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The food cold-chain and climate change

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ABSTRACT

Any noticeable increase in ambient temperature resulting from climatic change will have a substantial effect on the current and developing food cold-chain. A rise in temperature will increase the risk of food poisoning and food spoilage unless the cold-chain is extended and improved. The little data that is available suggests that currently the cold-chain accounts for approximately 1% of CO_2 production in the world, however this is likely to increase if global temperatures increase significantly. Using the most energy efficient refrigeration technologies it would be possible to substantially extend and improve the cold-chain without any increase in CO_2, and possibly even a decrease.

1. Introduction

Climate change has been described as 'the single most important issue that we face as a global community' (Blair, 2004). Many recent publications (Brander, 2009; Fraser, 2006; Gregory, 2009; Miraglia et al., 2009; Patterson & Lima, 2010) that consider relationships between climate change and food concentrate, on preharvest factors. While Jacxsens et al. (2009) look at the food supply chain but not the refrigeration aspects of it. This review concentrates on the relationship between the refrigerated cold-chain for food and climatic change.

Refrigeration stops or reduces the rate at which changes occur in food. These changes can be microbiological (growth of microorganisms), physiological (e.g. ripening, senescence and respiration), biochemical (e.g. browning reactions, lipid oxidation and pigment degradation) and/or physical (e.g. moisture loss). An efficient and effective cold-chain is designed to provide the best conditions for slowing, or preventing, these changes for as long as it is practical.

Refrigeration is important in both maintaining the safety and quality of many foods and enabling food to be supplied to an increasingly urbanised world. In reality, less than 10% of such perishable foodstuffs are in fact currently refrigerated (Coulomb, 2008). It is estimated that post-harvest losses currently account for 30% of total production (Coulomb, 2008). The production of food involves a significant carbon investment that is squandered if the food is then not utilised. Thus there is a balance to be achieved. The International Institute of Refrigeration (IIR), (2009) estimate that, in theory, if developing countries could acquire the same level of refrigerated equipment as that in industrialized countries, over 200 million tonnes of perishable foods would be preserved, this being roughly 14% of the current consumption in these countries (Table 1).

So, what is the relationship between the cold-chain and climatic change? Before undertaking a review of publications on the topic it is important to be clear what we are trying to review. After much thought, we consider that there are two very different aspects to the question:

1. What will be the effect of climatic change, especially the predicted increase in average world temperature, on the cold-chain?
2. How much does the cold-chain, and potential changes to it, contribute to climatic change, especially an increase in world temperature?

When considering the second question, are there new technologies, changes to existing technologies, or alternative processes, that could make a substantial difference in the future?

The food manufacturing industry utilises chilling and freezing processes as a means of preserving foods. Refrigeration of these foods is continued during transportation, retail distribution and home storage to maintain the foods at the desired temperatures. These are important steps in maintaining the safety, quality and

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Table 1
Refrigeration requirements and losses due to lack of refrigeration (adapted from International Institute of Refrigeration (IIR), 2009).

	World population	Developed countries	Developing countries
Population in 2009 (billion inhabitants)	6.83	1.23	5.60
Refrigerated storage capacity (m^3/1000 inhabitants)	52	200	19
Number of domestic refrigerators (/1000 inhabitants)	172	627	70
Food losses (all products) (%)	25	10	28
Losses of fruit and vegetables (%)	35	15	40
Loss of perishable foods through a lack of refrigeration (%)	20	9	23

shelf life of foods for the consumer, and the processes from primary cooling through to domestic storage make up the 'food cold-chain'.

