq
Forage and fodder production	73-220	1268-381	779-892	Mt CO2-eq
Livestock production	191	53	2227	Mt CO2-eq
Slaughter, rendering, meat processing	14-21	18-27	5-15	Mt CO2-eq
Distribution and retail	0-263	0-244	0-134	Mt CO2-eq
Total GHG emissions	380.1 - 873.8	374.2 - 1014.9	3090.3 - 3406.1	Mt CO2-eq

3.8. Data availability

In general, more data is available on feed and livestock production compared to agricultural input production and post-farm processes. Meat processing, distribution and retail lack statistical data and research which complicates estimating the relative importance of these life cycle stages for the full life cycle. Even the data on meat products of FAOSTAT [6], which is meat sector specific, is problematic as different definitions for the meat output creates uncertainty in the calculated outputs of meat and other products. More research is needed to further quantify the physical flows of the researched life cycle stages.

4. Conclusions

With the available data, the CC impact of energy use and direct GHG emissions in the pig, chicken and cattle meat life cycle could be estimated. Though cattle meat dominates with an estimated 3090.3-3406.1 Mt CO2-eq, pig and chicken, with respectively 380.1-873.8 and 374.2-1014.9, have a sizable amount of GHG emissions which need to be addressed if the meat sector is to be decarbonised. Agricultural inputs and post-farm processes have a relatively high contribution to the total GHG impacts of chicken and pig meat, but not for cattle. Uncertainty and unavailability of data are largest in the output quantity, energy consumption and direct GHG emissions of post-farm and agricultural input processes. The estimates from this study cannot be taken as estimates for the meat sector as a whole, since transport, packaging, food waste, waste management, and meat from other species were excluded. In order to gain a more complete understanding of the total CC impacts of the meat sector, further research is necessary to reduce the uncertainty in the considered life cycle stages and to quantify the processes and meat products that have been excluded from this study.

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