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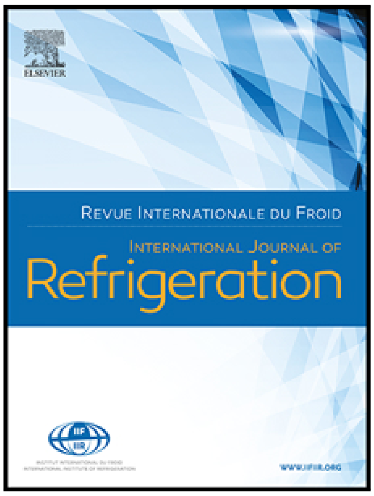

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Carbon emissions from refrigeration used in the UK food industry

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ABSTRACT

The food and beverage industry is the largest manufacturing sector in the UK. Food cold chains are energy intensive and use high global warming refrigerants. The aim of this work was to benchmark the existing UK cold chain and provide robust evidence-based data on greenhouse gas (GHG) emissions in 2019. Only emissions from refrigeration within UK borders was considered. Both Scope 1 emissions from refrigerant leakage (fugitive) and diesel for the transport refrigeration units (TRUs) as well as Scope 2 emissions from electrical power usage were estimated. These were estimated to be 14.1 $MtCO_2e$ per annum which represents 3.5% of the total UK annual territorial GHG emissions. Eighty-three percent of the Scope 1 emissions were fugitive, and 56% of these were from retail refrigeration. Agriculture and fisheries were the sectors with the lowest fugitive emissions accounting for only 3.7% of the total. Scope 2 emissions accounted for 54% of the emissions and tended to increase towards the consumer end of the cold chain, with 1.5% in agriculture and fisheries and 38% in domestic refrigeration. The FAOSTAT value of GWP used for f-gas emissions is not representative of UK emissions. UK government statistics may be underestimating domestic refrigerator emissions as they are not using real life energy consumption.

Key words: Greenhouse gas emissions, Cold chain, Global warming

1 INTRODUCTION

The food and beverage industry is the largest manufacturing sector in the UK. The agri-food sector was worth £120 bn and accounted for 9.4% of national gross value added (GVA) in 2018. The agri-food sector employs 4.1 m people (DEFRA, 2020).

Conventional cold chains for food are energy intensive. For example, domestic refrigerators and freezers consume almost 4% of global electricity (IIR, 2019). The refrigeration systems applied also use refrigerants, which often have high global warming potentials (GWPs). The leakage of these refrigerants to the atmosphere and the associated CO_2e emissions from the electricity used to power the refrigeration systems is significant. The food cold chain alone is responsible for a third of hydrofluorocarbon (HFC) emissions, or 1% of global greenhouse gas (GHG) emissions and food refrigeration is estimated to be responsible for 2-4% of the UK's total GHG emissions (Ravishanka et al., 2020).

Availability of information varies across the food cold chain, with some sectors providing little information. For example, the Chilled Food Association (CFA, 2022) state on their web site: 'There is no official collection of market data either in the UK, EU or internationally'. Evidence from sources such as climate change levy (CCL) data shows that sectors such as cold storage and retail have reduced carbon emissions over the last 5-10 years and so it is essential when benchmarking the cold chain that up-to-date information is used in the assessment.

The aim of this work was to benchmark the existing UK cold chain (chilled and frozen) and provide robust evidence-based data on emissions in 2019. Only emissions from the refrigeration were considered, both direct from refrigerant leakage and indirect from electrical power usage. This paper expands upon a paper presented at the 7th IIR Conference on Sustainability and the Cold Chain, 2022 (Foster et al, 2022). It presents emissions in terms of the different Scopes defined under the GHG Protocol and compares with two international databases that provide international food emissions (EDGAR-FOOD and FAOSTAT).

2 METHOD

The cold chain was split into sectors with UK Standard Industrial Classification (SIC, 2007) codes. The SIC codes do not mirror the cold chain sectors. For example, there are likely to be many SIC codes in agriculture food and fisheries which do not have cold chain emissions and food service includes canteens which may operate in many different SIC code industries.

- Agriculture and Fisheries (SIC Code 01 and 03)
- Food and beverage production (SIC Code 10-11)
- Refrigerated warehouses (SIC Code 52.10)
- Retail (SIC Code 47.11 and 47.2)
- Food service (SIC Code 56)
- Transport between all sectors (SIC Code 49.2 and 49.4)
- Domestic (SIC code N/A)

The GHG Protocol (WBCSD and WRI, 2004) have defined three scopes of emissions. This study only deals with Scope 1 and Scope 2 emissions.