There have been a number of international reports on the impact of climate change on "access to food" and "food security" (Schmidhuber & Tubiello, 2007). Access to food refers to the ability of individuals, communities, and countries to purchase sufficient quantities and qualities of food. Over the last 30 years, falling real prices for food and rising real incomes have led to substantial improvements in access to food in many developing countries. Increased purchasing power has allowed a growing number of people to purchase not only more food but also more nutritious food with more protein, micronutrients, and vitamins. Climate change will increase the dependency of developing countries on imports and accentuate existing focus of food insecurity on sub-Saharan Africa and to a lesser extent on South Asia (Schmidhuber & Tubiello, 2007). As Garnett (2008a) states, while all regions of the world will ultimately suffer from the consequences of a warming climate, agricultural production in northern latitudes (including the UK), may initially benefit. Countries in the southern hemisphere, on the other hand, and particularly those that are already agriculturally vulnerable are already beginning to suffer the negative consequences of a warmer, more volatile climate. They will not be able to grow as much or be as confident about the yield as they can currently are so the number of people at even greater risk of hunger will grow. There is therefore a strong moral case for countries to ensure that their farming sector is robust enough to grow enough food not just for their own populations, but also for people overseas (Garnett, 2008a, 2008b). Consequentially an effective and efficient cold-chain will be required to deliver this food around the world.

To provide safe food products of high organoleptic quality, attention must be paid to every aspect of the cold-chain from initial chilling or freezing of the raw ingredients, through storage and transport, to retail display. Removing the required amount of heat from a food is a difficult, time and energy consuming operation, but critical to the operation of the cold-chain. As a food moves along the cold-chain it becomes increasingly difficult to control and maintain its temperature. This is because the temperatures of bulk packs of refrigerated product in large storerooms are far less sensitive to small heat inputs than single consumer packs in open display cases or in a domestic refrigerator/freezer. Failure to understand the needs of each process results in excessive weight loss, higher energy use, reduced shelf life or a deterioration in product quality.

If climatic change results in a substantial rise in average ambient temperatures this will impose higher heat loads on all systems in the cold-chain. In systems that have capacity to cope with these higher loads this will just require the refrigeration plants to run for longer periods and use more energy. In many other cases during cooling operations the food will take longer to cool or during temperature maintenance processes the food temperature will not be maintained at current levels. In Section 2 we review the likely effect of climate change on the cold-chain.

A substantial amount of energy is used just to maintain the current cold-chain and as countries develop their own cold-chains this will increase. In Section 3, using available literature, an attempt has been made to identify the current major uses of energy in the food cold-chain and the changes that are likely to occur in the future. In addition to the generation of CO_2 the refrigerants currently used in cold-chain have considerable global warming potential (GWP). Using existing technology substantial savings in the energy used per unit of product could be achieved and these are reviewed in Section 4. In the final section the use of alternative refrigerants and alternative refrigeration cycles with a reduced GWP are reviewed.

2. The effect of climatic change on the cold-chain

It is reported that, between 1900 and 2005, there has been a 0.45 °C rise in average world temperature (Carbon Disclosure Project, 2006). The rate of rise appears to be increasing with a 0.1 °C rise in last 9 years. Local rises can be much higher, in the UK in the first quarter of 2007 temperatures were on average 2.1 °C warmer than in the first quarter of 2006 (Department of Trade and Industry (DTI), 2007). However, such changes could be due to natural variability. In Australia (Commonwealth Scientific and Industrial Research Organisation, 2001), it is estimated that global warming will cause temperatures to rise 0.4–2 °C by 2030, and 1–6 °C by 2070.

There is clear evidence that food poisoning in many countries is affected by seasonal changes, with a higher incidence in the summer and fewer cases during the winter (Bentham, 2002; Hall, D'Souza & Kirk, 2002). Hot summers may produce particularly large increases in food poisoning. There is thus concern that a rise in global temperatures due to global warming will bring with it a subsequent rise in the incidence of food poisoning (Schmidhuber & Tubiello, 2007). High temperatures favour the multiplication of pathogenic microorganisms in food. For example, multiplication of the salmonellas is strongly temperature dependent with growth occurring above about 7 °C and reaching an optimum at 37 °C (Bentham, 2002). Semenza and Menne (2009) state that colonisation of broiler chicken flocks with campylobacter also increases rapidly with rising temperatures. The risk of campylobacteriosis is positively associated with mean weekly temperatures, although the strength of association is not consistent in all studies. Warmer summer temperatures and humid conditions can enhance the survival of microbes in the environment, leading to increased contamination of food, and increased risk of infection (Charron, Waltner-Toews, & Maarouf, 2005). High temperatures may also affect infection rates in food animals, for example by the multiplication of bacteria in animal feed (Bentham, 2002). In addition, some seasonal behaviour may also exacerbate the risk of food disease transmission, such as outdoor barbequing, al fresco meals, etc. (Bentham, 2002; Charron et al., 2005). On farms, the microbial ecology may change with altered climate, potentially changing the species composition of pathogens and their infectivity to people (Charron et al., 2005).

