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Carbon emissions from chilled and frozen cold chains for a typical UK Sunday roast chicken meal

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About RD&T

RD&T were formed in August 2009 from the refrigeration group at FRPERC (Food Refrigeration and Process Engineering Research Centre), University of Bristol. FRPERC was acknowledged as the leading research centre in the UK for work on refrigeration and food.

RD&T specialise in:

- Retail and commercial cabinet testing, development and optimisation.
- Design and optimisation of prototype refrigeration systems.
- Heat and mass transfer modelling.
- Energy reduction and optimisation of refrigeration facilities and systems.

RD&T consist of ex FRPERC employees Judith Evans, Tim Brown and Dr Alan Foster. RD&T are located on the University of Bristol's Langford campus (the site used by FRPERC). Refrigerated cabinet testing is carried out by the same personnel and uses the same facilities as those used by FRPERC when part of the University of Bristol.

RD&T are ISO 9001, 14001 and 18001 accredited.



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Executive summary

Carbon dioxide equivalent (CO_{2e}) emissions from the frozen and chilled cold chains for a typical UK Sunday roast meal for 4 persons were calculated. The meal consisted of chicken, peas, carrots and roast potatoes. In the assessment the emissions from post harvest or slaughter to consumption by the consumer were considered for:

1. Energy used to refrigerate the products.
2. Energy used for frying/roasting of the potatoes and for blanching of the frozen vegetables.
3. Energy used to bring the products from the supermarket to the consumers' homes.
4. Refrigerant emissions from the refrigeration systems throughout the cold chains.
5. Emissions associated with waste throughout the cold chains.

Only food produced in the UK was considered. This was due to the fact that the UK produces and supplies a large proportion of the foods considered in the study.

Data were collected from a range of sources, mainly peer reviewed publications, reports and research publications, but some information was obtained from other researchers and companies. Sources of data are referenced throughout the work.

An analysis of the emissions from the chicken, pea, carrot and potato cold chains was carried out. At each stage of these cold chains, the product which would typically be wasted was estimated and the weight of product at each stage which would be required to obtain the final meal weight was determined. A summary of the overall emissions are shown in Table 1.

The overall emissions from individual products are shown in Figure 1. The greatest emissions from the products considered were from potatoes followed by chicken. This was primarily due to the greater weight of these products in the meal (200 g per portion for potatoes and 125 g per portion for chicken). The emissions from carrots were slightly higher than from peas due to the greater waste from carrots.

The major differences in emissions between the frozen and chilled cold chains were due to differences in the energy used (which was less for chilled food) and the food waste (which was less for frozen). As waste was a significant factor in the emissions from frozen food, and the information available on waste from frozen foods was not extensive, it would be beneficial to obtain more detailed information on waste from frozen products,

Table 1. Emissions from a meal for 4.

	Chilled meal for 4 persons (kg CO _{2e})	Frozen meal for 4 persons (kg CO _{2e})
Emissions from all sources considered in the study	6.546	6.329
Emissions from energy (indirect)	2.982	4.239
Emissions from refrigerant emissions (direct)	0.076	0.131
Emissions from waste	3.488	1.960

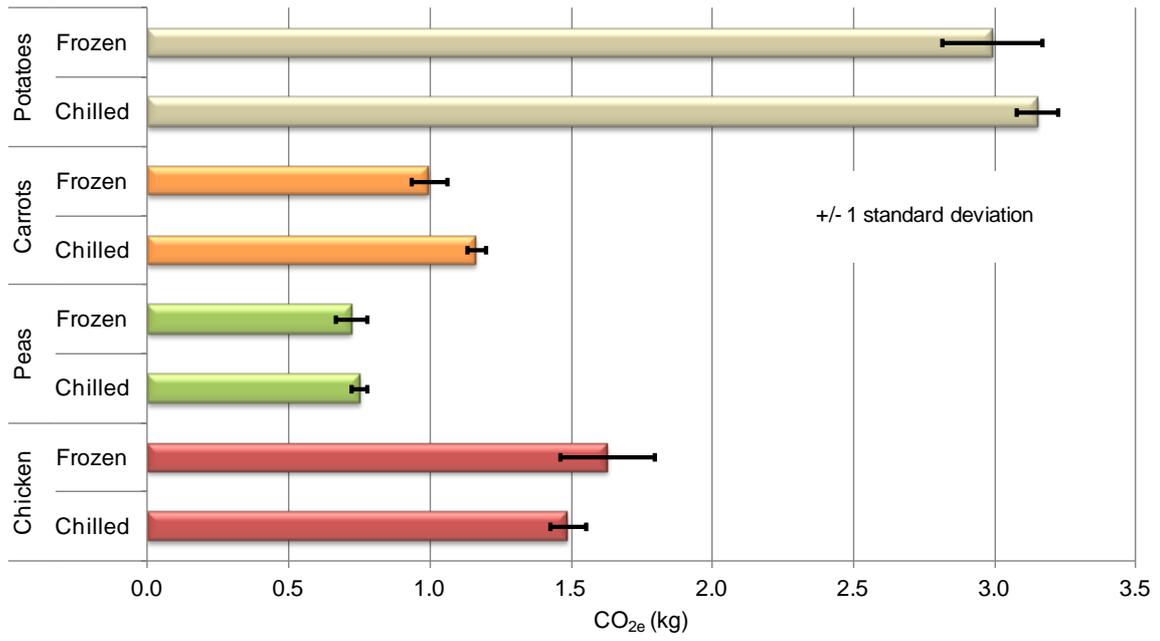


Figure 1. Overall emissions from products considered.

Aim

To compare the carbon dioxide equivalent emissions (CO_{2e}) associated with the production of a chicken roast dinner from frozen and chilled components, including emissions from the following sources:

1. Energy used for refrigeration of the food (chilling, freezing, retail and domestic storage).
2. Refrigerant loss.
3. Food waste.
4. Transport to the home (from supermarket).
5. Cooking of the meal in the home.
6. Blanching of vegetables in the primary food freezing stage.
7. Roasting/frying of roast potatoes in the primary processing stage and in the home.

Data collection and conversions

Data were collated from industry information, peer reviewed papers, conference publications, web sites and RD&T data.

Data were collected on all stages of the cold chains from harvest/slaughter to consumption by the consumer. The cold chains considered covered direct chains to the consumer (ignored any catering or meals out of the home).

All energy data were converted to specific energy consumption (SEC, kJ/kg). All energy figures were presented as end use energy (and not primary energy supply). If any sources presented information as primary energy this was converted to end use energy by assuming 40% electricity generation efficiency (i.e. primary energy divided by 2.5).

An electricity CO_{2e} conversion of 0.5246 kWh/kg CO₂ was used (Carbon Trust, 2011).

A natural gas CO_{2e} conversion of 0.1836 kWh/kg CO₂ was used (Carbon Trust, 2011).

A CO_{2e} conversion factor of 4.2 kg CO₂/kg of avoidable food waste (WRAP, 2009) was used and assumed to apply to all food waste (unavoidable as well as avoidable).

Refrigerant emissions were assessed through the Global Warming Potential (GWP) of the refrigerants used. GWP figures over a 100 year time horizon were taken from UNEP (2010) TEAP (Technology and Economic Assessment Panel).

All emissions were converted to, and presented as, CO_{2e}.

Study boundaries

The carbon emissions for chilled and frozen cold chains for a typical roast chicken Sunday roast were assessed for:

1. Chicken
2. Peas
3. Carrots
4. Potatoes

Any gravy added to the meal was ignored as it was considered to have identical carbon emissions for chilled and frozen meals.

The system boundaries for the study are shown in Figure 2. The work excluded any emissions associated with the food prior to the point that the food entered the primary processing stage and covered emissions from energy usage, refrigerant emissions and waste from each stage of the cold chain shown in Figure 2. Emissions prior to the food entering the processing stage were considered to be identical for chilled and frozen foods and therefore in this comparative study they could be ignored.

The study was constrained to emissions for production of the meal and excluded energy used by any associated process (e.g. offices, dry good storage in supermarkets, non refrigerated and non cooking energy in the home). The only exception to this was the blanching of vegetables (in the primary processing stage for frozen vegetables) and the roasting/frying of the roast potatoes (in the primary processing stage for frozen potatoes and in the home for chilled potatoes) which were included in the calculations. Blanching and frying are relatively energy intensive processes and fundamental to the frozen storage and meal preparation process and therefore it was considered to give an unfair advantage to the frozen cold chain if they were excluded. The study also excluded any emissions from the food packaging. As far as possible, like for like data for chilled and frozen products were analysed.

Only food from the UK was considered in the study. This was considered to be valid as the majority of annual consumption of each of the products evaluated is produced in the UK (Figure 3).

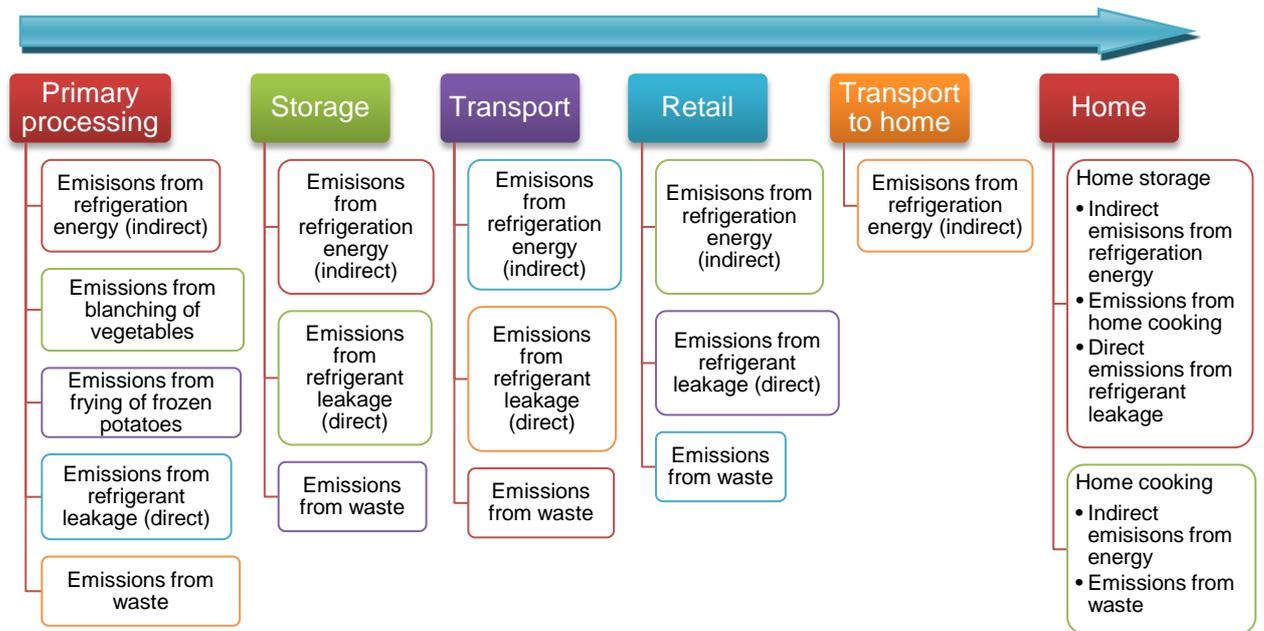


Figure 2. System boundaries for study.

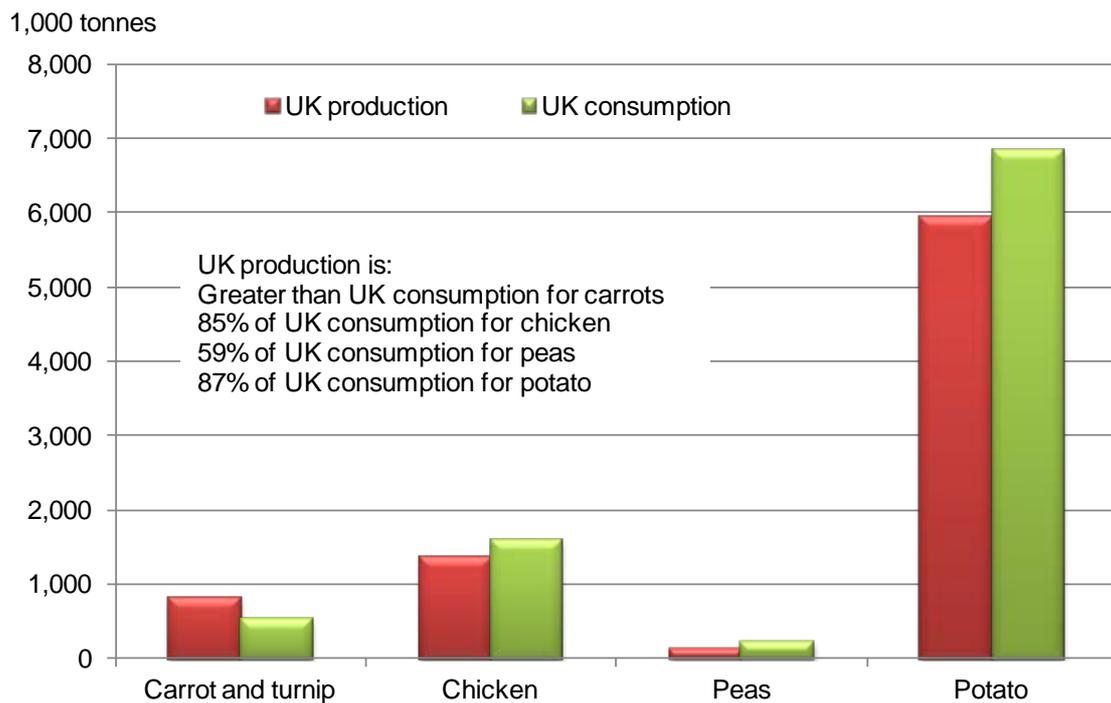


Figure 3. UK production of each food type considered (Audsley et al, 2009).

Typical meal

Carlsson-Kanyama et al (2003) provide information on constituents of a typical roast chicken meal (Table 2). The 465 g meal size was similar to roast chicken meal sizes of 400 and 430 g quoted by the FSA (2012) in their Foodbase database. The Carlsson-Kanyama data report cooked weight of food. It is unclear whether the Foodbase database reports cooked or uncooked weight of foods.

Table 2. Typical roast chicken meal constituents (Carlsson-Kanyama et al (2003)).

Constituent	kg per portion
Chicken	0.125
Peas	0.070
Carrots	0.070
Potatoes	0.200
Total	0.465
Water	0.150
Oil	0.020

Chicken

Chicken cold chains

Typical chilled and frozen cold chains for chicken are shown in Figure 4.