Scope 1 emissions are the direct GHG emissions from the sectors. Stationary equipment is almost entirely powered by electricity from the electrical grid and not directly powered from fossil fuels. However, mobile refrigeration, e.g., transport refrigeration predominantly uses diesel fuel to power the transport refrigeration unit (TRU). Therefore, the Scope 1 emissions include fugitive emissions for all sectors and diesel fuel in the transport sector. Only the emissions associated with the refrigeration of the vehicle were considered and emissions to drive the vehicle were excluded.

The main GHG refrigerants are the fluorinated gases (f-gases) which are hydrofluorocarbons (HFCs). Emissions of f-gases can occur at various stages of the refrigeration equipment life-cycle, manufacturing, installation, over the operational lifetime and at disposal.

The most comprehensive source of information for direct emissions is the UK Greenhouse Gas Inventory (NAEI, 2021). This contains national greenhouse gas emission estimates for the period 1990-2019 and is the UK's National Inventory Report (NIR) submitted to the United Nations Framework Convention on Climate Change (UNFCCC). It includes losses during manufacture/initial charging and at decommissioning as well as losses in use.

Scope 2 emissions are the indirect GHG emissions from the generation of electricity purchased by the sectors. A carbon intensity of the grid in 2019 of 0.22 $kgCO_2e/kWh$ (BEIS, 2021) was used to convert grid electricity to GHG emissions.

A literature review of reports and peer reviewed papers was conducted with the aim of finding the latest and most comprehensive data on emissions. A level of confidence was attached to the results which considered the quality of data, agreement between separate sources and age of the data.

For electrical energy consumption, the Digest of UK Energy Statistics (DUKES) and Energy consumption in the UK (ECUK, 2020) was widely used. This data is compiled by the Department for Business, Energy & Industrial Strategy (BEIS) and contains data for many years up until the current year. The UK Statistics Authority has designated these statistics as National Statistics, in accordance with the Statistics and Registration Service Act 2007 and therefore they were considered as the most accurate data available. DUKES data does not always differentiate the energy consumed by refrigeration systems in each of the cold chain sectors and therefore further analysis and assumptions were often required. Energy consumption values shown were collated per year for 2019, unless otherwise stated.

3 RESULTS

3.1 Scope 1 emissions (fugitive)

3.1.1 Agriculture and fisheries

The UK GHG Inventory provides emissions for different parts of agriculture but does not differentiate directly for direct emissions from refrigeration. A study by SKM Enviros (2011) estimated 0.05 $MtCO_{2e}$ of direct emissions from agriculture. No other studies were found.

3.1.2 Food and beverage manufacture

This sector typically has very large refrigeration systems, that can be blast freezers, glycol chillers etc., often with in excess of 500 kg of refrigerant. However, there are also medium sized systems with typically 10 to 100 kg of refrigerant that can be used for cooling product or short-term cold storage.

The only data that could be found for direct emissions for food manufacturing only (not cold storage) was from SKM Enviros (2011), who estimated 0.89 $MtCO_2e$ of direct emissions for food and beverage manufacture. This is based on 2010 data and is made up of 0.54 and 0.35 $MtCO_2e$ from HFCs and HCFCs respectively.

3.1.3 Refrigerated warehouses

These systems tend to be large industrial systems commonly using ammonia which has a GWP of 0. This sector tends to maintain temperature, not reduce it, although some sites have blast freezers.

The only data that could be found for direct emissions for cold storage only was from SKM Enviros (2011), who estimated 0.18 $MtCO_2e$ of direct emissions. SKM Enviros (2011) does not mention products other than the food and beverage sector. However, refrigerated warehouses are used for other temperature-sensitive products, such as pet food, pharmaceutical, cosmetic, horticulture and human tissue. The authors were not able to find comprehensive data on the proportion of cold storage used for food. However, based on number of warehouses who are part of the cold chain federation (CCF, 2022), pet food, funeral care, horticulture and pharmaceutical products account for 11% of the warehouses. If we assume the non-food warehouses have the same emissions as the food warehouses, we can estimate that the food share of cold store warehouses is 11% less at 0.16 $MtCO_2e$.Industrial (food manufacturing + refrigerated warehouses)

The UK GHG Inventory shows emissions from industrial systems. This includes industrial process refrigeration (not necessarily food) and cold storage. Larger refrigeration systems tend to use ammonia.

According to the UK GHG Inventory for 2019 industrial refrigeration accounted for 1.34 $MtCO_{2e}$ of emissions. This includes food factories, cold stores, petrochemicals, pharmaceuticals, printing, and plastics. It is assumed that the food manufacturing and cold storage industry represents approximately 75% (1.01 $MtCO_2e$) of industrial refrigeration facilities, with the remaining 25% being in the chemical and pharmaceutical industries (ICF, 2011).

The sum of food and beverage manufacture (section 3.1.2) and cold refrigerated warehouses (section 3.1.3) is therefore 1.07 $MtCO_2e$. This matches closely with the value from this section.