A number of studies have investigated the direct relationship between environmental temperatures and the occurrence of food poisoning. D'Souza, Becker, Hall, and Moodie (2003) found a significant positive association between mean temperature of the previous month and the number of salmonellosis notifications in the current month in five Australian cities, with the estimated increases for a 1 °C increase in temperature ranging from 4% to 10%, depending on the city. Kovats et al. (2004) found, on average, a linear association between temperature and the number of reported cases of salmonellosis above a threshold of 6 °C. The relationships were very similar in The Netherlands, England and Wales, Switzerland, Spain and the Czech Republic. While Fleury, Charron, Holt, Allen, and Maarouf (2006) found a strong association between ambient temperature and the occurrence of three enteric pathogens (Salmonella, pathogenic *Escherichia coli* and Campylobacter) in Alberta, Canada, and of Campylobacter in Newfoundland-Labrador. However, the relationships were not linear. For Alberta, the log relative risk of Salmonella, Campylobacter and *E. coli* weekly case counts increased by 1.2%, 2.2% and 6.0%, respectively, for every 1 °C increase in weekly mean temperature. For Newfoundland-Labrador the log relative risk increased by 4.5% for Campylobacter for every 1 °C increase in weekly mean temperature.

A number of countries have made projections of the effect of climate change on the increase in cases of food poisoning. A UK report (Bentham, 2002) in 2001/2002 estimated that cases in the UK could rise by about 10,000 extra cases per year. A further revision of this report in 2008 (Bentham, 2008) considered that there were no grounds for revising that estimate. While an Australian report estimates that cases in Australia could rise to around 79,000 additional cases per year by 2050 (Department of Climate Change, 2009).

It is very clear from the microbiological data, that if the food industries response to a 2–4 °C rise in ambient temperatures, were to allow a similar rise in the temperature of chilled food then food poisoning and spoilage would increase. It is an accepted crude approximation that bacterial growth rates can be expected to double with every 10 °C rise in temperature (Gill, 1986). Below 10 °C, however, this effect is more pronounced and chilled storage life is halved for each 2–3 °C rise in temperature. Thus the generation time for a pseudomonad (a common form of spoilage bacteria) might be 1 h at 20 °C, 2.5 h at 10 °C, 5 h at 5 °C, 8 h at 2 °C or 11 h at 0 °C (Harrigan & Park, 1991). In the usual temperature range for chilled meat, −1.5 °C to 5 °C, for example there can be as much as an eightfold increase in growth rate between the lower and upper temperature. Surveys of temperatures in chilled retail display cabinets show that temperatures can range from −1 °C to 16 °C (Evans, Scarcelli, & Swain, 2007; James & Evans, 1990), whilst mean temperatures in domestic refrigerators throughout the world range from 5 to 6 °C, with many operating at significantly higher temperatures (James, Evans, & James, 2008). Thus, it is clear that the temperatures achieved in both retail display and domestic storage, need to be lowered rather than allowed to rise in the foreseeable future if food safety is not to be compromised and high quality shelf life assured. Keeping food at current or lower temperatures will result in an increase in the energy used by food refrigeration systems as ambient temperatures rise. Sarhadian (2004) measured the average power consumed by refrigeration equipment in a catering establishment in different ambient (Fig. 1). Increasing the ambient temperatures from 17 to 25 °C resulted in an 11% increase in average power consumed.