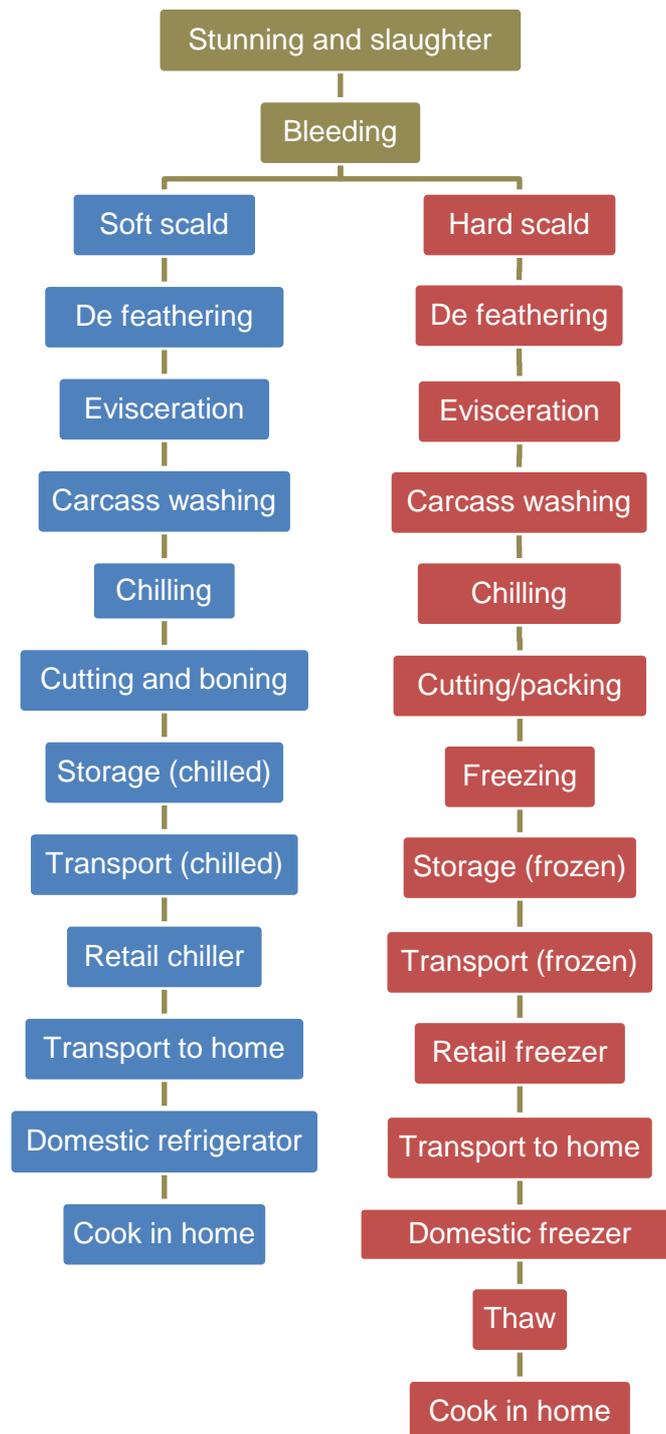


Figure 4. Typical chicken cold chains (blue for chilled, red for frozen).

Details of the calculation and assumptions made to calculate the emissions from the chicken cold chains are presented in Appendix 1.

Overall emissions associated with chicken

Totalised emissions from waste, energy and refrigerant loss for a meal for 4 persons are shown in Table 3 and Figure 5. Overall emissions from the frozen cold chain were 0.14 kg less CO_{2e} than the chilled chain.

Where possible standard deviations for the data used were calculated. Standard deviations for the waste and direct emissions could not be calculated as there were no replicate data. Figure 5 shows individual standard deviations for each stage (where available) for indirect emissions (energy) and Figure 6 shows the total emissions and total standard deviations for the indirect sources. It should be noted that standard deviations could not be calculated for chilled primary processing, frozen storage, chilled and frozen transport to the home and chilled and frozen cooking due to a lack of replicate data.

Table 3. All emissions in chilled and frozen chicken cold chains (for family meal for 4).

	CO _{2e} emissions	
	Chilled	Frozen
Waste (g)	464.0	266.6
Refrigerant emissions (direct) (g)	26.8	44.1
Energy consumption (indirect):		
Primary processing (g)	135.4	205.9
Storage (g)	0.3	5.1
Transport (g)	89.2	102.0
Retail (g)	19.1	60.0
Domestic-transport home (g)	47.2	48.5
Domestic-storage (g)	40.0	279.7
Domestic-cook (g)	663.9	614.4
TOTAL (g)	1486.0	1626.3
Total (kg)	1.49	1.63

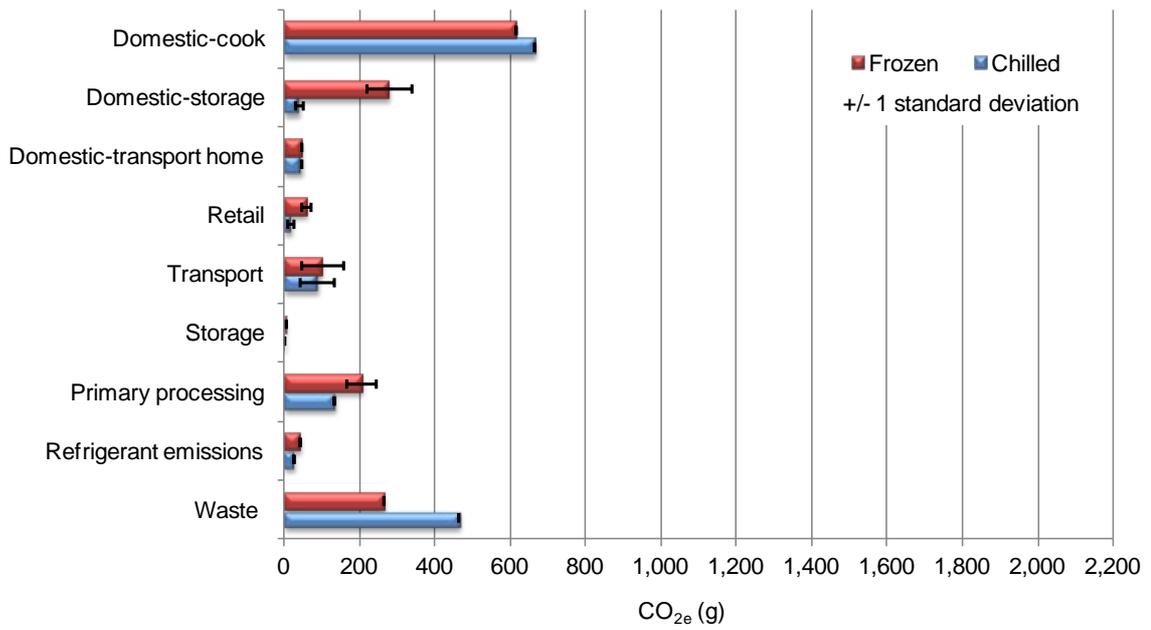


Figure 5. Emissions of CO_{2e} from the chicken cold chains for chilled and frozen product (for family meal for 4).

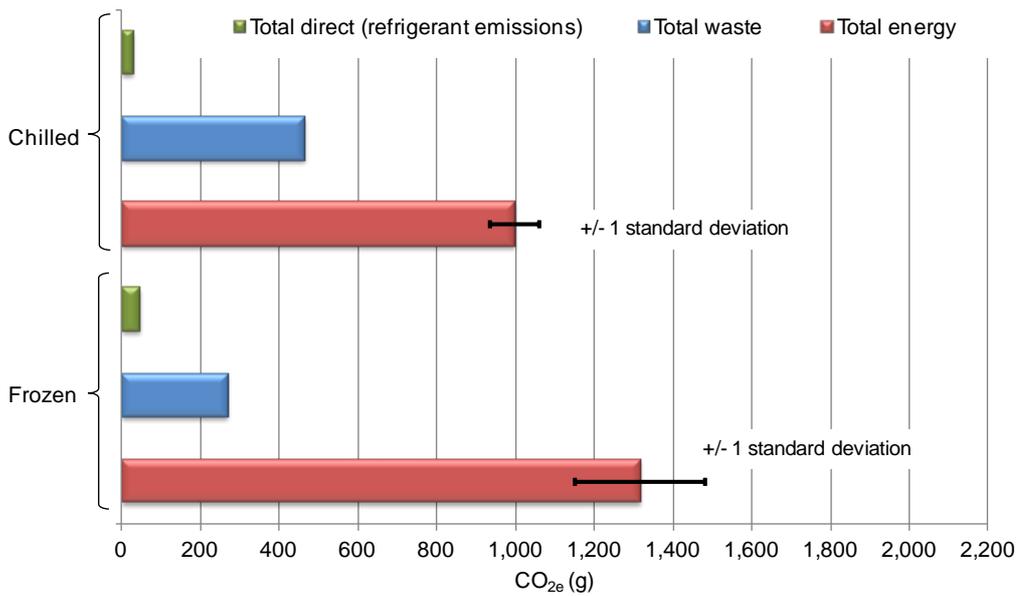


Figure 6. Total emissions (from energy, waste and direct sources) and standard deviations (where available) of CO_{2e} from the chicken cold chains for chilled and frozen product (for family meal for 4).

Peas

Pea cold chains

Typical chilled and frozen cold chains for peas are shown in Figure 7.

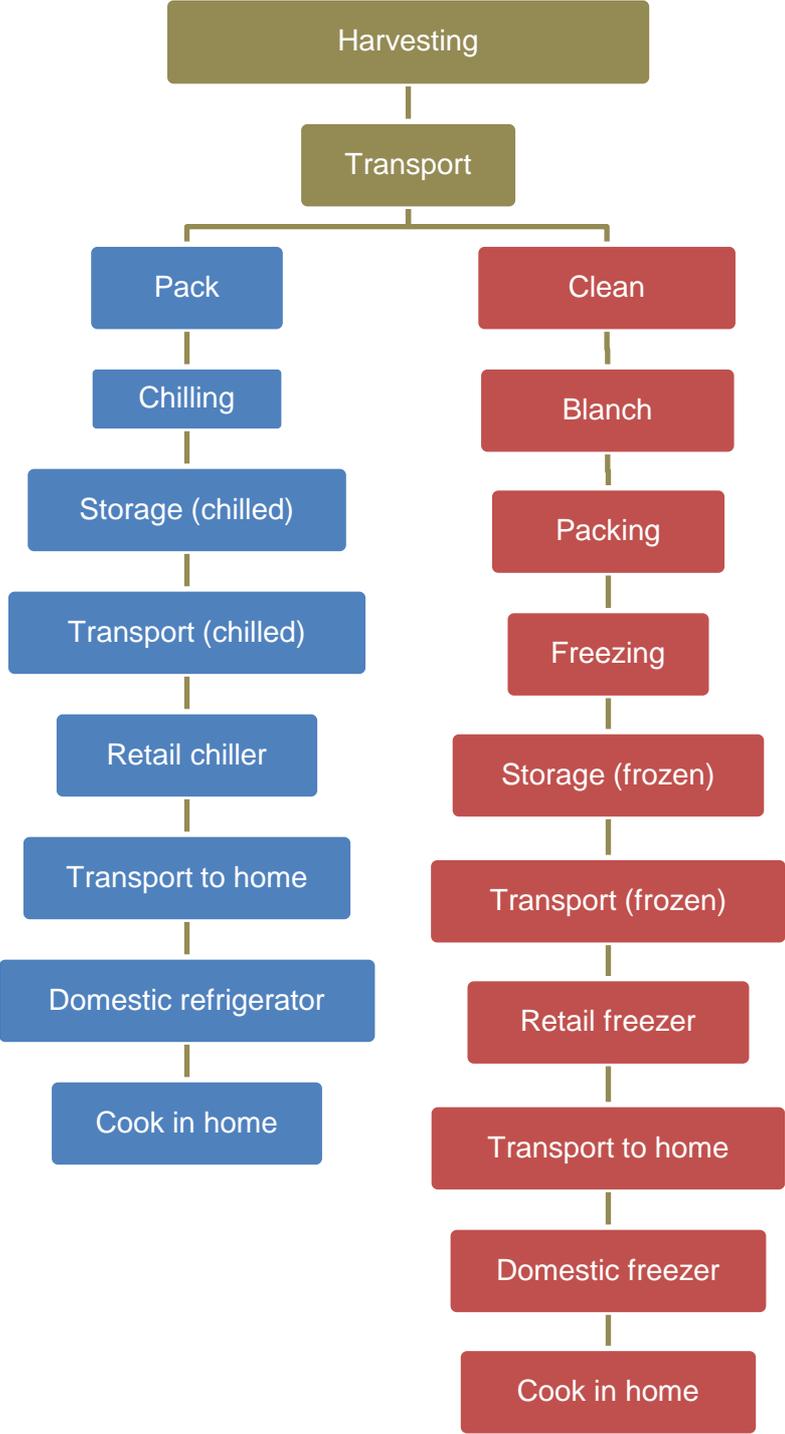


Figure 7. Typical pea cold chains (blue for chilled, red for frozen).

Details of the calculation and assumptions made to calculate the emissions from the pea cold chains are presented in Appendix 2.

Overall emissions associated with peas

Totalised emissions from waste, energy and refrigerant loss are shown in Table 4 and Figure 8. Overall emissions from the frozen cold chain were 0.03 kg less CO_{2e} than those from the chilled chain.

Where possible standard deviations for the data used were calculated. Standard deviations for the waste and direct emissions could not be calculated as there were no replicate data. Figure 8 shows individual standard deviations for each stage (where available) for indirect emissions (energy) and Figure 9 shows the total emissions and total standard deviations from the indirect sources. It should be noted that standard deviations could not be calculated for chilled and frozen storage, chilled and frozen transport to the home and chilled and frozen cooking due to a lack of replicate data.

Table 4. All emissions in chilled and frozen pea cold chains (for family meal for 4).

	CO _{2e} emissions	
	Chilled	Frozen
Waste (g)	369.1	145.2
Refrigerant emissions (direct) (g)	15.4	17.8
Energy consumption (indirect):		
Primary processing (g)	5.9	69.8
Storage (g)	0.4	9.2
Transport (g)	40.5	41.1
Retail (g)	7.5	26.9
Domestic-transport home (g)	19.5	19.6
Domestic-storage (g)	16.5	115.4
Domestic-cook (g)	274.0	275.3
TOTAL (g)	748.6	720.3
Total (kg)	0.75	0.72

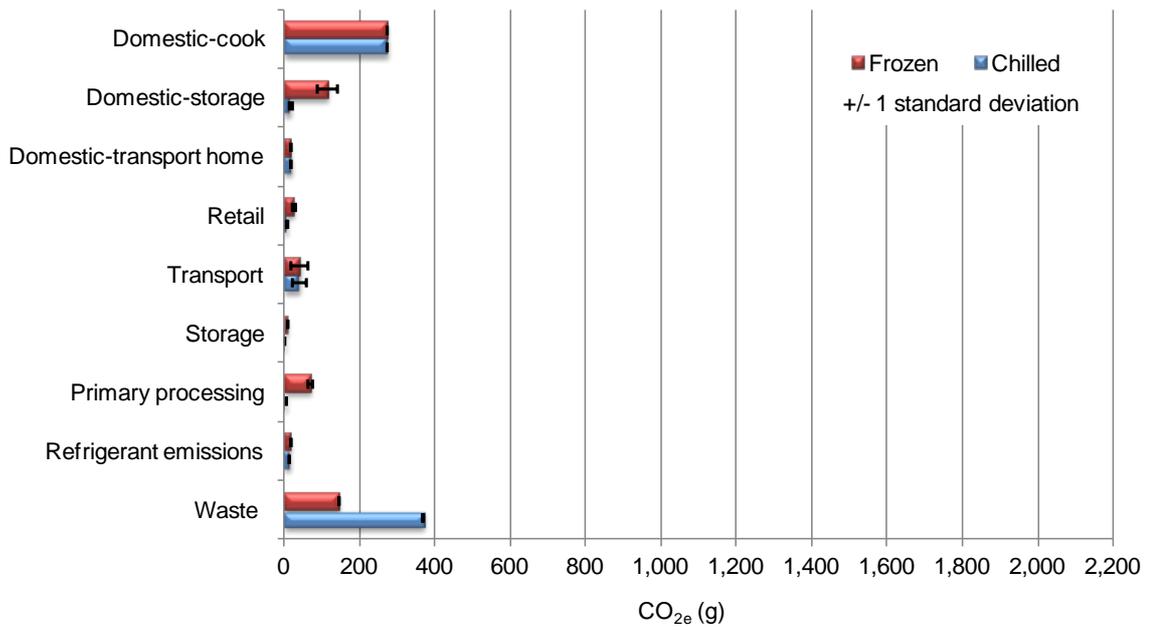


Figure 8. Emissions of CO_{2e} from the pea cold chains for chilled and frozen product (for family meal for 4).