3.1.4 Land transport refrigeration

Data from the UK GHG Inventory shows emissions from large trucks and iso-containers of 0.23 $MtCO_2e$ and vans and light trucks of 0.02 $MtCO_2e$ (total of 0.25 $MtCO_2e$). These emissions will also include some non-food sector emissions as described in section 3.1.3.

3.1.5 Marine refrigeration (fishing)

Ziegler et al (2013) reported that modern pelagic vessels have cooling systems that use environmentally harmless refrigerants (e.g., ammonia) and only a small proportion of pelagic vessels were still using the hydrochlorofluorocarbon (HCFC) R22. R22 is still however common in demersal vessels.

Data from the UK GHG Inventory shows emissions from marine refrigeration of 0.44 $MtCO_2e$.

3.1.6 Air transport

Air transport of food between countries in the UK is carried out using insulated containers and not subject to refrigeration, therefore, there are no refrigeration-based emissions in this sector.

3.1.7 Retail

According to the BRA (2018) there were 8,000 to 12,000 multi evaporator refrigeration systems in retail premises in the UK. In addition, there were a similar number of single compressor systems in commercial and/or retail premises. Whilst progress has been made in converting these systems away from R404A, a significant proportion still (at the time of publication) use R404A as the refrigerant.

Large supermarkets tend to use centralised "pack" systems. In small shops there is widespread use of integral systems and small split systems (with a remote condensing unit serving one or more display cases) (SKM Enviros, 2011).

According to (Lamb, 2021) about a quarter of retailers' systems use CO_2 as the refrigerant, and the trend for this proportion continues to increase.

The only data on direct emissions for commercial refrigeration excluding food service that could be found were those from SKM Enviros (2011) who estimated 3.0 $MtCO_2e$ of direct emissions in retail, being 2.6 $MtCO_2e$ from HFCs and 0.4 $MtCO_2e$ from HCFCs.

3.1.8 Food Service

This sector is mainly small systems including integrals (e.g. beverage coolers, food display cases) and small split systems (e.g. cellar cooling in pubs and small walk-in cold stores).

The only data on direct emissions that could be found for food service refrigeration were again those from SKM Enviros (2014) who estimated 0.45 $MtCO_2e$, with 0.24 $MtCO_2e$ being from HFCs and 0.21 $MtCO_2e$ from HCFCs.

3.1.9 Commercial including food service and retail

The UK GHG Inventory shows emissions from commercial systems. The emissions for this sector were reported as 3.19 $MtCO_2e$ in 2019. The sum of the retail (Section 3.1.7) and food service emissions (Section 3.1.8) was 3.45 $MtCO_2e$ which is similar to the value reported here.

3.1.10 Domestic

In 2013, 98% of all household refrigeration appliances were using isobutane (R600a) (VHK and ARMINES, 2015) which has a GWP of 3.

According to the UK Greenhouse Gas Inventory for 2019, domestic refrigeration emissions were 0.15 $MtCO_2e$.

3.2 Scope 1 emissions (diesel)

3.2.1 Transport refrigeration

This sector is split into land and marine refrigeration. It only considers transport within and not outside of the UK border.

3.2.1.1 Road transport

In this sector the refrigeration systems can be powered directly from the vehicle's main engine, or from a separate diesel-powered auxiliary TRU. TRUs are categorised in policy as Non-Road Mobile Machinery (NRMM), which means they have not been subject to the same regulation, or research into emissions and are also not included in emissions estimates for the transport sector (CCF, 2021).

According to CCF (2021) there is a lack of data, e.g., number of temperature controlled vehicles on the road and the emissions from these vehicles. Although these vehicles are registered, there is no specific classification for temperature-controlled vehicles and a significant number on UK roads are not registered or operated by UK companies.

According to McGinlay (2004) there were 47,500 refrigeration units on heavy good vehicles (HGVs) with an average power rating of 11.5 kW and an annual usage of 2,500 hours per year. Fuel consumption is typically 3 L/h when the unit is at full capacity (100% compressor run time). Based on carbon intensity of diesel fuel of 2.63 kg of CO_2e per litre this gives 0.7 MtCO_2e for HGVs (based on estimated 75% compressor run time). This covers articulated and non-articulated goods vehicles but does not include vans where the refrigeration system is likely driven by the vehicle engine.

CCF (2021) estimate that there are 30,000 refrigerated trailers/semi-trailers (articulated HGVs) operated by UK based transport businesses and a further 15,000 rigid (non-articulated) HGVs and 25,000 vans (LGVs). If we assume there are a total of 70,000 TRUs and each TRU produces the same emissions as that calculated previously, this gives emissions of 1.02 MtCO_2e. This aligns relatively well with data from SKM Enviros (2011) who estimated 1.2 MtCO_2e of indirect emissions from refrigeration used in food transport in 2010.