In addition, if climate change were to result in higher levels of microorganisms being present on meats and produce prior to processing it could have a significant affect on the shelf life or storage requirements of chilled foods. With higher numbers, fewer doublings are required to reach a spoilage level of *ca.* 10^8 organisms/cm^2. For example, at a specific temperature, starting with one organism/cm^2, 27 doublings would be needed; while for an initial load of 10^3 organisms/cm^2, the number of doublings is reduced to 17. Thus lower storage temperatures may be needed to maintain required shelf-lives.

Currently food is frozen to and generally maintained at a temperature below −18 °C throughout storage, transport, retailing and domestic storage. In the case of frozen food, if the food industries response to a 2–4 °C rise in ambient temperatures were to allow a similar rise in the food temperature, then food poisoning and spoilage would not increase. However, if this were universally adopted then the high quality storage life of many temperature sensitive food products including ice cream, frozen desserts, oily fish and tuna would deteriorate.

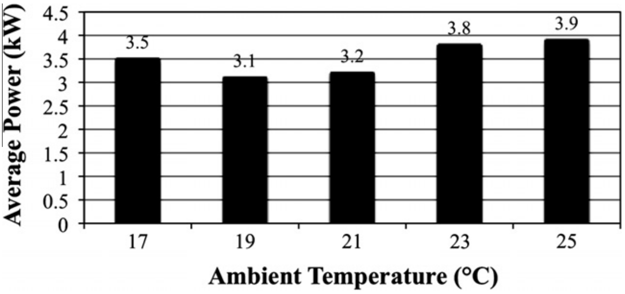

Fig. 1. Relationship between power consumed in refrigeration plant in a catering establishment and ambient temperature (adapted from Sarhadian, 2004).

3. The effect of the cold-chain on climatic change

Energy is required to maintain the cold-chain and the generation of this energy contributes to CO_2 production and climatic change. In addition the manufacture and direct loss of refrigerant used in the refrigeration systems also contributes. However, it is difficult to obtain reliable data on the contribution either source actually makes.

Mattarolo (1990) estimated that 40% of all food requires refrigeration and that 15% of the electricity consumed worldwide is used for refrigeration. This 15% figure is in agreement with International Institute of Refrigeration estimates (Coulomb, 2008). Estrada-Flores and Platt (2007) estimated that the total energy spent in the Australian food industry to keep an unbroken cold-chain from farm to consumer is about 19,292 GW h/year, or 18 MtC (Million tonnes of Carbon). In the UK, food, drink and tobacco manufacturers use more energy than is used in iron and steel production (Department for Environment, Food and Rural Affairs, 2006). Around 14% of total energy consumption is used in producing and processing food (Department of Trade and Industry (DTI), 2002), with 11% of electricity consumed by the food industry, totalling 22.4 MtC for food and catering (Department for Business Enterprise and Regulatory Reform, 2005). The food and drink manufacturing, food retail and catering sectors are currently responsible for approximately 4% of the UK's annual greenhouse gas emissions (Anon., 2007). With about 2.4% of the UK's greenhouse gas emissions due to food refrigeration (although 'embedded' refrigeration in foods grown or manufactured and imported from overseas, could increase this figure to at least 3–3.5%) (Garnett, 2007). The Carbon Disclosure Project Report (Carbon Disclosure Project, 2006) states that worldwide food only accounts for 1% of total CO_2 emissions.

In addition, detailed estimates of what proportion of this is used for refrigeration processes in the cold-chain are less clear and often contradictory (James et al., 2009). Garnett (2008a) states that in the UK food and drink related refrigeration emissions (i.e. including refrigeration in supermarkets, catering outlets, pubs and cellars, staff catering and so forth) emissions work out at 1.46 MtC, equivalent to 0.97% of the UK's CO_2 emissions, and refrigerant leakages contribution to the UK's total GHG emissions is also 0.97%. In addition Garnet states that 280,000 tC is used by refrigeration systems in food manufacture and 1.9 MtC in domestic refrigeration.