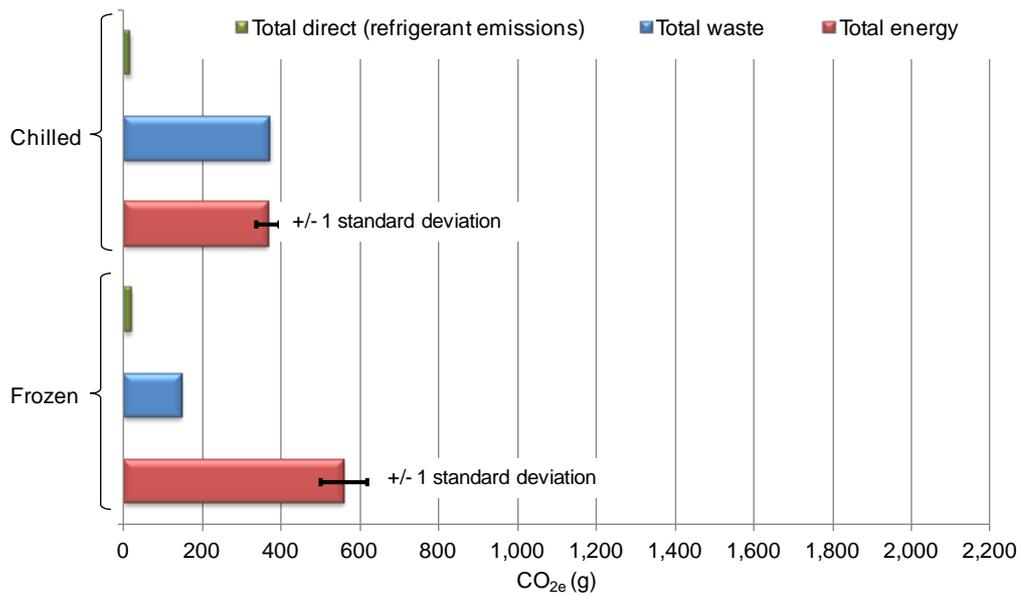


Figure 9. Total emissions (from energy, waste and direct sources) and standard deviations (where available) of CO_{2e} from the pea cold chains for chilled and frozen product (for family meal for 4).

Carrots

Carrot cold chains

Typical chilled and frozen cold chains for carrots are shown in Figure 10.

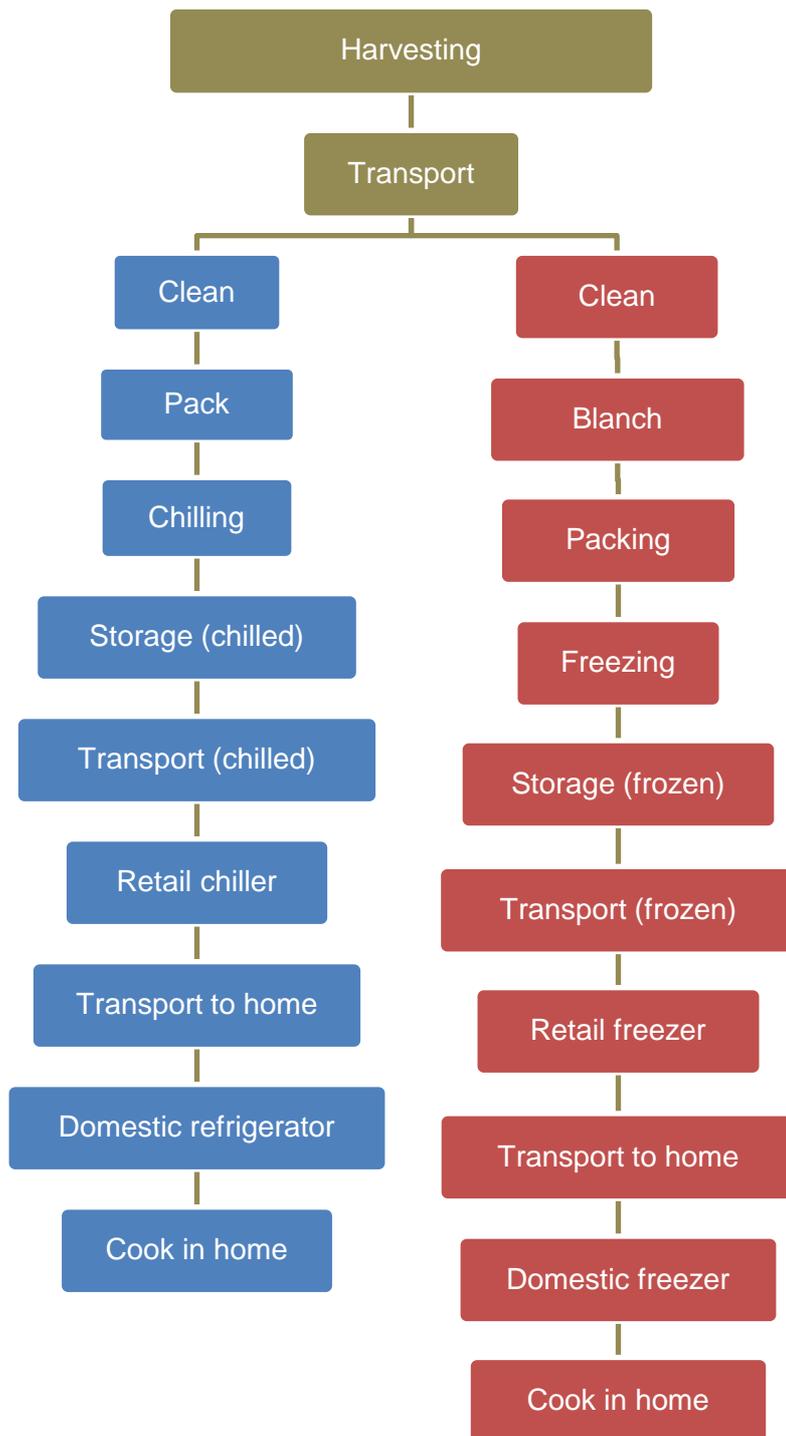


Figure 10. Typical carrot cold chains (blue for chilled, red for frozen).

Details of the calculation and assumptions made to calculate the emissions from the carrot cold chains are presented in Appendix 3.

Overall emissions associated with carrots

Totalised emissions from waste, energy and refrigerant loss are shown in Table 5 and Figure 11. Overall emissions from the frozen cold chain were 0.17 kg less CO_{2e} than those from the chilled chain.

Where possible standard deviations for the data used were calculated. Standard deviations for the waste and direct emissions could not be calculated as there were no replicate data. Figure 11 shows individual standard deviations for each stage (where available) for indirect emissions (energy) and Figure 12 shows the total emissions and total standard deviations from the indirect sources. It should be noted that standard deviations could not be calculated for chilled and frozen storage, chilled and frozen transport to the home and chilled and frozen cooking due to a lack of replicate data.

Table 5. All emissions in chilled and frozen carrot cold chains (for family meal for 4).

	CO _{2e} emissions	
	Chilled	Frozen
Waste (g)	628.6	395.7
Refrigerant emissions (direct) (g)	18.1	17.8
Energy consumption (indirect):		
Primary processing (g)	88.2	70.7
Storage (g)	1.4	10.3
Transport (g)	47.7	41.2
Retail (g)	8.8	26.9
Domestic-transport home (g)	23.2	19.6
Domestic-storage (g)	19.6	137.4
Domestic-cook (g)	326.1	275.4
TOTAL (g)	1,161.7	994.8
Total (kg)	1.16	0.99

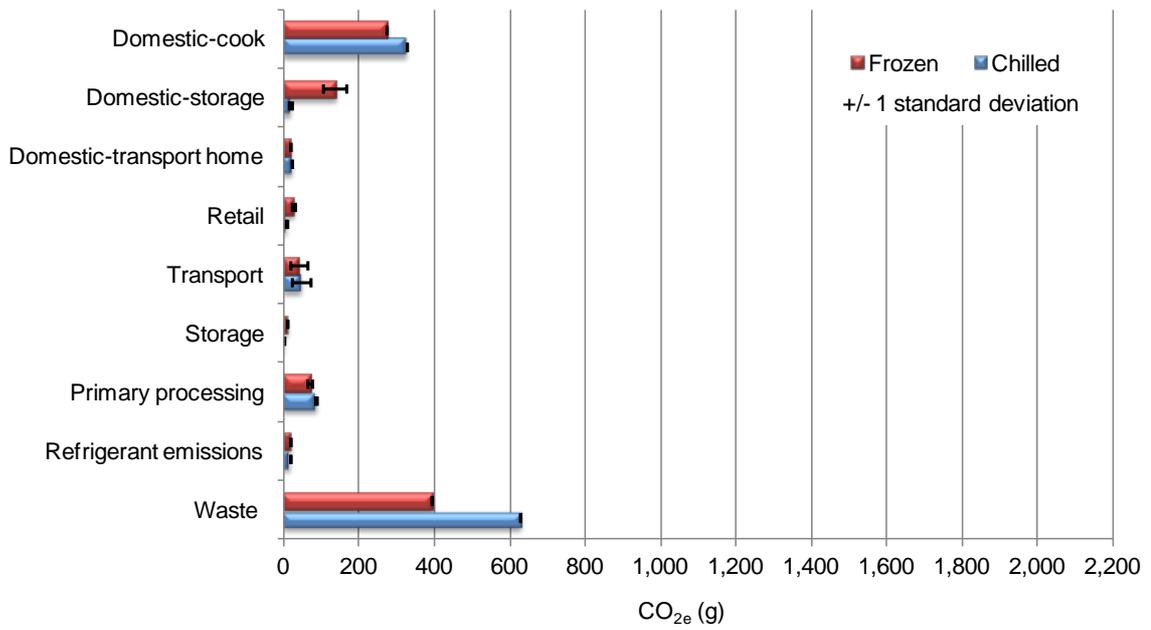


Figure 11. Emissions of CO_{2e} from the carrot cold chains for chilled and frozen product (for family meal for 4).

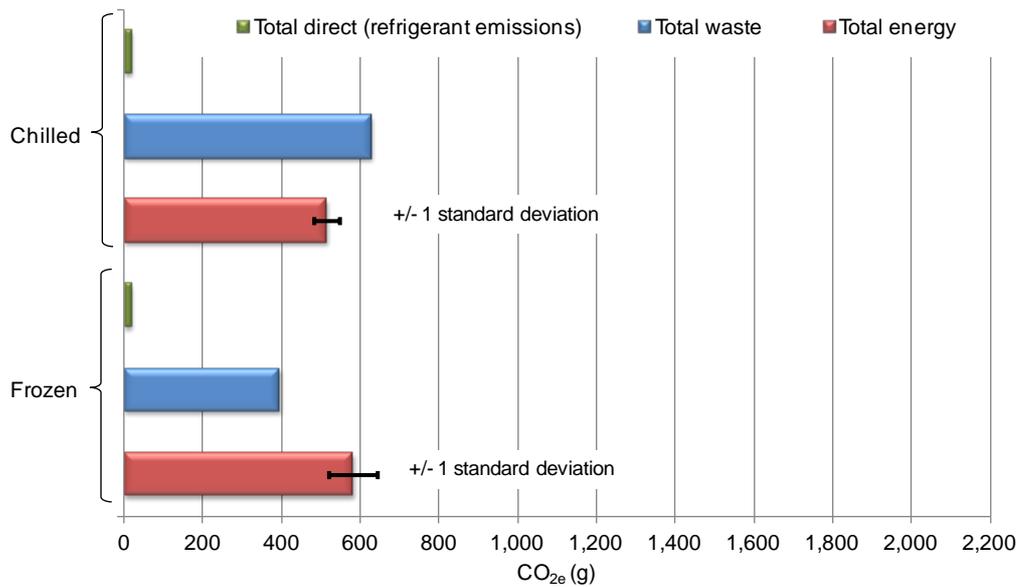


Figure 12. Total emissions (from energy, waste and direct sources) and standard deviations (where available) of CO_{2e} from the carrot cold chains for chilled and frozen product (for family meal for 4).

Potatoes

Potato cold chains

Typical chilled and frozen cold chains for potatoes are shown in Figure 13.

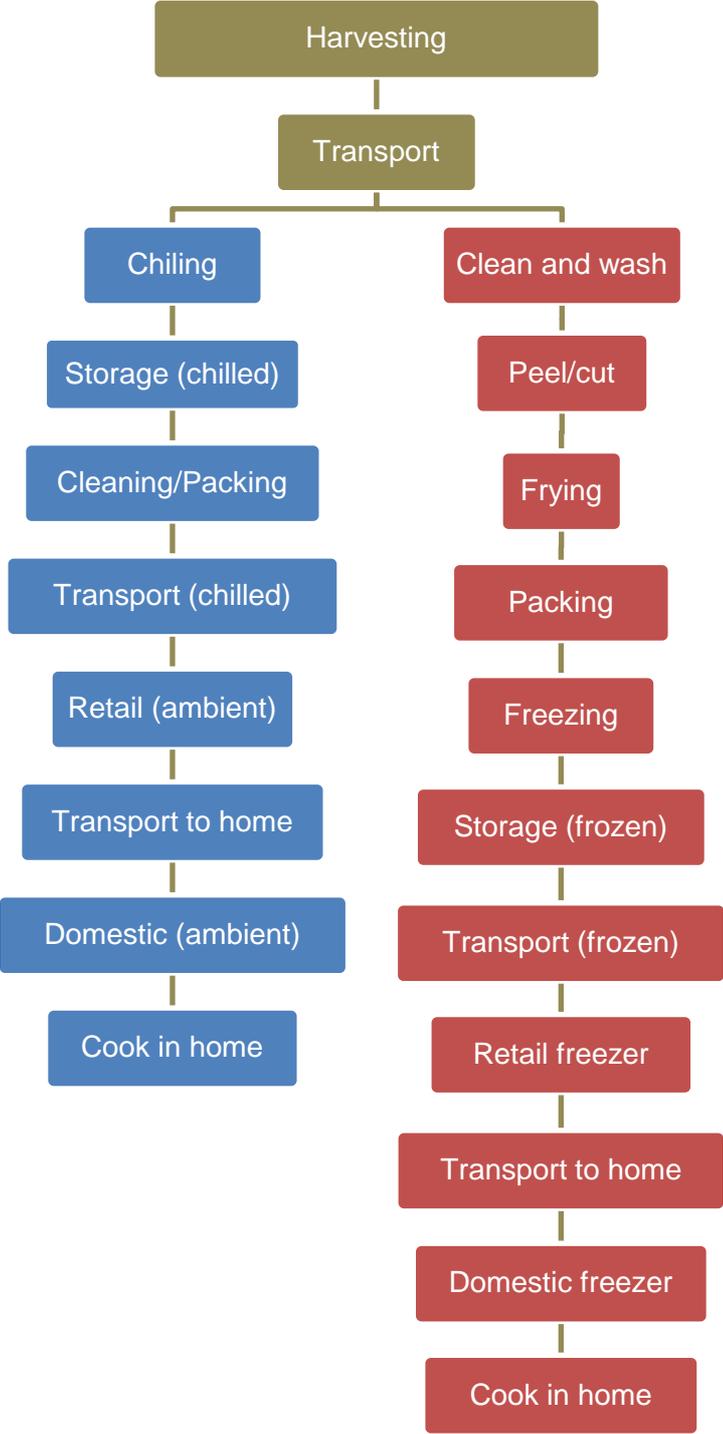


Figure 13. Typical potato cold chains (blue for chilled, red for frozen).

Details of the calculation and assumptions made to calculate the emissions from the potato cold chains are presented in Appendix 4.

Overall emissions associated with potatoes

Totalised emissions from waste, energy and refrigerant loss are shown in Table 6 and Figure 14. Overall emissions from the frozen cold chain were 0.16 kg less CO_{2e} than those from the chilled chain.