The emissions were considered to be between the 1.02 MtCO_2e calculated using a number of different sources and 1.2 MtCO_2e estimated by SKM Enviros (2011). A medium confidence was attributed to these data. These emissions will also include some non-food sector emissions as described in section 3.1.3.

3.2.1.2 Marine refrigeration (fishing)

According to Gabrielii and Jafarzadeh (2020) refrigeration is a small proportion of the GHG emissions of UK fisheries. Primary production is in most cases the largest contributor with transport the largest contributor in some cases.

According to the National Atmospheric Emissions Inventory (NAEI) fishing vessels emitted 0.78 MtCO_2e in 2019 due to their fuel use. It is unknown what proportion of this is used for refrigeration. However, in a study on Norwegian seafood products (Ziegler et al. 2013), fuel use accounted for 63% to 87% and refrigerant leakage 13% to 37% of total GHG emissions.

It has not been possible to determine a value for the emissions of refrigeration from fishing vessels, however, it appears that this is small compared to that from road transport and therefore in this analysis has been ignored.

Total Scope 1 emissions from all sectors were estimated at 6.51 MtCO_2e of which 5.39 MtCO_2 were fugitive. Figure 1 shows the refrigerant emissions (MtCO_2e) in each of the food sectors. Over half of the fugitive emissions (56%) are from retail. The smallest emitter is agriculture and fisheries at 0.9% of fugitive emissions.

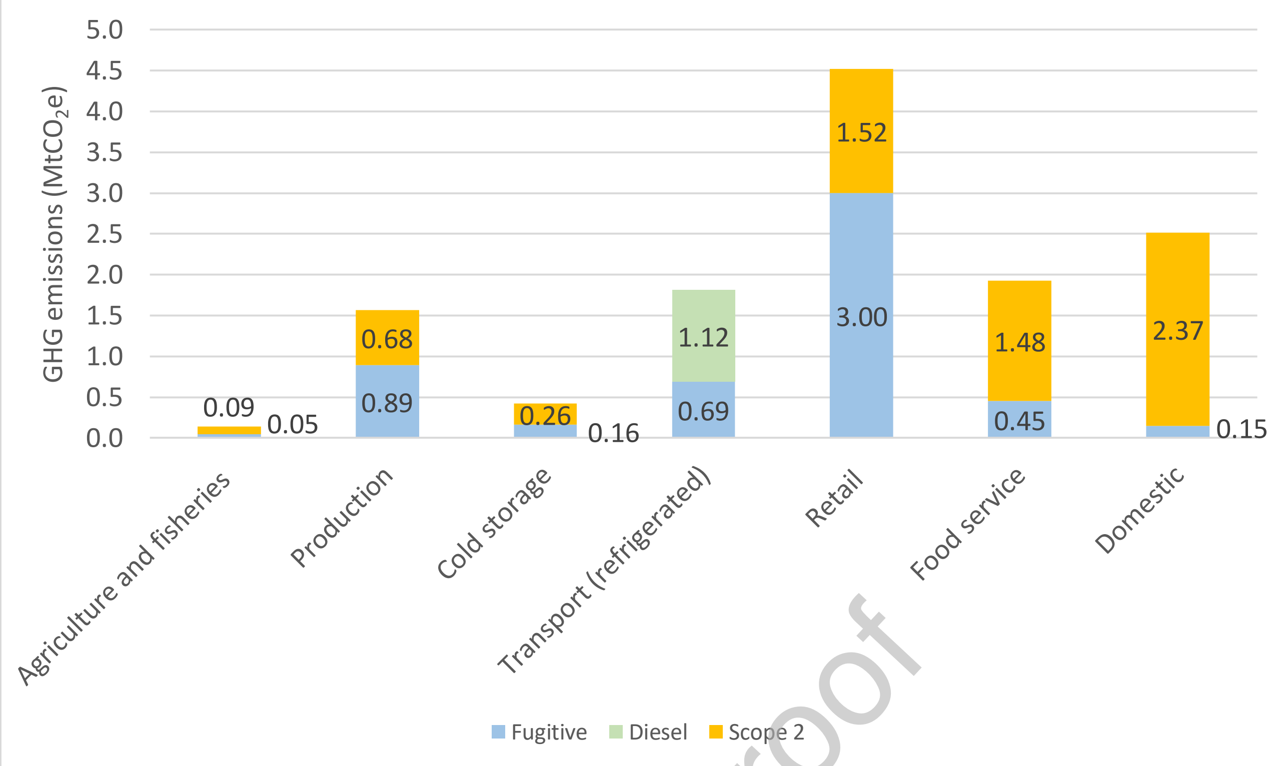

Figure 1. Scope 1 (fugitive and diesel) and Scope 2 emissions for cold chain sectors

3.3 Scope 2 emissions (Electrical energy)

3.3.1 Agriculture and fisheries

During 2011, the UK farming and fishing sector accounted for 55.1 $MtCO_2e$ GHG emissions (DEFRA 2014). Unlike other sectors, energy consumption is a small proportion of the emissions, with enteric fermentation in ruminating animals and oxidisation of nitrogen in fertilisers the sources of most of these emissions.