Looking at individual operations through the cold-chain and commodities provides some idea of which combinations contribute most to climate change.

3.1. Primary chilling and secondary cooling

Primary chilling is the first and most important stage of the cold-chain for a refrigerated food. The rate of temperature reduction often determines the subsequent safety and quality of the food. In primary cooling systems, the majority of the total heat load should be the product load since the purpose of a primary chilling system is to extract this load. The total product heat load is dependent on the type of food product, its initial temperature (at harvest or slaughter), the final temperature to which the product is required to be cooled to prior to storage, and the mass of the product that is being cooled. The rate of release of heat from the food is also a function of the chilling system used, its operating temperature(s) and the heat transfer coefficient(s) achieved.

Swain, Evans, and James (2009) calculated the energy required to cool different raw food materials using the overall weight of annual UK production multiplied by the enthalpy change required to reduce the temperature post-harvest/slaughter to its recommended storage temperature. In the UK, milk is the raw material that requires the most cooling with an estimated energy value at least 2.5 times more than all the other major materials added together and over 4.5 times more than all types of meat combined. In addition to milk and meat the primary chilling of vegetables, especially potatoes, requires the extraction of substantial quantities of heat.

3.2. Transportation

Sea, air and land transportation systems are expected to maintain the temperature of the food within close limits to ensure its optimum safety and high quality shelf life. It is estimated that there are approximately 1300 specialised refrigerated cargo ships, 80,000 refrigerated railcars, 650,000 refrigerated containers and 1.2 million refrigerated trucks in use worldwide (Heap, 2006). The type of transportation used will substantially affect the energy used. It has been estimated that the same amount of fuel can transport 5 kg of food only 1 km by personal car, 43 km by air, 740 km by truck, 2400 km by rail, and 3800 km by ship (Brodt, Chernoh, & Feenstra, 2007). Refrigeration accounts for roughly 40% of the total energy requirement during distribution, making the distribution of frozen food around 1.7 times as energy-intensive as the distribution of groceries at ambient temperature (McKinnon & Campbell, 1998).

Air-freighting is increasingly being used for high value perishable products, such as strawberries, asparagus and live lobsters (Sharp, 1988; Stera, 1999). However, foods do not necessarily have to fall into this category to make air transportation viable since it has been shown that ‘the intrinsic value of an item has little to do with whether or not it can benefit from air shipment, the deciding factor is not price but mark-up and profit’ (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2006). Air is the most intensive form of transport with the highest CO_2 emissions per tonne of the commercial transportation systems (AEA Technology, 2005; Department for Environment, Food and Rural Affairs, 2005; Garnett, 2008a). UK studies show that while less than 1% of all food consumed in the UK is carried by air it accounts for 11% of total food transport CO_2 (including car trips), 1.5% of fruit and vegetables are carried by air but it accounts for 40% of the total CO_2 (or 50% of freight CO_2) used in transport of vegetables.

Over a million refrigerated road vehicles are used to distribute refrigerated foods throughout the world (Billiard, 2005; Gac, 2002). Freight transport consumes nearly 25% of all the petroleum worldwide and produces over 10% of carbon emissions from fossil fuels (Estrada-Flores, 2008). Food transport accounts for one quarter of all Heavy-Goods Vehicle miles in the UK, with the average number of miles that food travelling doubling in the last 30 years (Department for Environment, Food and Rural Affairs, 2005). It has been reported in that in the US foods are typically transported over an average distance of 2100 km before arriving on the consumer's plate (Miller, 2001). A study by Nestlé demonstrated that transport generated roughly 15 kg of CO_2 emissions per tonne of product delivered. This represents approximately 10% of the total CO_2 generated during the manufacturing process (Carbon Disclosure Project, 2006).