Where possible standard deviations for the data used were calculated. Standard deviations for the waste and direct emissions could not be calculated as there were no replicate data. Figure 14 shows individual standard deviations for each stage (where available) for indirect emissions (energy) and Figure 15 shows the total emissions and total standard deviations from the indirect sources. It should be noted that standard deviations could not be calculated for chilled and frozen transport to the home and chilled and frozen cooking due to a lack of replicate data.

Table 6. All emissions in chilled and frozen potato cold chains (for family meal for 4).

	CO _{2e} emissions	
	Chilled	Frozen
Waste (g)	2026.1	1152.2
Refrigerant emissions (direct) (g)	15.7	50.9
Energy consumption (indirect):		
Primary processing (g)	14.4	357.5
Storage (g)	5.7	25.6
Transport (g)	135.1	117.9
Retail (g)	0.0	64.2
Domestic-transport home (g)	63.2	56.1
Domestic-storage (g)	0.0	374.6
Domestic-cook (g)	889.1	788.7
TOTAL (g)	3,149.3	2,987.8
Total (kg)	3.15	2.99

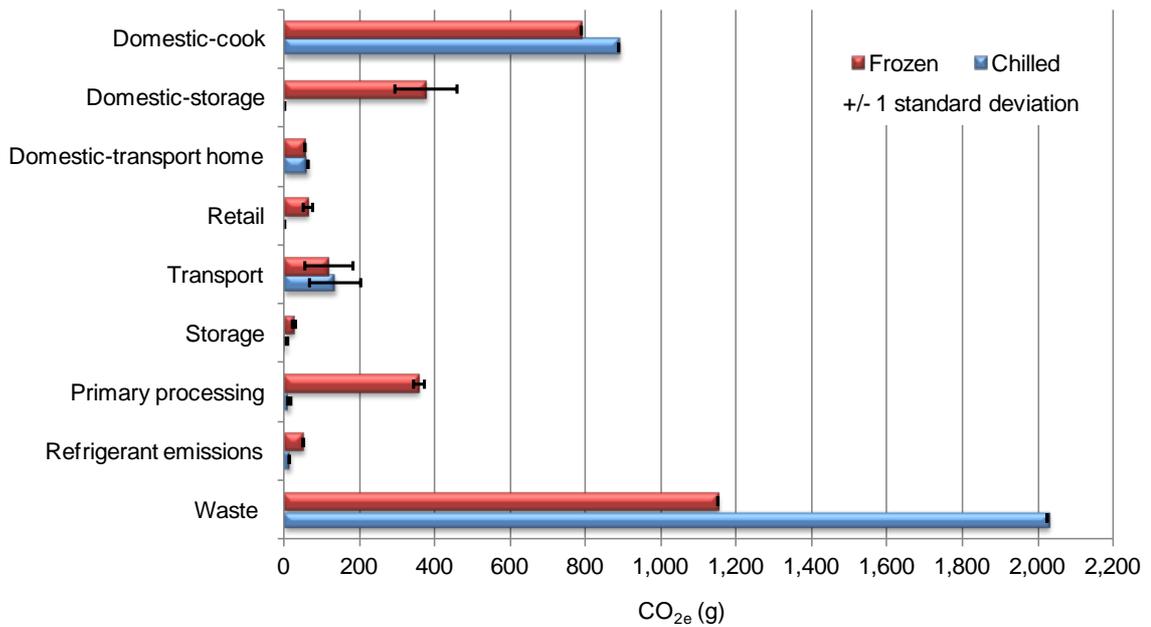


Figure 14. Emissions of CO_{2e} from the potato cold chains for chilled and frozen product (for family meal for 4).

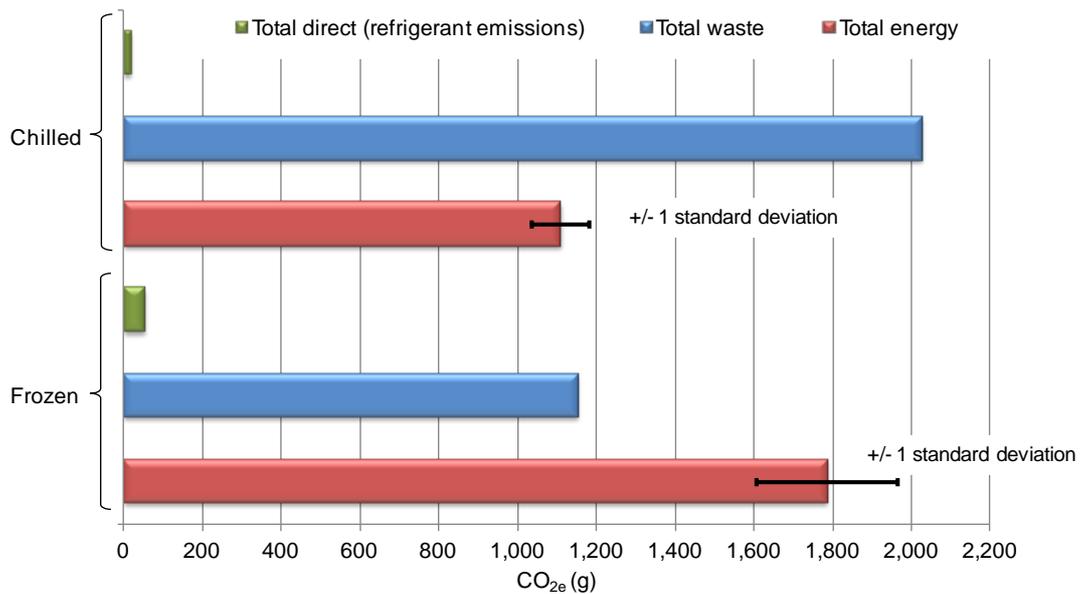


Figure 15. Total emissions (from energy, waste and direct sources) and standard deviations (where available) of CO_{2e} from the potato cold chains for chilled and frozen product (for family meal for 4).

Whole roast meal

Emissions from chicken, peas, carrots and potatoes were totalised as emissions associated with a meal for a family of 4 (Table 7). Total emissions in each stage of the cold chains examined are shown in Figure 16. Standards deviations are presented wherever possible as described in each section dealing with individual products. Total emissions for each constituent of the meal are shown in Figure 17 and totalised emissions for the whole chilled and frozen cold chains are shown in Figure 18.

Emissions from energy and refrigerant leakage were greater in the frozen cold chain than from the chilled cold chain. Excluding waste the emissions associated with the frozen meal for 4 were 4.37 kg CO_{2e} whereas the emissions associated with the chilled meal were 3.06 kg CO_{2e}. Emissions associated with waste were higher for the chilled meal: 3.49 kg CO_{2e} for the chilled meal compared to 1.96 kg CO_{2e} for the frozen meal.

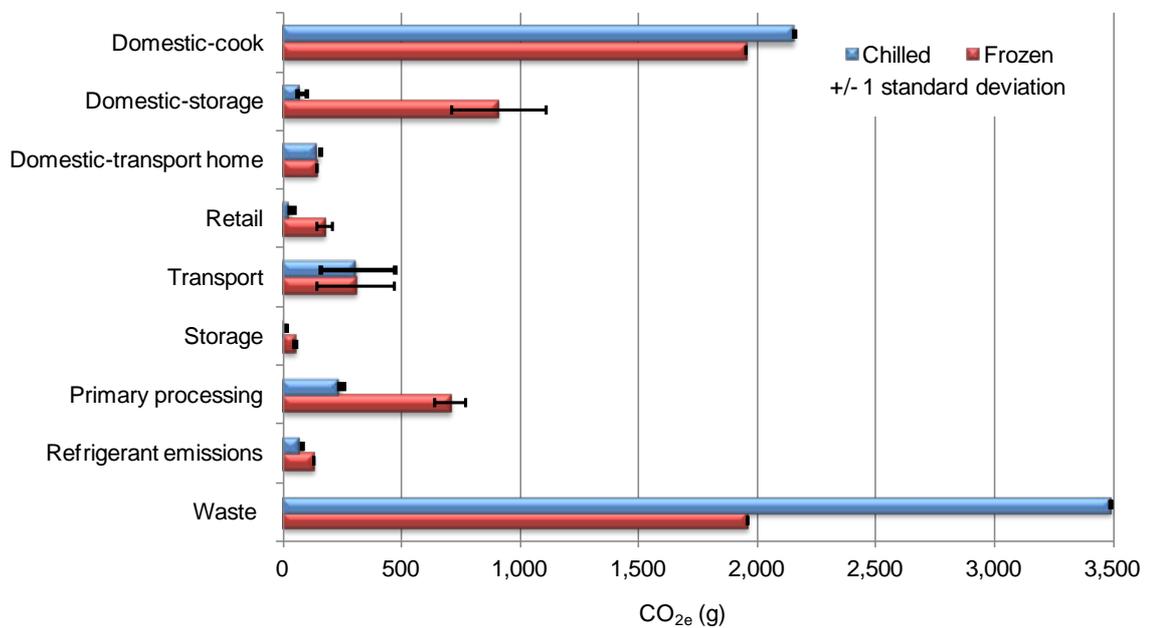


Figure 16. Total emissions in each stage of the cold chains for the chilled and frozen meals.

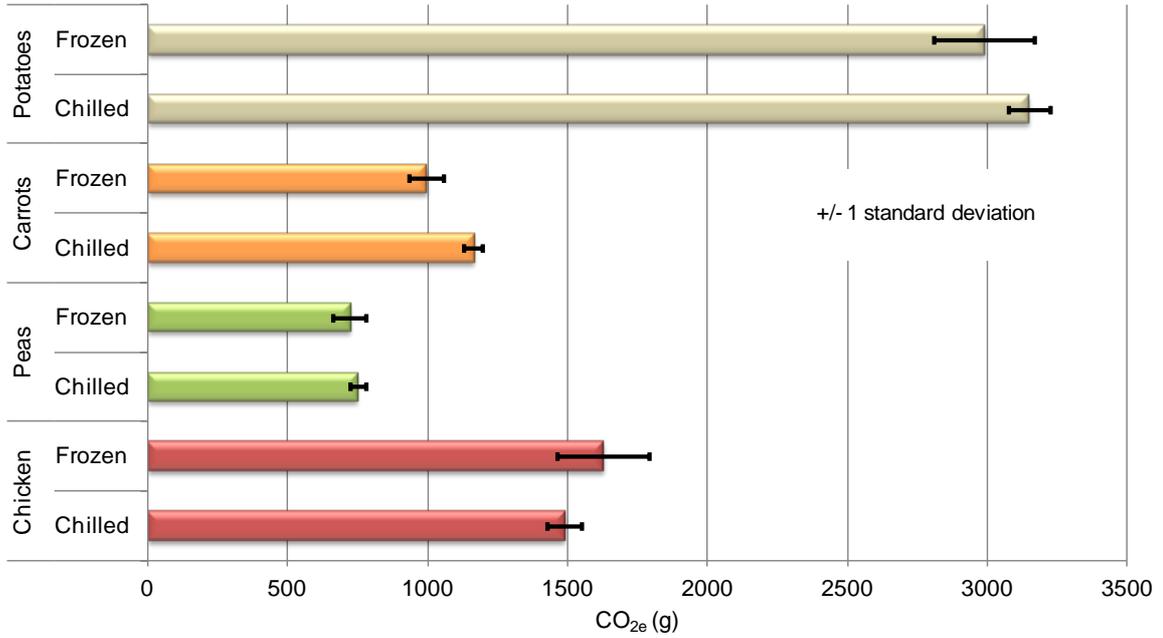


Figure 17. Total emissions for each chilled and frozen constituent of the meal.

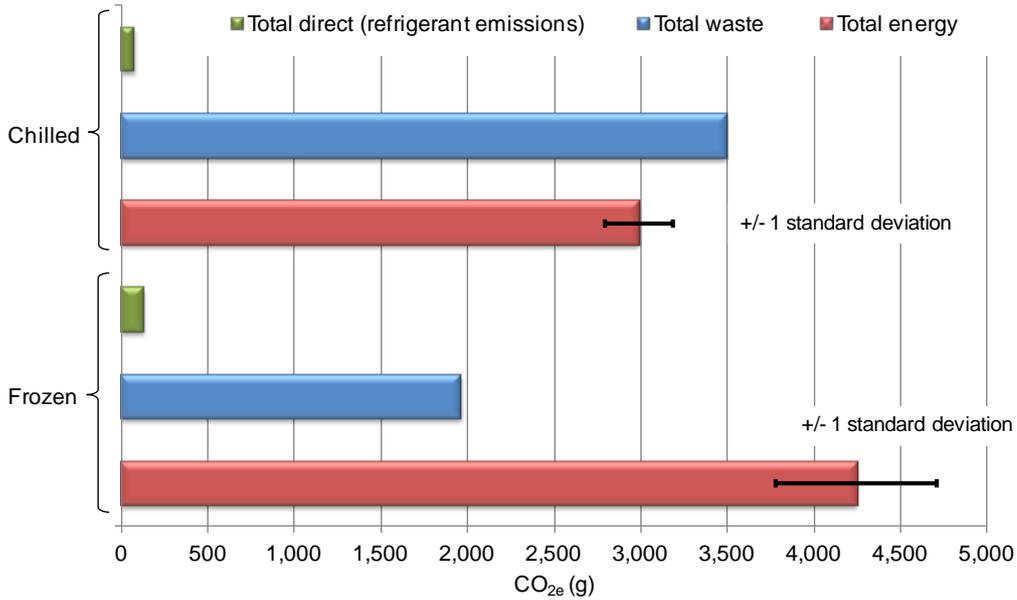


Figure 18. Total emissions (from energy, waste and direct sources) and standard deviations (where available) of CO_{2e} from the chilled and frozen meals (for family meal for 4).

All figures CO _{2e} (g)	Chicken				Peas				Carrots				Potatoes				TOTAL			
	Chilled	sd	Frozen	sd	Chilled	sd	Frozen	sd	Chilled	sd	Frozen	sd	Chilled	sd	Frozen	sd	Chilled	sd	Frozen	sd
Waste	464.0	n/a	266.6	n/a	369.1	n/a	145.2	n/a	628.6	n/a	395.7	n/a	2026.1	n/a	1152.2	n/a	3487.8	n/a	1959.7	n/a
Refrigerant emissions	26.8	n/a	44.1	n/a	15.4	n/a	17.8	n/a	18.1	n/a	17.8	n/a	15.7	n/a	50.9	n/a	75.9	n/a	130.6	n/a
Primary processing	135.4	n/a	205.9	37.5	5.9	1.9	69.8	5.2	88.2	2.1	70.7	5.2	14.4	3.6	357.5	14.8	243.9	7.5	703.9	62.6
Storage	0.3	0.1	5.1	n/a	0.4	n/a	9.2	n/a	1.4	n/a	10.3	n/a	5.7	2.7	25.6	5.3	7.8	2.8	50.2	5.3
Transport	89.2	44.5	102.0	55.1	40.5	20.2	41.1	22.2	47.7	23.8	41.2	22.2	135.1	67.4	117.9	63.7	312.5	155.9	302.2	163.3
Retail	19.1	7.1	60.0	11.0	7.5	1.8	26.9	4.9	8.8	2.2	26.9	4.9	0.0	0.0	64.2	11.8	35.3	11.2	177.9	32.6
Domestic-transport home	47.2	n/a	48.5	n/a	19.5	n/a	19.6	n/a	23.2	n/a	19.6	n/a	63.2	n/a	56.1	n/a	153.1	n/a	143.8	n/a
Domestic-storage	40.0	10.3	279.7	61.6	16.5	4.2	115.4	25.4	19.6	5.0	137.4	30.2	0.0	0.0	374.6	82.4	76.1	19.6	907.2	199.6
Domestic-cook	663.9	n/a	614.4	n/a	274.0	n/a	275.3	n/a	326.1	n/a	275.4	n/a	889.1	n/a	788.7	n/a	2153.1	n/a	1953.7	n/a
TOTAL (g)	1486.0	62.0	1626.3	165.2	748.6	28.1	720.3	57.7	1161.7	33.1	994.8	62.6	3149.3	73.7	2987.8	178.0	6545.6	196.9	6329.1	463.5
Total (kg)	1.49	0.06	1.63	0.17	0.75	0.03	0.72	0.06	1.16	0.03	0.99	0.06	3.15	0.07	2.99	0.18	6.55	0.20	6.33	0.46

sd=standard deviation

Table 7. Totalised emissions for a meal for a family of 4.