Dairying accounts for 57%, potatoes 23%, horticultural field crops 10%, protected crops 5% and poultry 5% of the refrigeration energy (Warwick and FEC Services, 2007). The main use of refrigeration and cooling in dairying is the rapid removal of "body heat" from milk, whilst in the case of field vegetables it is the removal of "field heat" after harvest. Refrigeration and cooling are also used during the storage of crops.

According to DUKES data for 2019 (BEIS, 2020), agriculture (including tobacco and fisheries) used 1.51 million tonnes oil equivalent (Mtoe) (17.50 TWh) of final energy, of which 0.362 Mtoe (4.21 TWh) was electrical consumption. DUKES does not break the consumption down to the level of refrigeration.

Warwick and FEC Services (2007) calculated that in 2005, 1.15 TWh (6%) of energy use in agriculture was for refrigeration. This energy consumption was primary energy consumption (energy of primary energy source, e.g. power station) and was based on climate change levy (CCL) returns. Therefore, the final energy consumption (energy consumption at system/appliance) would be 2.6 times less (primary energy factor at the time) which equals 0.44 TWh (2.3% of the total energy consumption).

If we assume that 2.3% of the energy consumption in 2019 was refrigeration and compare this to the DUKES energy consumption for 2019 (17.50 TWh) this provides a refrigeration energy consumption of 0.40 TWh. This is 9% less than the refrigeration energy consumption presented by Warwick and FEC Services (2007) in 2005.

SKM Enviros (2011) carried out a study into GHG emissions from refrigeration systems in the UK food chain in the period October 2010 to May 2011. They estimated energy consumption of 0.44 TWh for refrigeration which was 11% of total energy consumption for the sector. This exactly matches the value from Warwick and FEC Services (2007).

The sources above provide good consensus on an energy consumption for the sector of between 0.40 and 0.44 TWh.

3.3.2 Food and beverage processing/manufacturer

Thermal processes, such as refrigeration and heating, account for the majority of energy use in food processing, with process heating generally the most important (Ladha-Sabur et al., 2019)

Much of the refrigeration energy in this sector is used to extract heat from products to chill or freeze them. Once heat is extracted from the food, the refrigeration system energy is much less as there is only a requirement to maintain the food at the correct temperature in a holding room. Meat and milk processing are high users of refrigeration, with up to 90% of total energy being used for cooling and refrigeration (Compton et al., 2018)

During 2011, the food manufacturing sector accounted for 13 $MtCO_2e$ of GHG emissions and 5.2 Mtoe (60 TWh) of primary energy was used (DEFRA 2014). Natural gas accounted for 62% and electricity 30% of total energy consumption in food and beverage manufacturing in 2011.

DUKES data for 2019 (BEIS, 2020) shows the manufacture of food products used 214 ktoe (2.49 TWh) of refrigeration and beverages used 0.051 Mtoe (0.59 TWh) of final energy giving a total of 3.08 TWh.

3.3.3 Refrigerated warehouses

The Refrigerated warehouse sector was considered separately from small walk-in cold storage rooms which are used in food manufacture, retail and food service. The emissions from cold rooms within food manufacturing and retailing are considered in their respective sectors. The refrigerated warehouse sector was considered as cold storage facilities not within these other sectors, however, some double accounting cannot be avoided. Most of these systems are large industrial systems.

In 2018, the 425 cold store warehouses registered under the Cold Chain Federation's (CCFs) climate change agreement (CCA) used 3.5 TWh of primary energy (CCF, 2020). The final electrical energy consumption was therefore 1.35 TWh, using the conversion factor used by CCF.

Based on CCAs in 2017 and 2018 (Environment Agency, 2019), the 238 cold storage organisations (some organisations have more than 1 store) who submitted a CCA, had total emissions of 1.37 $MtCO_2e$ over the 2 years, or an average of 0.685 $MtCO_2e$ per year. This does not include direct emissions from refrigerant leakage and is derived from a specific calculation from electrical consumption that does not take into account renewables in the grid. An energy consumption of 1.32 TWh was calculated using CCA equations and current electrical carbon intensity of the grid. This is 2% less than that reported by (CCF, 2020).

As not all cold storage organisations will be part of a CCA, there may be more emissions from these organisations than reported via the CCL. There is no comprehensive database that covers all refrigerated warehouses in the UK. Fikiin et al. (2017) compared the Global Cold Chain Alliance (GCCA) database and their study using Google maps and found facilities with a total of 39.4 million m^3 cold storage space in the UK. This was calculated from 253 cold store facilities with a floor area of 3.65 million m^2. This study showed that the reported warehouse volume from the GCCA database was only about 15% of what was calculated using the Google maps method. As the number of refrigerated warehouses reported by CCF (2020) and CCF and SCR (2020) is higher than that reported by Fikiin et al. (2017) it seems reasonable to assume that the CCAs used in this study cover the vast majority of store energy consumption.

SKM Enviros (2011) estimated 0.9 TWh of electrical consumption for cold storage and 80% of this (0.68 TWh) was directly for refrigeration. As this data was based on 200 questionnaires and was 10 years old, it was not given the high confidence of the previous data.

Using an energy consumption of 1.32 TWh and reducing it by 11% (as presented in section 3.1.3 for fugitive emissions, as some cold stores are not used for food) generates emissions of 0.26 $MtCO_2e$ emissions from food warehouses.

3.3.4 Retail

In this sector refrigeration in supermarkets is typically from large distributed systems serving many retail display cases. The cooling demands in retail are a "holding load" – the aim is that product is received at the correct temperature and must be kept at that temperature in bulk storage or in retail display cabinets.

During 2011 it was estimated that food retail accounted for 4.9 Mtoe of primary energy (56.7 TWh), therefore 19.4 TWh of final energy consumption (based on primary/final energy ratio in 2011 of 2.93 (DEFRA, 2014). The proportion of store electrical consumption which is due to refrigeration has been reported by Foster et al. (2018) as 33% and Tassou et al. (2011) as between 29% for a hypermarket and 60% for a small store. Using a value of 33% provides a refrigeration energy consumption of 6.40 TWh.

SKM Enviros (2011) estimated that during 2010 retail stores consumed 27.3 TWh of electricity of which 27% (7.36 TWh) was used in refrigeration.

BEIS (2016) modelled data based on telephone survey responses for the period 2014/15 and showed that the retail sector consumed 21.7 TWh of electrical energy. For large retail chains (100+ outlets) the proportion of refrigeration to electrical energy consumption was 42.3%. Cooled storage in the retail sector was shown to be 6.96 TWh, including cooling in large food shops with floor area exceeding 750 m^2 (3.27 TWh) and small shops (3.63 TWh).

Using data from Vasquez-Nicholson (2016) which details the number, type and size of stores from the UK supermarket chains and multiplying this by specific energy consumption provided by Foster et al (2018 and 2019) gives a total electrical energy consumption of 11.79 TWh. Using the proportion of this electrical energy consumption that is from refrigeration (33%) provided by Foster et al (2018) gives a total refrigeration consumption of 3.89 TWh. As this data only includes the main retailers it compares well with the data from BEIS (2016) for large food shops.

These three reported figures from SKM Enviros (2011), DEFRA (2014) and BEIS (2016) were reasonably close (minimum value within 13% of maximum value) and therefore a mean value of 6.91 TWh was chosen.

3.3.5 Food service

The food service sector is made up of many sub sectors, e.g., restaurants (eat in and take-away), pubs and clubs, cafés, hotels, leisure, staff canteens, health care and education. Foods and beverages are mainly refrigerated in small systems including integral systems (e.g., beverage coolers, food display cases) and small split systems (e.g. cellar cooling in pubs and small walk-in cold stores).

SKM Enviros (2011) estimated for 2010 that 14.8 TWh of electrical consumption was used in food service, of which 4.16 TWh was for refrigeration (28%).

Electricity consumption data collected by Mudie et al., (2016) in a sample of fourteen UK public house-restaurants (gastro pubs) showed that refrigeration represented the largest consumption in each of the study kitchens, using 41% of the electricity (13% walk in freezer, 5% walk in fridge and 23% other refrigeration). This was 28% of the total energy (including gas) of the kitchen, with the kitchen using 63% of the whole business electrical consumption.

Kemna et al., (2021) stated that there were 9.14 million professional refrigeration products (storage cabinets, process chillers and condensing units) in stock in the EU (assumed EU 28, including UK) in 2020. The energy consumption of equipment used in this sector for 2020 was 9 TWh for storage cabinets and 28 TWh for condensing units. However, condensing units are also likely to be used in other sectors such as retail. The UK had 14.2% of the population of the EU, therefore if we pro rata based on population the energy consumption is 1.28 TWh per year for storage cabinets in the UK.