Comparable data for the whole cold chain

During the work additional data for the whole cold chain were found for several products and these are shown in Appendix 5. The data demonstrate the great variability in data available. For example the data for frozen peas vary by a factor of 4-5 and potatoes by a factor of 31. This sometimes reflects the system boundaries which vary quite considerably but also reflects the processes throughout the cold chain and the variability in final product produced.

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Appendix 1. Chicken: details of data and assumptions

Waste

The waste from each cold chain was considered first as this has an influence on the mass of food at each stage of the cold chain that should be considered in the indirect emission calculations (i.e. the losses throughout the cold chain are taken into account to obtain the final cooked meal portion).

There is limited information on waste for products outside of the home. The references shown in Table 8 were used to calculate waste throughout the chicken cold chains. In all calculations it was assumed that the portion of chicken meat considered did not include bones. The only waste data found for meat during production were obtained from Estrada-Flores and Platt (2007) who estimated that 0.2% of the product was wasted. Information for storage and transport was obtained from Audsley et al (2009) and information for retail from Tassou (2008). Data on food wasted in the home were obtained from Defra and WRAP reports (2009, 2010 and 2012). Defra (2010) reported that 14% of chilled poultry is wasted in the home. This was divided into 7.3% pre cooking and 6.7% post cooking waste using information from WRAP (2012). The same post cooking waste for frozen food was assumed. For frozen food pre cooking waste was assumed to be 2% based on advice from WRAP (2012).

Losses during thawing were assumed to be 10% for the frozen product according to information from Agnelli and Mascheroni (2002) for 'conventionally' frozen chicken (as opposed to cryogenically frozen chicken). Cooking losses were assumed to be 26% for the chilled chicken (RD&T data) and 20% for the frozen chicken based on home oven cooking at approximately 160°C. No data were found for cooking losses from chicken that had been previously frozen and so data that compared cooking losses for chilled and previously frozen beef from Boles and Swan (2002) were used as a guide.

Losses from thawing and during cooking in the home were excluded from the waste emissions calculations as the WRAP data used for the calculation of emissions primarily apply only to product that is thrown away.

Based on this information a 188 g portion of chilled chicken was required to generate a 125 g portion post cooking. For the same portion of frozen chicken a 181 g original portion was required. Excluding waste from thawing and cooking, 28 g was wasted from the chilled chicken and 16 g from the frozen chicken. For a family of 4 this resulted in CO_{2e} emissions of 464 g for the chilled chicken and 267 g for the frozen chicken.

Table 8. Waste throughout cold chain for chilled and frozen chicken.

Stage of cold chain	Chilled			Frozen		
	Weight loss (%)	Weight at end of each stage (g)	Reference	Weight loss (%)	Weight at end of each stage (g)	Reference
Start weight (g)		188			181	
Primary production	0.2%	188	Estrada-Flores and Platt(2007)	0.2%	181	Estrada-Flores and Platt(2007)
Storage	1.0%	186	Audsley et al (2009)	1.0%	179	Audsley et al (2009)
Transport	0.0%	186	Audsley et al (2009)	0.0%	179	Audsley et al (2009)
Retail	2.0%	182	Tassou (2008)	1.0%	177	Tassou (2008)
Home storage	7.3%	169	Defra (2010), WRAP	2.0%	174	Assumption
Total loss (g) prior to thawing, cooking and consumption		19			7	
Thaw	n/a	n/a	n/a	10.0%	156	Agnelli and Mascheroni (2002)
Cook	26.0%	125	RD&T data	20.0%	125	Bolesa and Swan (2002)
Presented to eat		125			125	
Home after cook	6.7%	117	Defra (2010), WRAP	6.7%	117	Defra (2010), WRAP
Total loss after cooking (assumed to originate from meal)		71			64	
Total loss (g) in cold chain (excluding cooking and thawing)		28			16	
Waste CO_{2e} (g) per portion		116			67	
Waste CO_{2e} (g) for family of 4		464			267	

Indirect emissions

In all calculations for indirect emissions, the mass of chicken shown in Table 8 was used for each stage of the cold chain.

Meat processing

No data were found for individual sections of the cold chain in the meat processing plant but data were reported by Ramirez et al (2006) for slaughtering, rendering and meat processing and storage in the slaughterhouse (Table 9). Data for whole and cut up chicken are presented in Table 9. In both cases the freezing process was more energy intensive.

Table 9. Energy and carbon emissions in chicken slaughterhouse.

Data source	Sector	Process	SEC (MJ/t) (primary energy)	SEC (kJ/kg) (end use energy)	kJ for product in meal (average of range used)	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Ramirez et al (2006)	Slaughter house	Whole chilled	3096	1238.4	232.4	33.9	135.4
Ramirez et al (2006)	Slaughter house	Cut up deboned chilled	3852	1540.8	289.1	42.1	168.5
Ramirez et al (2006)	Slaughter house	Whole frozen	4258-5518	1703.2-2207.2	353.2 (mean)	51.5	205.9
Ramirez et al (2006)	Slaughter house	Cut up deboned frozen	5014-6274	2005.66-2509.6	407.8 (mean)	59.4	237.7

(Data used in calculation in bold)

Storage

Information on SEC required to store chicken was obtained from a number of sources (Table 10). The data were calculated from general cold storage figures (not specific to one product) and adjusted according to the product density in the cold store. The data from Tassou (2008) and ICE-E (2012) were used to calculate energy used for storage of chilled and frozen chicken. No information was found on residence times in chilled stores for chicken. Therefore an assumption was made that chilled chicken was stored for 2 days and that frozen chicken was stored for 30 days.

Table 11 shows the SEC for the storage process and total emissions for the chicken portion. The freezing process was more energy intensive and this was exacerbated by the greater storage period for the frozen product.

Table 10. SEC for storage of chicken.

Process	kJ/kg/day	Reference
Storage-general	2.6	Werner et al (2006)
Storage-general	2.8	Estrada-Flores and Platt (2007)
Storage-general	3.1	Estrada-Flores and Platt (2007)
Chilled general	1.1	ICE-E (2012)
Chilled chicken storage	1.6	Tassou (2008)
Frozen general	1.6	ICE-E (2012)
Mixed general	1.6	ICE-E (2012)

Table 11. Energy and carbon emissions in chicken storage.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
ICE-E	Storage	Chilled	2.2	0.4	0.1	0.2
Tassou (2008)	Storage	Chilled	3.1	0.6	0.1	0.3
	Storage	Chilled mean	2.7	0.5	0.1	0.3
ICE-E	Storage	Frozen	48.8	8.7	1.3	5.1

(Data used in calculation in bold)

Transport

A large data set was found for emissions associated with transport of food but no specific data for transport of chicken was found (Table 12). Information on transport distances were obtained from Marquardt (2012) who stated that typical transport distances for local delivery within Germany were 500 km (this was a similar figure to that used for the UK by Tassou, 2008). Assuming all journeys were 500 km and making the assumptions listed in Table 12 average values for transport of chicken were calculated (Table 13). Chilled transport was slightly more energy intensive than the frozen transport (due to the greater weight of product).

Table 12. SEC for transport of food.

Vehicle type	kJ/kg/km	Reference
Transport-chilled (1 drop), large rigid	1.6	Tassou et al (2009)
Transport-chilled (1 drop), city artic	1.6	Tassou et al (2009)
Transport-chilled (1 drop), 32 ton artic	1.1	Tassou et al (2009)
Transport-chilled (1 drop), 38 ton artic	1.1	Tassou et al (2009)
Transport-chilled (multi drop), medium rigid	3.7	Tassou et al (2009)
Transport-chilled (multi drop), large rigid	1.7	Tassou et al (2009)
Transport-chilled (multi drop), city artic	1.6	Tassou et al (2009)
Transport-chilled (multi drop), 32 ton artic	1.2	Tassou et al (2009)
Transport-chilled (multi drop), 38 ton artic	1.2	Tassou et al (2009)
Transport-frozen+multi (1 drop), medium rigid	3.8	Tassou et al (2009)
Transport-frozen+multi (1 drop), large rigid	1.7	Tassou et al (2009)
Transport-frozen+multi (1 drop), city artic	1.7	Tassou et al (2009)
Transport-frozen+multi (1 drop), 32 ton artic	1.2	Tassou et al (2009)
Transport-frozen+multi (1 drop), 38 ton artic	1.2	Tassou et al (2009)
Transport-frozen+multi (multi drop), medium rigid	4.0	Tassou et al (2009)
Transport-frozen+multi (multi drop), large rigid	1.8	Tassou et al (2009)
Transport-frozen+multi (multi drop), city artic	1.7	Tassou et al (2009)
Transport-frozen+multi (multi drop), 32 ton artic	1.3	Tassou et al (2009)
Transport-frozen+multi (multi drop), 38 ton artic	1.2	Tassou et al (2009)

Table 13. Energy and carbon emissions in food transport of chicken.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Tassou et al (2009)	Transport	Chilled mean	824.0	153.1	22.3	89.2
Tassou et al (2009)	Transport	Frozen mean	978.8	175.0	25.5	102.0

(Data used in calculation in bold)

Retail

Data were found on energy used in supermarkets for refrigeration of chilled and frozen goods. Specific information on energy required to store chilled or frozen chicken could not be extracted and so information on energy was calculated per metre length of cabinet in supermarkets described by Rhiemeier et al (2009), Colombo (2010) and Tassou et al (2011) for all chilled or frozen foods. The stocking density in supermarket cabinets for chicken was taken from Tassou (2008) and checked by a visit to a large supermarket. Stocking densities in the large supermarket were broadly similar to those presented by Tassou (2008). Storage life in supermarkets was taken from Tassou (2008) as 24 hours for chilled chicken (assumed to be similar to fresh packaged meat) and as 96 hours for frozen chicken which was assumed to be similar to that for the frozen foods presented by Tassou (2008).

Data from the above sources are presented in Table 14. Mean values for chilled and frozen chicken were calculated from the 4 data sources which showed that frozen chicken storage in supermarkets was more energy intensive than chilled storage.

Table 14. Energy and carbon emissions in retail display of chicken.

Data source	Sector	Type of cabinet	SEC (kJ/kg) (end use energy)	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Rhiemeier et al (2009)	Retail	Chilled remote	97.6	17.8	2.6	10.4
Colombo et al (2011)	Retail	Chilled remote	257.8	46.9	6.8	27.4
Tassou et al (2011)	Retail	Chilled remote	201.1	36.6	5.3	21.3
Rhiemeier et al (2009)	Retail	Chilled integral	162.7	29.6	4.3	17.3
Mean chilled	Retail	Chilled	179.8	32.7	4.8	19.1
Rhiemeier et al (2009)	Retail	Frozen remote	474.7	84.0	12.2	49.0
Colombo et al (2011)	Retail	Frozen remote	650.7	115.2	16.8	67.1
Tassou et al (2011)	Retail	Frozen remote	506.6	89.7	13.1	52.3
Rhiemeier et al (2009)	Retail	Frozen integral	692.3	122.6	17.9	71.4
Mean frozen	Retail	Frozen	581.1	102.9	15.0	60.0

(Data used in calculation in bold)

Transport to home

It was assumed that energy to transport the same weight of food to the home would be identical for both frozen and chilled chicken. Data on energy required to transport food to the home from a supermarket were taken from Audsley et al (2009) and are shown in Table 15. The slight differences in emissions were due to variation in the weight of product brought to the home. Audsley et al (2009) used data from work by Pretty et al

(2005) that used a weighted average of emissions from car and bus transport combined with zero emissions associated with some product that was bought home by foot or by bicycle. Audsley et al assumed that the average basket of purchased food weighed 28 kg and the mean distance travelled was 6.4 km. This gave a weighted average of 0.48 MJ/kg of product.

Table 15. Energy to transport chicken to the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Audsley et al (2009)	Transport to home	Chilled	480.0	81.0	11.8	47.2
Audsley et al (2009)	Transport to home	Frozen	480.0	83.3	12.1	48.5

(Data used in calculation in bold)

Domestic storage

A large number of data sets were found for home storage in domestic refrigerators (UKHES (2010), Lot 13 (2005)). None of these were specifically for chicken and so data were analysed assuming chicken was part of the food mix in the appliance.

Some data were from fridge-freezers where the energy could not be split between chilled and frozen storage and so these data sets were ignored. Only data from refrigerators that provided either chilled or frozen storage were used for the analysis. Data from American studies were ignored due the variations in sizes of appliances between the USA and the UK. For the analysis, data from 44 refrigerators and 48 freezers (upright and chest) from UKHES (2010) were used. Data from Lot 13 (Preparatory study for Eco-design requirements for EuP (Tender TREN/D1/40-2005)) were also used as this referred to European refrigerators.

Storage times in freezers was assumed to be 82 days in accordance with consumer expectation for storage of meat described in the 2010 WRAP report on freezer usage. Storage time for chilled chicken was assumed to be 4 days.

Refrigerators were assumed to have a stocking density of 0.15 kg/litre and freezers a stocking density of 0.5 kg/litre. Using these assumptions the emissions shown in Table 16 were calculated.

Table 16. Energy used to store chicken in the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
UKHES (2010)	Domestic	Chilled	302.0	51.0	7.4	29.7
Lot 13 (2005)	Domestic	Chilled	332.0	56.0	8.2	32.7
Lot 13 (2005)	Domestic	Chilled	487.6	82.3	12.0	48.0
Lot 13 (2005)	Domestic	Chilled	505.0	85.2	12.4	49.7
UKHES (2010)	Domestic	Frozen	3,351.6	565.6	82.4	329.7
UKHES (2010)	Domestic	Frozen	3,143.3	530.4	77.3	309.2
Lot 13 (2005)	Domestic	Frozen	1,882.0	317.6	46.3	185.1
Lot 13 (2005)	Domestic	Frozen	2,325.2	392.4	57.2	228.7
Lot 13 (2005)	Domestic	Frozen	1,977.4	333.7	48.6	194.5
Lot 13 (2005)	Domestic	Frozen	2,256.5	380.8	55.5	221.9
Lot 13 (2005)	Domestic	Frozen	3,493.9	589.6	85.9	343.7
Lot 13 (2005)	Domestic	Frozen	2,361.6	398.5	58.1	232.3
Lot 13 (2005)	Domestic	Frozen	3,315.9	559.5	81.5	326.2
Lot 13 (2005)	Domestic	Frozen	3,372.6	569.1	82.9	331.7
Lot 13 (2005)	Domestic	Frozen	3,162.3	533.6	77.8	311.0
Lot 13 (2005)	Domestic	Frozen	3,485.8	588.2	85.7	342.9
Mean	Domestic	Chilled	406.6	68.6	10.0	40.0
Mean	Domestic	Frozen	2,844.0	479.9	69.9	279.7

(Data used in calculation in bold)

Cooking in the home

The assumption was made that frozen chicken was thawed in the refrigerator and then cooked. Weight loss during thawing was taken into account in the waste calculation (see above). No energy associated with thawing was included as the chicken would be below the refrigerator temperature and would actually provide cooling to the appliance. This was considered to be minimal and was ignored. Both chilled and frozen chicken were assumed to be cooked from, and to, the same temperatures in an identical process.