According to modelled data based on telephone survey responses for the period 2014/15, the hospitality sector consumed 8.76 TWh of electrical energy (BEIS, 2016). Hospitality was defined as cafes, hotels, pubs, restaurants and takeaways. It did not include hospitality premises that were present in other building types and therefore underestimated the number of sites (97,100 as opposed to 257,000 according to SKM Enviros (2014). The largest sub sector for cooled storage was pubs which accounted for 70% (BEIS, 2016).

Cooled storage accounted for 1.35 TWh of energy consumption (15%). This value is 5% higher than storage cabinets reported in Kemna et al. (2021).

According to a study by SKM Enviros (2014) there were 1 $MtCO_2e$ emissions from soft beverage refrigeration in food service. Based on the electricity emission factor given this means that 1 TWh of energy was consumed. It was reported that 80% of the emissions in food service and retail are from bottle coolers.

Data from a database provided by the Food Equipment Association (FEA) was used to estimate the energy consumed by all the refrigeration equipment in the UK's food service industry. This database contains up to date data on number of facilities and estimates the number of items of refrigerated equipment in each facility. The database showed an average of 19.2 refrigerated appliances per site. This was much larger than the 5.8 refrigerated appliances per site provided by ICF (2011). Using European stock data for appliances from Kemna et al. (2021) and EC (2015) and correcting based on population and energy consumptions for appliances from a number of sources (SKM Enviros, 2014; Mudie et al., 2016; Fisher et al., 2012; Pentland, 2021) an energy consumption of 9.28 TWh was calculated.

There is a wide range of emissions values reported which reflects the disparate nature of food service. The emissions were between 4.16 and 9.28 TWh.

3.3.6 Domestic (in the home)

DUKES shows energy consumption from 4 types of domestic cold appliances. These were chest freezers, fridge-freezers, refrigerators and upright freezers (BEIS, 2020). The total energy consumption for these appliances in 2019 was 10.75 TWh. As this data is direct and from Government statistics with no further analysis required, this value is given high confidence.

3.3.7 Entire UK food chain

The refrigeration electrical energy consumption of the entire UK food cold chain was estimated as 29.1 TWh in 2019, leading to carbon emissions of 6.4 $MtCO_2e$ (using 0.22 $kgCO_{2e}$/kWh electrical emissions factor, as stated in Section 2). Figure 1 shows the Scope 2 emissions in the UK food cold chain.

The total Scope 1 and Scope 2 emissions from refrigeration in the food cold chain were estimated to be 12.90 $MtCO_2e$ per annum in 2019.

The total UK annual territorial greenhouse gas emissions in 2019 were 454.8 $MtCO_2e$ (BEIS, 2020). Therefore, food refrigeration represents 2.8% of this. Figure **2** shows UK annual territorial greenhouse gas emissions split into different sectors. Food refrigeration has slightly lower GHG emissions to the sum of both the agriculture and industrial sectors.

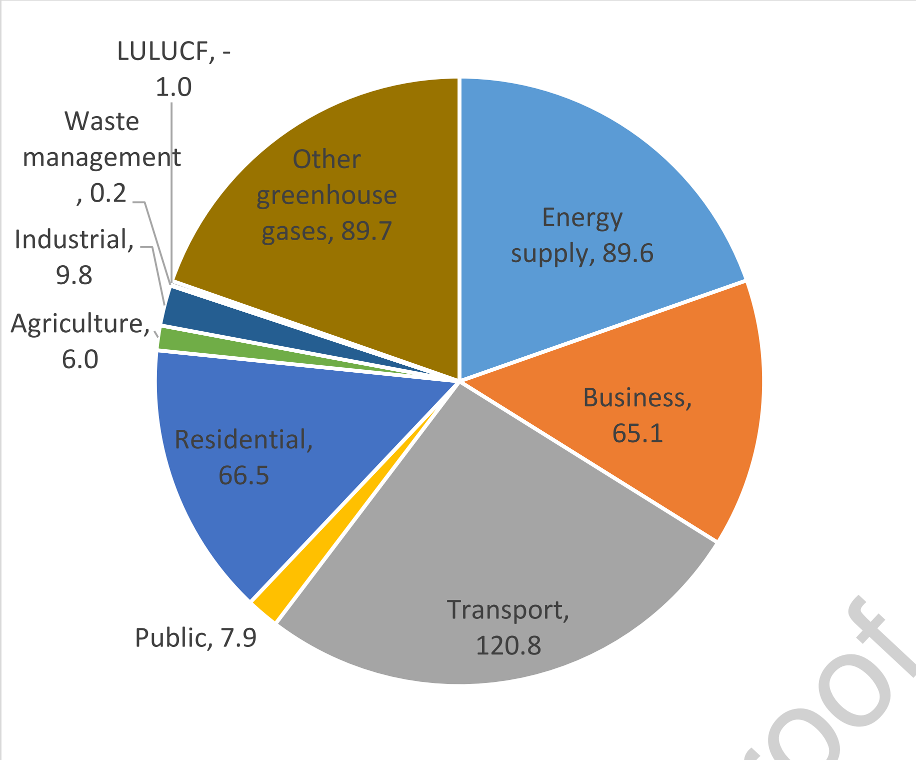

Figure 2. UK annual territorial greenhouse gas emissions 2019 LULUCF stands for Land use, land use change and forestry.

3.4 Data uncertainty

The sector with the largest single emission is from Scope 1 in retail which accounts for 55% of total Scope 1 emissions at 3.0 $MtCO_2e$. This has been compared to two international databases that provide international food emissions. These are Emissions Database for Global Atmospheric Research (EDGAR) or specifically EDGAR-FOOD and the UN Food and Agriculture Organization (FAO) corporate statistical database, FAOSTAT.

EDGAR-FOOD show UK f-gas emissions related to the food sector of 5.68 $MtCO_2e$. However, this is shown as entirely within the retail sector. In this paper we estimate total fugitive total emissions of 5.43 $MtCO_2e$, with 64% of this within the retail and food services sector.

FAOSTAT provide UK food related f-gas emissions of 12.55 $MtCO_2e$ also entirely within the retail sector. FAOSTAT emissions are very high, compared to EDGAR-FOOD and the data presented in this paper. This is because instead of calculating the emissions of each f-gas independently they use an average GWP, which is the mean of all the f-gases, this gives an applied GWP >5000, which is larger than that for R404A which was the most common refrigerant. Now due to regulations, high GWP refrigerants are being replaced by much lower GWP gases. This assumption accounts for the large discrepancy.

From this we can conclude that this paper reports similar overall fugitive emissions to EDGAR-FOOD, but with the added benefit of splitting the emissions into the different cold chain sectors. This paper offers more accurate fugitive emissions than FAOSTAT due to their inaccurate estimation of GWP of refrigerants used in the UK.

The next single emission presented is from Scope 2 in domestic which accounts for 37% of Scope 2 emissions at 2.37 $MtCO_2e$. It is not possible to directly compare to EDGAR-FOOD and FAOSTAT, as they report total emissions from all of the food sector, therefore include cooking and other kitchen appliances, not just refrigeration. In the UK, the electrical product information from ECUK (2020) presents energy consumption from 4 types of domestic cold appliances (chest freezer, fridge-freezer, refrigerator and upright freezer). The 2019 UK stock energy consumption and number of appliances from DUKES is shown in Table 1. The total energy consumption from these appliances was 10.75 TWh. Fridge-freezers had the highest total energy consumption, and this was because there were more of them (more than the sum of the other 3 appliances). The largest energy consumption per individual appliance was for chest freezers, which was the least numerous type of appliance.

Table 1. Stock energy consumption and number of different types of domestic refrigerator for 2019.

	Chest Freezer	Fridge-freezer	Refrigerator	Upright Freezer
Number of appliances owned by households in the UK (thousands)	4,225	19,365	7,011	7,049
Total energy (GWh/a)	1457	6364	1053	1880
Energy per appliance (kWh/a)	345	329	150	267

These energy consumption figures are lower than those measured in households (i.e., 'real life' not test conditions) in England by Biglia et al. (2018). They measured averages of 420, 390, 274 and 342 kWh/a for chest freezers, fridge-freezers, refrigerators and upright freezers respectively. For the most common appliance (fridge-freezers) real life consumption was 19% higher than UK Government statistics. This suggests UK Government statistics, used for this study may be underestimating the real energy consumption of domestic refrigerators.

4 DISCUSSION AND CONCLUSIONS

Scope 1 and 2 GHG emissions related to food refrigeration in the UK were estimated to be 12.9 MtCO2e per annum over the period 2019/2020 which represents 3.2% of the total UK annual territorial greenhouse gas emissions. Scope 2 emissions accounted for 50% of the emissions. Eighty-three percent of the Scope 1 emissions were fugitive, the rest was from diesel from TRUs.

Scope 2 emissions tended to increase towards the consumer end of the cold chain, with 1.4% in agriculture and fisheries and 37% in domestic refrigeration.

More than half of the fugitive emissions (56%) were from retail refrigeration. Agriculture and fisheries at 0.9% and domestic at 2.8% were the sectors with the least fugitive emissions.

This work has shown that the FAOSTAT value of GWP used for f-gas emissions is not representative of UK emissions. It has also shown that UK government statistics maybe underestimating domestic refrigerator emissions as they are not using real life energy consumption. Further work is ongoing to extend emissions to all food related emissions (not just refrigeration) and to further extend to countries within Europe. This is being carried out in an EU funded project called ENOUGH (https://enough-emissions.eu/).

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