Data on cooking in the home were obtained from Audsley et al (2009). Cooking intensities of up to 10 MJ/kg were reported by Audsley et al which originated from gas and electricity. Using an equal mix of gas and electricity in the calculations the emissions from cooking are shown in Table 17. Slight differences in emissions are due to variation in the weight of product prior to cooking.

Table 17. Energy used to cook chicken in the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Audsley (2009)	Domestic	Cook-chilled	10,000	1687	166.0	663.9
Audsley (2009)	Domestic	Cook-frozen	10,000	1562	153.6	614.4

(Data used in calculation in bold)

Direct emissions

Direct emissions were calculated from typical refrigerants and typical refrigerant charges used in each stage of the cold chain and their associated emissions. Global Warming Potentials (GWPs) of refrigerants were taken from UNEP (2010) using a 100 year horizon.

Production facilities and cold stores for both chilled and frozen chicken are most likely to operate using ammonia (R717) as the refrigerant. As ammonia has a GWP of less than 1 any emissions generated directly from refrigerant losses are minimal and can be ignored. Similarly emissions from domestic refrigerators can be ignored as refrigerant charges are low (usually less than 75 g), refrigerant leakage is low (0.5% per year) Schwarz, 2005, IPCC/TEAP 2005) and the refrigerant most commonly used is R600a (iso-butane) which has a GWP of approximately 20.

Therefore the majority of direct emissions are from transport and retail. Transport vehicles use a variety of refrigerants, most typically have high GWPs. Assuming that both chilled and frozen vehicles use the same refrigerant (R404A with a GWP of 3,700) and that the most common vehicles used to transport food on the road are 32 tonne articulated lorries (Tassou, 2008, claims that they account for 80% of the total tonne-km goods movements in the UK) with a refrigerant charge of 7.5 kg the emissions shown in Table 18 were calculated. It was assumed that pallets of chicken were 500 kg and that 15 tonnes were transported in each journey. Each vehicle was assumed to travel 100,000 km per year and each journey was 500 km. Information on emissions from transport vehicles were taken from confidential discussions with manufacturers of refrigerated transport equipment.

Information to calculate emissions from retail were calculated for a typical supermarket. Throughput of food in chilled and frozen cabinets was calculated using food stocking densities from Tassou (2008) and RD&T information on typical supermarket layouts and refrigerant charges. Typical refrigerant leakage rates for retail were taken from Carbon Trust (2010).

Table 18. Direct emissions in chilled and frozen chicken cold chains.

Sector	Refrigerant	Typical refrigerant charge per system (kg)	GWP	Leakage (%/year)	Throughput for typical system (tonnes/year)	CO _{2e} (g/kg of product)	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
FROZEN								
Production	R717	>300	0	n/a	n/a	n/a	n/a	n/a
Storage	R717	>100	0	n/a	n/a	n/a	n/a	n/a
Transport	R404A	7.5	3700	30	1500	5.6	1.0	4.0
Retail	R404A	100	3700	20	1307	56.6	10.0	40.1
Home	R600a	<0.1	~20	n/a	n/a	n/a	n/a	n/a
Total							11.0	44.1
CHILLED								
Production	R717	>300	0	n/a	n/a	n/a	n/a	n/a
Storage	R717	>50	0	n/a	n/a	n/a	n/a	n/a
Transport	R404A	7.5	3700	30	1500	5.6	1.0	4.1
Retail	R404A	200	3700	30	4752	31.1	5.7	22.7
Home	R600a	<0.1	~20	n/a	n/a	n/a	n/a	n/a
Total							6.7	26.8

(Data used in calculation in bold)

Appendix 2. Peas: details of data and assumptions

Waste

Based on the similar assumptions used for chicken, the waste throughout the pea cold chains was calculated (Table 19). Where appropriate, different proportions of chilled and frozen chain waste were used in the calculations. Sources of information are listed in Table 19. It was assumed that peas entering both the chilled and frozen cold chains were shelled prior to being chilled or frozen (Green and Foster, 2005). An assumption was made that frozen peas were cooked from frozen and that there were no thawing losses from frozen peas. Cooking losses were considered to be zero from both chilled and frozen peas.

Defra (2010) reported that 18% of processed vegetables (assumed to be chilled) are wasted in the home. This was divided into 15.7% pre cooking and 2.3% post cooking waste using information from WRAP (2012). For waste from frozen peas similar assumptions to those used for chicken were applied.

Emissions from waste from the chilled chain were greater (369 g CO_{2e} for a family of 4) than from the frozen cold chain (145 g CO_{2e} for a family of 4).

Table 19. Waste throughout cold chain for chilled and frozen peas.

Stage of cold chain	Chilled			Frozen		
	Weight loss (%)	Weight at end of each stage (g)	Reference	Weight loss (%)	Weight at end of each stage (g)	Reference
Start weight (g)		90			77	
Primary production	5.4%	85	Estrada-Flores and Platt(2007)	5.4%	73	Estrada-Flores and Platt(2007)
Storage	1.0%	84	Audsley et al (2009)	1.0%	72	Audsley et al (2009)
Transport	0.0%	84	Audsley et al (2009)	0.0%	72	Audsley et al (2009)
Retail	2.0%	83	Tassou (2008)	1.0%	71	Tassou (2008)
Home storage	15.7%	70	Defra (2010), WRAP	2.0%	70	Assumption
Cook	0.0%	70	Assumption	0.0%	70	Assumption
Presented to eat		70			70	
Home after cook	2.3%	68	Defra (2010), WRAP	2.3%	68	Defra (2010), WRAP
Total loss after cooking (assumed to originate from meal)		22			9	
Waste CO_{2e} (g) per portion		92			36	
Waste CO_{2e} (g) for family of 4		369			145	

Indirect emissions

In all calculations for indirect emissions, the weights of peas shown in Table 19 were used for each stage of the cold chains.

Pea processing

Data on blanching of vegetables were taken from Togeby et al (1986). Energy required for blanching was reported to vary between 0.95 GJ/t to 2.1 GJ/t. The typical figure of 1 GJ/t reported by Togeby was used in calculations (Table 20). The assumption was made that the energy for blanching came from electrical sources (emissions would be less if gas were used).

Limited information on primary processing (freezing or chilling) of peas was found and therefore data on processing of horticulture products were used to expand the data set. For freezing of peas, data from Cleland (1982) on freezing of vegetables in 5 different plants in New Zealand (2 of which were pea freezing plants) were used. Data from Buschmann (2012) presented data on processing of peas and so this was used in addition to the data from Cleland.

Data on chilling were very limited and so data from Estrada-Flores and Platt (2007) was extracted for chilling of horticulture products. Due to the limited data on chilling of peas a further calculation was made using a heat transfer mathematical model where the thermal properties of the peas were calculated and used to predict cooling times. Using the enthalpies calculated and estimating the Carnot COP (coefficient of performance) of the refrigeration system (based on evaporating and condensing temperatures) the energy used for chilling was estimated as being 7.7 times less than that for freezing. The SEC for chilling peas could then be calculated relative to the mean SEC for freezing. This was lower but comparable with the data calculated from Estrada-Flores and Platt (2007). Data for freezing and chilling of peas are presented in Table 20. In all cases the freezing process was more energy intensive.

Table 20. Energy and carbon emissions in pea chilling and freezing.

Data source	Sector	Process	SEC (kJ/kg) (end use energy)	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Togebly et al (1986)	Primary processing	Blanching	1000.0	59.8	8.7	34.9
Cleland (1982)	Primary processing	Freezing	670.0	48.8	7.1	28.4
Cleland (1982)	Primary processing	Freezing	690.0	50.3	7.3	29.3
Cleland (1982)	Primary processing	Freezing	780.0	56.8	8.3	33.1
Cleland (1982)	Primary processing	Freezing	900.0	65.6	9.6	38.2
Cleland (1982)	Primary processing	Freezing	940.0	68.5	10.0	39.9
Buschmann (2012)	Primary processing	Freezing	n/a		10.2	40.8
Mean freezing			796.0	58.0	8.7	35.0
Total for freezing (blanching + freezing)			1796.0	117.8	17.5	69.8
Estrada-Flores and Platt (2007).	Primary processing	Chilling	168.8	12.3	1.8	7.2
Calculation	Primary processing	Chilling	103.4	7.5	1.1	4.5
Mean chilling			136.1	9.9	1.5	5.9

(Data used in calculation in bold)

Storage

Data on storage of frozen peas were presented in Buschmann (2012) but the carbon emissions were high (8.52 g CO_{2e}/single portion of product) compared to other sources of data and so were ignored.

Limited other SEC data for storage of peas were found and therefore a similar approach to that used for chicken was used where the general cold storage data were adjusted according to the density of peas stored (Table 21). Using these assumptions the emissions shown in Table 22 were calculated. The storage times applied were 7 days for chilled peas and 150 days for frozen peas. The storage time for frozen peas was estimated based on average storage time for vegetables from Marquardt (2012). Frozen storage was more energy intensive than chilled storage due to the longer storage period.

Table 21. SEC for storage of peas.

Process	kJ/kg/day	Reference
Storage-general	2.3	Werner et al (2006)
Storage-general	2.5	Estrada-Flores and Platt (2007)
Storage-general	2.8	Estrada-Flores and Platt (2007)
Chilled general	1.1	ICE-E (2012)
Frozen general	1.6	ICE-E (2012)
Frozen peas	1.3	Tassou (2008)
Mixed general	1.6	ICE-E (2012)

Table 22. Energy and carbon emissions in storage of peas.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
ICE-E	Storage	Chilled	7.9	0.7	0.1	0.4
ICE-E	Storage	Frozen	244.1	17.6	2.6	10.3
Tassou (2008)	Storage	Frozen	194.4	14.0	2.0	8.2
Mean frozen	Storage	Frozen	219.2	15.8	2.3	9.2

(Data used in calculation in bold)

Transport

The same data and assumptions to those used for chicken were used for the transport of peas. This was a valid assumption as the SEC data extracted was not food specific. Using the data shown in Table 12 average values for transport of peas were calculated (Table 23). Chilled transport was slightly more energy intensive than the frozen transport (due to the greater weight of product).

Table 23. Energy and carbon emissions in food transport of peas.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Tassou et al (2009)	Transport	Chilled mean	824.0	69.5	10.1	40.5
Tassou et al (2009)	Transport	Frozen mean	978.8	70.6	10.3	41.1

(Data used in calculation in bold)

Retail

Data on retail storage of frozen peas were presented in Buschmann (2012) but the carbon emissions were high (11.9 g CO_{2e}/single portion of product) compared to other sources of data and so were ignored. Therefore similar data to those used for chicken were used to calculate the SEC for retail storage of peas. The stocking density in supermarket cabinets for peas was taken from Tassou (2008) and checked by a visit to a large supermarket. Storage life in supermarkets was taken from Tassou (2008) as 36 hours for chilled peas (assumed to be similar to other fresh produce) and as 96 hours for frozen peas.

Data calculated for storage of peas are presented in Table 24. Mean values for chilled and frozen peas were calculated from the 4 data sources which showed that frozen pea storage in supermarkets was more energy intensive than chilled storage.

Table 24. Energy and carbon emissions in retail display of peas.

Data source	Sector	Type of cabinet	SEC (kJ/kg) (end use energy)	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Rhiemeier et al (2009)	Retail	Chilled remote	123.6	10.2	1.5	6.0
Colombo et al (2011)	Retail	Chilled remote	163.3	13.5	2.0	7.9
Tassou et al (2011)	Retail	Chilled remote	127.4	10.5	1.5	6.1
Rhiemeier et al (2009)	Retail	Chilled integral	206.0	17.0	2.5	9.9
Mean chilled	Retail	Chilled	155.1	12.8	1.9	7.5
Rhiemeier et al (2009)	Retail	Frozen remote	527.5	37.7	5.5	22.0
Colombo et al (2011)	Retail	Frozen remote	723.0	51.6	7.5	30.1
Tassou et al (2011)	Retail	Frozen remote	562.9	40.2	5.9	23.4
Rhiemeier et al (2009)	Retail	Frozen integral	769.2	54.9	8.0	32.0
Mean frozen	Retail	Frozen	645.6	46.1	6.7	26.9

(Data used in calculation in bold)

Transport to home

The same assumptions were made for transport of peas to the home as for chicken. Data on energy required to transport food to the home are shown in Table 25. Similar data for transport of frozen peas was presented by Buschmann (2012) who stated that 4.2 g CO_{2e} was used to transport peas to the home per single portion of product

Table 25. Energy to transport peas to the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Audsley et al (2009)	Transport to home	Chilled	480.0	33.4	4.9	19.5
Audsley et al (2009)	Transport to home	Frozen	480.0	33.6	4.9	19.6

(Data used in calculation in bold)

Domestic storage

The same basic data and assumptions used to calculate SECs for chicken were used. Storage time from frozen product was assumed to be 82 days and chilled product 4 days. Using these assumptions the emissions shown in Table 26 were calculated.

Table 26. Energy used to store peas in the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
UKHES (2010)	Domestic	Chilled	302.0	21.0	3.1	12.3
Lot 13 (2005)	Domestic	Chilled	332.0	23.1	3.4	13.5
Lot 13 (2005)	Domestic	Chilled	487.6	34.0	4.9	19.8
Lot 13 (2005)	Domestic	Chilled	505.0	35.2	5.1	20.5
UKHES (2010)	Domestic	Frozen	3,351.6	233.4	34.0	136.0
UKHES (2010)	Domestic	Frozen	3,143.3	218.9	31.9	127.6
Lot 13 (2005)	Domestic	Frozen	1,882.0	131.1	19.1	76.4
Lot 13 (2005)	Domestic	Frozen	2,325.2	161.9	23.6	94.4
Lot 13 (2005)	Domestic	Frozen	1,977.4	137.7	20.1	80.3
Lot 13 (2005)	Domestic	Frozen	2,256.5	157.1	22.9	91.6
Lot 13 (2005)	Domestic	Frozen	3,493.9	243.3	35.5	141.8
Lot 13 (2005)	Domestic	Frozen	2,361.6	164.4	24.0	95.9
Lot 13 (2005)	Domestic	Frozen	3,315.9	230.9	33.6	134.6
Lot 13 (2005)	Domestic	Frozen	3,372.6	234.8	34.2	136.9
Lot 13 (2005)	Domestic	Frozen	3,162.3	220.2	32.1	128.4
Lot 13 (2005)	Domestic	Frozen	3,485.8	242.7	35.4	141.5
Mean	Domestic	Chilled	406.6	28.3	4.1	16.5
Mean	Domestic	Frozen	2,844.0	198.0	28.9	115.4

(Data used in calculation in bold)

Cooking in the home

The assumption was made that frozen peas were cooked directly from frozen. Due to frozen peas having been blanched prior to freezing the cooking times of frozen and chilled peas were considered to be similar. Weight loss during cooking was assumed to be zero from both chilled and frozen peas.

The same data sources for the cooking process as were used for chicken were used. The emissions calculated for cooking are shown in Table 27.

Table 27. Energy used to cook peas in the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Audsley (2009)	Domestic	Cook-chilled	10,000	696	68.5	274.0
Audsley (2009)	Domestic	Cook-frozen	10,000	700	68.8	275.3

(Data used in calculation in bold)

Direct emissions

Direct emissions were calculated using similar assumptions and figures to those used for chicken. The only difference was that R422D (an R22 'drop-in') was used as the refrigerant for pea chilled stores as ammonia is rarely used in smaller produce stores. Emissions calculated for pea storage are shown in Table 28.

Table 28. Direct emissions in chilled and frozen pea cold chains.

Sector	Refrigerant	Typical refrigerant charge per system (kg)	GWP	Leakage (%/year)	Throughput for typical system (tonnes/year)	CO _{2e} (g/kg of product)	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
FROZEN								
Production	R717	>300	0	n/a	n/a	n/a	n/a	n/a
Storage	R717	>100	0	n/a	n/a	n/a	n/a	n/a
Transport	R404A	7.5	3700	30	1500	5.6	0.4	1.6
Retail	R404A	100	3700	20	1307	56.6	4.0	16.2
Home	R600a	<0.1	~20	n/a	n/a	n/a	n/a	n/a
Total							4.4	17.8
CHILLED								
Production	R717	>300	0	n/a	n/a	n/a	n/a	n/a
Storage	R422D	75	2700	15	3200	9.5	0.8	3.2
Transport	R404A	7.5	3700	30	1500	5.6	0.5	1.9
Retail	R404A	200	3700	30	4752	31.1	2.6	10.3
Home	R600a	<0.1	~20	n/a	n/a	n/a	n/a	n/a
Total							3.8	15.4

(Data used in calculation in bold)

Appendix 3. Carrots: details of data and assumptions

Waste

Similar assumptions were made on waste from carrots as were made for peas. The only difference was that peas were assumed to be shelled in the field for both chilled and frozen product (and therefore the waste from pods were outside of the boundary of this study) whereas the carrots would need to be peeled and 'top and tailed' prior to freezing or before consumption in the home if chilled. Data on weight loss of carrots during peeling were found. Lehto et al (2005) claimed that 30-40% of the weight of vegetables and potatoes are peel waste. Mahmood et al (1998) also claimed that 20-50% of raw potatoes were wasted as peel. These figures appeared high and so were checked experimentally by peeling main crop carrots. Peeling weight loss was found to be on average 15.4% with a standard deviation of 3.2%. Therefore peeling losses were considered in the analysis to be 15.4%.

Defra (2010) reported that 17% of root vegetables (assumed to be chilled) are wasted in the home. This was divided into 14.8% pre cooking and 2.2% post cooking waste using information from WRAP (2012). For waste from frozen carrots similar assumptions to those used for chicken and peas were applied.

Where appropriate different levels of waste were applied to the calculations. Sources of information are listed in Table 29. Emissions associated with waste from the chilled chain were greater (629 g CO_{2e} for a family of 4) than from the frozen cold chain (396 g CO_{2e} for a family of 4).

Table 29. Waste throughout cold chain for chilled and frozen carrots.

Stage of cold chain	Chilled			Frozen		
	Weight loss (%)	Weight at end of each stage (g)	Reference	Weight loss (%)	Weight at end of each stage (g)	Reference
Start weight (g)		106			92	
Primary production	5.4%	100	Estrada-Flores and Platt(2007)	20.8%	73	General waste: Estrada-Flores and Platt (2007), plus; Peelings: 15.4%
Storage	1.0%	99	Audsley et al (2009)	1.0%	72	Audsley et al (2009)
Transport	0.0%	99	Audsley et al (2009)	0.0%	72	Audsley et al (2009)
Retail	2.0%	97	Tassou (2008)	1.0%	71	Tassou (2008)
Home storage	14.8%	83	Defra (2010), WRAP	2.0%	70	Assumption
Peel	15.4%	70	Experimental measurement	n/a	n/a	n/a
Cook	0.0%	70	Assumption	0.0%	70	Assumption
Presented to eat		70			70	
Home after cook	2.2%	69	Defra (2010), WRAP	2.2%	68	Defra (2010), WRAP
Total loss after cooking (assumed to originate from meal)		37			24	
Waste CO_{2e} (g) per portion		157			99	
Waste CO_{2e} (g) for family of 4		629			369	

Indirect emissions

In all calculations for indirect emissions, the weights of carrots shown in Table 29 were used for each stage of the cold chain.

Carrot processing

Similar data to those used for peas were used for carrots as limited specific information on primary processing (freezing or chilling) of carrots was found. The only exception was data from Buschmann (2012) that presented data on the processing of frozen and chilled carrots. The data on freezing of carrots from Buschmann (2012) was very similar to that presented by Cleland (1982). However, the data on chilled processing was very different from the only other data source but was selected to be used as it appeared the most reliable data source.

Data for freezing and chilling of carrots are presented in Table 30. In all cases the freezing process was more energy intensive.

Table 30. Energy and carbon emissions in carrot chilling and freezing.

Data source	Sector	Process	SEC (kJ/kg) (end use energy)	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Togebly et al (1986)	Primary processing	Blanching	1000.0	59.8	9.0	35.9
Cleland (1982)	Primary processing	Freezing	670.0	48.8	7.1	28.5
Cleland (1982)	Primary processing	Freezing	690.0	50.3	7.3	29.3
Cleland (1982)	Primary processing	Freezing	780.0	56.8	8.3	33.1
Cleland (1982)	Primary processing	Freezing	900.0	65.6	9.6	38.2
Cleland (1982)	Primary processing	Freezing	940.0	68.5	10.0	39.9
Buschmann (2012)	Primary processing	Freezing	n/a	n/a	9.9	39.8
Mean freezing			796.0	58.0	8.7	34.8
Total for freezing (blanching + freezing)			1796.0	117.8	17.7	70.7
Estrada-Flores and Platt (2007).	Primary processing	Chilling	168.8	12.3	1.8	7.2
Buschmann (2012)	Primary processing	Chilling	n/a	7.1	1.1	4.2
Mean chilling			132.9	9.7	22.1	88.2

(Data used in calculation in bold)

Storage

Data on storage of frozen and chilled carrots were presented in Buschmann (2012) but the carbon emissions were high (7.81 g CO_{2e} for frozen and 10.4 g CO_{2e} for chilled per single portion of product) compared to other sources of data and so were ignored. For conformity between the products a similar approach to that used for chicken and peas was used where the general cold storage data were adjusted according to the density of carrots stored (Table 31). Using these assumptions the emissions shown in Table 32 were calculated. The storage times applied were 21 days for chilled carrots and 150 days for frozen carrots. The storage time for frozen carrots was estimated based on the same assumptions as those used for peas.

Table 31. SEC for storage of carrots.

Process	kJ/kg/day	Reference
Storage-general	2.5	Estrada-Flores and Platt (2007)
Storage-general	2.2	Estrada-Flores and Platt (2007)
Storage-general	3.1	Werner et al (2006)
Chilled general	1.1	ICE-E (2012)
Frozen general	1.6	ICE-E (2012)
Frozen general	3.2	Werner et al (2006)
Mixed general	1.6	ICE-E (2012)

Table 32. Energy and carbon emissions in storage of carrots.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
ICE-E	Storage	Chilled	23.6	2.3	0.3	1.4
ICE-E	Storage	Frozen	244.1	17.6	2.6	10.3

(Data used in calculation in bold)

Transport

The same data and assumptions to those used for chicken and peas were used for the transport of carrots. Using the data shown in Table 12 average values for transport of carrots were calculated (Table 33). Chilled transport was slightly more energy intensive than the frozen transport (due to the greater weight of product).

Table 33. Energy and carbon emissions in food transport of carrots.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Tassou et al (2009)	Transport	Chilled mean	824.0	81.8	11.9	47.7
Tassou et al (2009)	Transport	Frozen mean	978.8	70.6	10.3	41.2

(Data used in calculation in bold)

Retail

Data on retail storage of frozen and chilled carrots were presented in Buschmann (2012). The carbon emissions presented were higher than comparable data for frozen retail storage (11.9 g CO_{2e}/portion) but relatively similar to other data sets for chilled storage (2.04 g CO_{2e}/single portion). This may have been due to differences in the time frozen products were stored in the UK and Germany (where the Buschmann data was collected). For conformity between the products a similar approach to that used for peas was used. The stocking density in supermarket cabinets for carrots was extrapolated from Tassou (2008) and checked by a visit to a large supermarket. Storage life in supermarkets was taken from Tassou (2008) as 36 hours for chilled carrots (assumed to be similar to other fresh produce) and as 96 hours for frozen carrots (similar to other frozen produce).

Data calculated for storage of carrots are presented in Table 34. Mean values for chilled and frozen carrots were calculated from the 4 data sources which showed that frozen carrot storage in supermarkets was more energy intensive than chilled storage.

Table 34. Energy and carbon emissions in retail display of carrots.

Data source	Sector	Type of cabinet	SEC (kJ/kg) (end use energy)	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Rhiemeier et al (2009)	Retail	Chilled remote	123.6	12.0	1.8	7.0
Colombo et al (2011)	Retail	Chilled remote	163.3	15.9	2.3	9.3
Tassou et al (2011)	Retail	Chilled remote	127.4	12.4	1.8	7.2
Rhiemeier et al (2009)	Retail	Chilled integral	206.0	20.0	2.9	11.7
Mean chilled	Retail	Chilled	155.1	15.1	2.2	8.8
Rhiemeier et al (2009)	Retail	Frozen remote	527.5	37.7	5.5	22.0
Colombo et al (2011)	Retail	Frozen remote	723.0	51.6	7.5	30.1
Tassou et al (2011)	Retail	Frozen remote	562.9	40.2	5.9	23.4
Rhiemeier et al (2009)	Retail	Frozen integral	769.2	54.9	8.0	32.0
Mean frozen	Retail	Frozen	645.6	46.1	6.7	26.9

(Data used in calculation in bold)

Transport to home

The same assumptions were made for transport of carrots to the home as for peas. Data on energy required to transport food to the home are shown in Table 35.

Table 35. Energy to transport carrots to the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Audsley et al (2009)	Transport to home	Chilled	480.0	39.8	5.8	23.2
Audsley et al (2009)	Transport to home	Frozen	480.0	33.6	4.9	19.6

(Data used in calculation in bold)

Domestic storage

No specific data was found for carrots and therefore the same basic data and assumptions used to calculate SECs for chicken and peas were used. Storage time for frozen product was assumed to be 82 days and chilled product 4 days. Using these assumptions the emissions shown in Table 36 were calculated.

Table 36. Energy used to store carrots in the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
UKHES (2010)	Domestic	Chilled	302.0	25.0	3.6	14.6
Lot 13 (2005)	Domestic	Chilled	332.0	27.5	4.0	16.0
Lot 13 (2005)	Domestic	Chilled	487.6	40.4	5.9	23.6
Lot 13 (2005)	Domestic	Chilled	505.0	41.9	6.1	24.4
UKHES (2010)	Domestic	Frozen	3,351.6	277.8	40.5	161.9
UKHES (2010)	Domestic	Frozen	3,143.3	260.5	38.0	151.9
Lot 13 (2005)	Domestic	Frozen	1,882.0	156.0	22.7	90.9
Lot 13 (2005)	Domestic	Frozen	2,325.2	192.7	28.1	112.3
Lot 13 (2005)	Domestic	Frozen	1,977.4	163.9	23.9	95.5
Lot 13 (2005)	Domestic	Frozen	2,256.5	187.0	27.3	109.0
Lot 13 (2005)	Domestic	Frozen	3,493.9	289.6	42.2	168.8
Lot 13 (2005)	Domestic	Frozen	2,361.6	195.8	28.5	114.1
Lot 13 (2005)	Domestic	Frozen	3,315.9	274.9	40.1	160.2
Lot 13 (2005)	Domestic	Frozen	3,372.6	279.5	40.7	162.9
Lot 13 (2005)	Domestic	Frozen	3,162.3	262.1	38.2	152.8
Lot 13 (2005)	Domestic	Frozen	3,485.8	288.9	42.1	168.4
Mean	Domestic	Chilled	406.6	33.7	4.9	19.6
Mean	Domestic	Frozen	2,844.0	235.7	34.4	137.4

(Data used in calculation in bold)

Cooking in the home

Chilled carrots were assumed to be peeled prior to cooking. Apart from the same assumptions on the cooking process were made as for peas. The emissions calculated for cooking are shown in Table 37.

Table 37. Energy used to cook carrots in the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Audsley (2009)	Domestic	Cook-chilled	10,000	828.9	81.5	326.1
Audsley (2009)	Domestic	Cook-frozen	10,000	699.9	68.8	275.4

(Data used in calculation in bold)

Direct emissions

Direct emissions were calculated using the same assumptions and figures to those used for peas. Emissions calculated for carrot storage are shown in Table 38.

Table 38. Direct emissions in chilled and frozen carrot cold chains.

Sector	Refrigerant	Typical refrigerant charge per system (kg)	GWP	Leakage (%/year)	Throughput for typical system (tonnes/year)	CO _{2e} (g/kg of product)	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
FROZEN								
Production	R717	>300	0	n/a	n/a	n/a	n/a	n/a
Storage	R717	>100	0	n/a	n/a	n/a	n/a	n/a
Transport	R404A	7.5	3700	30	1500	5.6	0.4	1.6
Retail	R404A	100	3700	20	1307	56.6	4.0	16.2
Home	R600a	<0.1	~20	n/a	n/a	n/a	n/a	n/a
Total							4.4	17.8
CHILLED								
Production	R717	>300	0	n/a	n/a	n/a	n/a	n/a
Storage	R422D	75	2700	15	3200	9.5	0.9	3.8
Transport	R404A	7.5	3700	30	1500	5.6	0.6	2.2
Retail	R404A	200	3700	30	4752	31.1	3.0	12.1
Home	R600a	<0.1	~20	n/a	n/a	n/a	n/a	n/a
Total							4.5	18.1

(Data used in calculation in bold)

Appendix 4. Potatoes: details of data and assumptions

Waste

The assumptions made for the potato cold chain were similar to those for carrots. Peelings from potatoes were measured experimentally and found to be 17.1% (with a standard deviation of 1.9%). In addition any weight gains during roasting/frying were taken into account. Data from Rywotycki (2002) indicated that potatoes gain between 7-10% of their weight during frying and so the assumption was made that there would be a 7% weight gain during the roasting process. Frozen roast potatoes were assumed to lose/gain this weight in primary processing whereas the chilled potatoes were peeled and roasted in the home. Weight loss/gains and sources of information are shown in Table 39. The weights of product listed were applied in the calculations for the various stages of the potato cold chain.

Defra (2010) reported that 29% of fresh potatoes are wasted in the home. This was divided into 18% pre cooking and 11% post cooking waste using information from WRAP (2012). For waste from frozen potatoes similar assumptions to those used for chicken, peas and carrots were applied.

Emissions associated with waste from the chilled chain were greater (2026 g CO_{2e} for a family of 4) than those from the frozen cold chain (1152 g CO_{2e} for a family of 4).

Table 39. Waste throughout cold chain for chilled and frozen potatoes.

Stage of cold chain	Chilled			Frozen		
	Weight loss (%)	Weight at end of each stage (g)	Reference	Weight loss (%)	Weight at end of each stage (g)	Reference
Start weight (g)		299			247	
Primary production:	Chilling: 5.0%	284	Transport Information Service (2012)	Peel: 17.1% Roast: -7.0% General waste: 5.4%	209	Measurement Rywotycki (2002) Estrada-Flores and Platt (2007)
Storage	1.0%	281	Audsley et al (2009)	1.0%	207	Audsley et al (2009)
Transport	0.0%	281	Audsley et al (2009)	0.0%	207	Audsley et al (2009)
Retail	2.0%	276	Tassou (2008)	1.0%	205	Tassou (2008)
Home storage	18.0%	226	Defra (2010), WRAP	2.0%	200	Assumption
Peel	17.1%	187	Measurement	0.0%	200	
Cook	-7.0%	200	Rywotycki (2002)	0.0%	200	Assumption
Presented to eat		200			200	
Home after cook	11.0%	178	Defra (2010), WRAP	11.0%	178	Defra (2010), WRAP
Total loss after cooking (assumed to originate from meal)		121			69	
Waste CO_{2e} (g) per portion		507			288	
Waste CO_{2e} (g) for family of 4		2026			1152	

Indirect emissions

In all calculations for indirect emissions, the weights of potatoes shown in Table 39 were used for each stage of the cold chain.

Potato processing

Similar data to those used for peas and carrots was used for freezing of potatoes as limited specific information on primary processing was found. Data from Rywotycki. (2002) were used for the frying/roasting process for frozen roast potatoes. It was assumed that the frying/roasting process was powered using electricity. Data on potato and produce chilling after harvest were available from Estrada-Flores and Platt (2007) and Chourasia and Goswami (2008). In addition the calculation was made of the SEC to chill potatoes using similar assumptions to those used for peas and carrots. Using this method the energy used for chilling was estimated as being 7.2 times less than that for freezing. The SEC for chilling potatoes could then be calculated relative to the mean SEC for freezing. This was lower than the data calculated from Estrada-Flores and Platt (2007) but very similar to the data presented by Chourasia and Goswami (2008). Data for freezing and chilling of potatoes are presented in Table 30. In all cases the freezing process was more energy intensive.

Table 40. Energy and carbon emissions in potato chilling and freezing.

Data source	Sector	Process	SEC (kJ/kg) (end use energy)	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Rywotycki. (2002)		Frying	2,143	447.2	65.2	260.7
Cleland (1982)	Primary processing	Freezing	670.0	139.8	20.4	81.5
Cleland (1982)	Primary processing	Freezing	690.0	144.0	21.0	83.9
Cleland (1982)	Primary processing	Freezing	780.0	162.8	23.7	94.9
Cleland (1982)	Primary processing	Freezing	900.0	187.8	27.4	109.5
Cleland (1982)	Primary processing	Freezing	940.0	196.2	28.6	114.4
Mean freezing			796.0	166.1	24.2	96.8
Total process			2938.9	613.4	89.4	357.5
Estrada-Flores and Platt (2007).	Primary processing	Chilling	168.8	35.2	5.1	20.5
Chourasia and Goswami (2008)	Primary processing	Chilling	94.8	19.8	2.9	11.5
Chourasia and Goswami (2008)	Primary processing	Chilling	106.6	22.2	3.2	13.0
Chourasia and Goswami (2008)	Primary processing	Chilling	118.4	24.7	3.6	14.4
Calculation	Primary processing	Chilling	110.6	21.6	3.1	12.6
Mean chilling			119.8	24.7	3.6	14.4

(Data used in calculation in bold)

Storage

SEC data for chilled storage of potatoes were available from ICE-E (2012) and Tassou et al (2009). The values of data from ICE-E were greater than those from Tassou et al and therefore a mean SEC from the 2 data sets was used in calculations. Data on SEC for frozen stored potato were obtained from Tassou et al and was combined with general data on SEC of frozen stores from ICE-E. A similar approach to that used for chicken, peas and carrots was used where the general cold storage data were adjusted according to the density of carrots stored (Table 41). Using these assumptions the emissions shown in Table 42 were calculated. The storage times applied were 30 days for chilled potatoes and 150 days for frozen potatoes. The storage time for frozen potatoes was estimated based on the same assumptions as those used for peas and carrots.

Table 41. SEC for storage of potatoes.

Process	kJ/kg/day	Reference
Storage-general	2.4	Estrada-Flores and Platt (2007)
Storage-general	2.6	Estrada-Flores and Platt (2007)
Storage-general	2.9	Estrada-Flores and Platt (2007)
Storage-general	3.2	Werner et al (2006)
Chilled potato	0.8	Tassou et al (2009)
Chilled general	1.1	ICE-E (2012)
Frozen general	1.6	ICE-E (2012)
Frozen potato	1.2	Tassou et al (2009)
Mixed general	1.6	ICE-E (2012)

Table 42. Energy and carbon emissions in storage of potatoes.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
ICE-E	Storage	Chilled	46.6	13.1	1.9	7.6
Tassou et al (2009)	Storage	Chilled	23.3	6.6	1.0	3.8
Mean chilled		Chilled	35.0	9.8	1.4	5.7
ICE-E	Storage	Frozen	244.1	50.4	7.3	29.4
Tassou et al (2009)	Storage	Frozen	181.4	37.5	5.5	21.9
Mean frozen			212.8	44.0	6.4	25.6

(Data used in calculation in bold)

Transport

Similar data and assumptions to those used for chicken, peas and carrots were used for the transport of potatoes. Using the data shown in Table 12 average values for transport of potatoes were calculated (Table 43). Chilled transport was slightly more energy intensive than the frozen transport (due to the greater weight of product).

Table 43. Energy and carbon emissions in food transport of potatoes.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Tassou et al (2009)	Transport	Chilled mean	824.0	231.7	33.8	135.1
Tassou et al (2009)	Transport	Frozen mean	978.8	202.3	29.5	117.9

(Data used in calculation in bold)

Retail

It was assumed that potatoes in the chilled cold chain were stored at ambient temperature in supermarkets. This was corroborated by a visit to a supermarket where only specialised or new potatoes were stored chilled. The main crop potatoes commonly used for roasting were all kept at ambient temperature.

Similar data were used to calculate the SEC for retail frozen storage of potatoes as was used for peas and carrots. The stocking density in supermarket cabinets for potato products was extrapolated from Tassou (2008) and checked by a visit to a large supermarket. Storage life in supermarkets was taken from Tassou (2008) as 96 hours for frozen potatoes (similar to other frozen produce).

Data calculated for storage of potatoes are presented in Table 44. A mean value for frozen potatoes was calculated from the 4 data sources.

Table 44. Energy and carbon emissions in retail display of potatoes.

Data source	Sector	Type of cabinet	SEC (kJ/kg) (end use energy)	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
	Retail	Chilled	0	0	0	0
Rhiemeier et al (2009)	Retail	Frozen remote	439.6	89.9	13.1	52.4
Colombo et al (2011)	Retail	Frozen remote	602.5	123.2	18.0	71.8
Tassou et al (2011)	Retail	Frozen remote	469.1	96.0	14.0	55.9
Rhiemeier et al (2009)	Retail	Frozen integral	641.0	131.1	19.1	76.4
Mean frozen	Retail	Frozen	538.0	110.1	16.0	64.2

(Data used in calculation in bold)

Transport to home

The same assumptions were made for transport of potatoes to the home as for peas and carrots. Data on energy required to transport food to the home are shown in Table 45.

Table 45. Energy to transport potatoes to the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Audsley et al (2009)	Transport to home	Chilled	480.0	108.5	15.8	63.2
Audsley et al (2009)	Transport to home	Frozen	480.0	96.2	14.0	56.1

(Data used in calculation in bold)

Domestic storage

It was assumed that potatoes in the chilled cold chain were stored at ambient temperature in the home and so only frozen potatoes incurred any energy usage. No specific data were found for frozen storage of potatoes and therefore the same basic data and assumptions used to calculate SECs for chicken, peas and carrots were used. Storage time for frozen product was assumed to be 82 days. Using these assumptions the emissions shown in Table 46 were calculated.

Table 46. Energy used to store potatoes in the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
UKHES (2010)	Domestic	Frozen	3,351.6	757.4	110.4	441.5
UKHES (2010)	Domestic	Frozen	3,143.3	710.3	103.5	414.0
Lot 13 (2005)	Domestic	Frozen	1,882.0	425.3	62.0	247.9
Lot 13 (2005)	Domestic	Frozen	2,325.2	525.4	76.6	306.3
Lot 13 (2005)	Domestic	Frozen	1,977.4	446.9	65.1	260.5
Lot 13 (2005)	Domestic	Frozen	2,256.5	509.9	74.3	297.2
Lot 13 (2005)	Domestic	Frozen	3,493.9	789.5	115.1	460.2
Lot 13 (2005)	Domestic	Frozen	2,361.6	533.7	77.8	311.1
Lot 13 (2005)	Domestic	Frozen	3,315.9	749.3	109.2	436.8
Lot 13 (2005)	Domestic	Frozen	3,372.6	762.1	111.1	444.2
Lot 13 (2005)	Domestic	Frozen	3,162.3	714.6	104.1	416.5
Lot 13 (2005)	Domestic	Frozen	3,485.8	787.7	114.8	459.2
Mean	Domestic	Frozen	2,844.0	642.7	93.7	374.6
Mean	Domestic	Chilled	0	0	0	0

(Data used in calculation in bold)

Cooking in the home

The same assumptions on the cooking process were made as for peas and carrots. It was assumed that the potatoes in the chilled cold chain were peeled prior to roasting and that the roasting increased the weight of potato as described in the potato waste section above. The emissions calculated for cooking are shown in Table 47.

Table 47. Energy used to cook potatoes in the home.

Data source	Sector	Process	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Audsley (2009)	Domestic	Cook-chilled	10,000	2260	222.3	889.1
Audsley (2009)	Domestic	Cook-frozen	10,000	2005	197.2	788.7

(Data used in calculation in bold)

Direct emissions

Direct emissions were calculated using similar assumptions and figures to those used for peas and carrots. Emissions calculated for potato storage are shown in Table 48.

Table 48. Direct emissions in chilled and frozen potato cold chains.

Sector	Refrigerant	Typical refrigerant charge per system (kg)	GWP	Leakage (%/year)	Throughput for typical system (tonnes/year)	CO _{2e} (g/kg of product)	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
FROZEN								
Production	R717	>300	0	n/a	n/a	n/a	n/a	n/a
Storage	R717	>100	0	n/a	n/a	n/a	n/a	n/a
Transport	R404A	7.5	3700	30	1500	5.6	1.1	4.6
Retail	R404A	100	3700	20	1307	56.6	11.6	46.3
Home	R600a	<0.1	~20	n/a	n/a	n/a	n/a	n/a
Total							12.7	50.9
CHILLED								
Production	R717	>300	0	n/a	n/a	n/a	n/a	n/a
Storage	R422D	75	2700	15	3200	8.4	2.4	9.4
Transport	R404A	7.5	3700	30	1500	5.6	1.6	6.2
Retail	R404A	200	3700	n/a	n/a	n/a	n/a	n/a
Home	R600a	<0.1	~20	n/a	n/a	n/a	n/a	n/a
Total							3.9	15.7

(Data used in calculation in bold)

Appendix 5: Comparable data for the whole cold chain

Data collected are shown in Table 49. Figure 19 shows a comparison between the total CO_{2e} emissions for a family of 4 for each product.

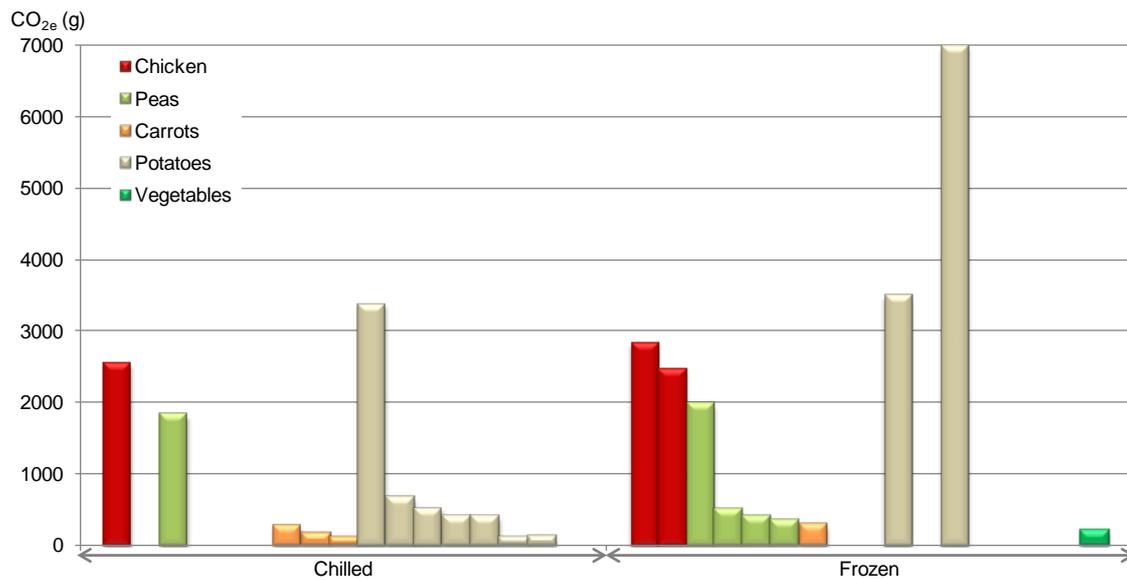


Figure 19. CO_{2e} emissions for each product for a family of 4.

Table 49. Energy used in whole cold chain for individual products.

Product	Process	Data source	System boundary	SEC (kJ/kg) for end use energy	kJ for product in meal	CO _{2e} (g) per portion	CO _{2e} (g) for family of 4
Chicken	Chilled	Carlsson-Kanyama et al (2003)	1	35,000	4,375	637.53	2550.14
Chicken	Frozen	Carlsson-Kanyama et al (2003)	1	39,000	4,875	710.40	2841.58
Chicken	Frozen	PROFEL (2012)	2	n/a	n/a	612.50	2450.00
Vegetables	Frozen	PROFEL (2012)	2	n/a	n/a	49.00	196.00
Peas	Chilled	Rao (1977)	3	44,766	3,134	456.63	1826.53
Peas	Frozen	Rao (1977)	3	48,341	3,384	493.10	1972.42
Peas	Frozen	Carlsson-Kanyama et al (2003)	1	10,000	700	102.01	408.02
Peas	Frozen	Carlsson-Kanyama et al (2003)	4	12,000	840	122.41	489.63
Peas	Frozen	Anon (1981)	5	4,658	326	47.51	190.06
Peas	Frozen	Buschmann (2012)	6	n/a	n/a	85.40	341.60
Carrots	Chilled	Carlsson-Kanyama et al (2003)	1	2,700	189	27.54	110.17
Carrots	Chilled	Carlsson-Kanyama et al (2003)	4	4,000	280	40.80	163.21
Carrots	Chilled	Buschmann (2012)	6	n/a	n/a	68.60	274.40
Carrots	Frozen	Buschmann (2012)	6	n/a	n/a	71.40	285.60
Potatoes-cooked	Chilled	Carlsson-Kanyama et al (1998)	1	4,600	920	134.06	536.26
Potatoes-baked	Chilled	Carlsson-Kanyama et al (1998)	1	29,000	5,800	845.19	3380.76
Potatoes-mashed (powder)	Chilled	Carlsson-Kanyama et al (1998)	1	5,600	1,120	163.21	652.84
Potatoes	Chilled	Williams et al (2008)	5	3,480	696	101.42	405.69
Potatoes	Chilled	Williams et al (2008)	5	3,440	688	100.26	401.03
Potatoes	Chilled	Williams et al (2008)	5	920	184	26.81	107.25
Potatoes	Chilled	Williams et al (2008)	5	1,000	200	29.14	116.58
Potatoes-French fries (1 portion)	Frozen (assumed)	Carlsson-Kanyama et al (1998)	1	60,000	12,000	1748.67	6994.67
Potatoes-French fries (4 portion)	Frozen (assumed)	Carlsson-Kanyama et al (1998)	1	30,000	6,000	874.33	3497.33

1. Farm production with production of farm inputs, drying of crops, processing, storage and transportation up to the retailer. Also include storage, preparation and cooking in households. Excluded production of capital goods (e.g. machinery and buildings, packaging material, waste treatment, transportation from the retailer to the consumer and dishwashing). Data from Sweden.
2. Pre-farm gate to the point of, but not including, preparation by the consumer.
3. Production to consumption
4. Farm production with production of farm inputs, drying of crops, processing, storage and transportation up to the retailer. Also include storage, preparation and cooking in households. Excluded production of capital goods (e.g. machinery and buildings, packaging material, waste treatment, transportation from the retailer to the consumer and dishwashing). Data from Central Europe.
5. Post farm gate.
6. Production of raw materials (such as vegetable growing and processing, transport, storage), as well as the distribution of the finished product to the trade. The usage phase with the consumer (shopping trip, preparation, washing up) and waste disposal was also taken into account.

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