Transport of food, consumed in the UK, accounted for an estimated 30 billion vehicle kilometres in 2002, of which 82% were in the UK (AEA Technology, 2005). Road transport accounted for most of the vehicle kilometres (Table 2), split between cars, HGVs (Heavy-Goods Vehicles) and LGVs (Light Goods Vehicles). Food transport produced 19 million tonnes of carbon dioxide in 2002, of which 10 million tonnes were emitted in the UK (almost all from road transport), representing 1.8% of the total annual UK CO_2 emissions, and 8.7% of the total emissions of the UK road sector (AEA Technology, 2005). The role of the consumer of this food should not be discounted either. It has been estimated that around one in ten car journeys in the UK are for food shopping (Department for Transport, 2007).

Improvements in energy efficiency would not only cut distribution costs, but also reduce atmospheric emissions. The use of diesel-powered refrigeration equipment substantially increases the level of emissions per tonne of product distributed. Unlike lorry tractor units, which have been subject to tightening EU emission standards, the refrigeration motors on much of the ‘reefer’ trailer fleet continue to produce high levels of noxious emissions per litre of fuel consumed (McKinnon & Campbell, 1998). The rise in supermarket home delivery services where there are requirements for mixed loads of products that may each require different storage temperatures is also introducing a new complexity to local land delivery (Cairns, 1996).

The concept of “food miles” is clearly of concern to countries with well-established export markets, such as Australia and New Zealand. However a comparison of dairy and sheep meat production by Saunders, Barber, and Taylor (2006) concluded that New Zealand produced products for the UK market were “by far more energy efficient” than those produced in the UK. This included the energy used in transportation. With production being twice as efficient in the case of dairy, and four times as efficient in case of sheep meat. This reflects the extensive production system in New Zealand compared with the UK and the proportion of energy used and carbon produced during the production of food rather than in its processing and transportation.

Table 2
Transport emissions, estimated for transporting food from its source to UK stores and onto consumers homes (adapted from AEA Technology, 2005).

Transport mode	CO_2 emissions as a proportion of total food transport emissions (%)	Transportation (tonne-km) as a proportion of total transportation (%)
(UK road total commercial)	39	35
UK road HGV[a]	33	19
UK road private cars	13	48
Overseas road HGV[a]	12	7
International by sea	12	0.04
International HGV[a]	12	5
International air freight	11	0.1
UK road LGV[b]	6	16
Overseas road LGV[b]	2	5
Rail, inland waterways	Insignificant	Insignificant

[a] HGV = Heavy-Goods Vehicles.

[b] LGV = Light (Local) Delivery Vehicles.

3.3. Storage

Following harvesting/production many foods are transported to centralised “cold stores” (Europe) or “refrigerated warehouses” (US) prior to distribution to retailers/end-users. Cold stores may be chilled or frozen and operate at a range of different temperatures depending on the product or customers requirements. When correctly used these facilities are only required to maintain the temperature of the product.

There is limited published data on energy consumption in cold stores (Duiven & Binard, 2002; Famarazi, Coburn, & Sarhadian, 2002; Werner, Vaino, Merts, & Cleland, 2006). The energy consumption of cold-stores depend on many factors, including the quality of the building, activities (chilled or frozen storage), room size, stock turnover, temperature of incoming product, external environmental conditions, etc. (Duiven & Binard, 2002).

FRPERC has carried out a comprehensive study of three large cold store complexes in the UK (James et al., 2009). The actual performances of the cold stores per cubic and square metre are shown in Table 3.

It is common practice in the frozen food industry to use refrigerated trailers as overspill storage space. In a survey of 1300 refrigerated trailers over a 48 h period, it was found that roughly a fifth of their time was spent loaded and stationary (McKinnon & Campbell, 1998).

3.4. Catering

Refrigerated Commercial Service Cabinets (CSCs) are used to store food and/or drink in commercial catering facilities. There are approximately 500,000 units in use in the UK (Market Transformation Programme, 2006). The vast majority of the cabinets sold are integral cabinets (refrigeration system on board the unit). Most of the market is for chilled or frozen upright cabinets with one or two doors or under counter units with up to four doors. The average energy consumption for chilled cabinets is 2920 kW h/year and for frozen is 5475 kW h/year (Market Transformation Programme, 2006).

The limited published data on energy consumption of CSCs in use are shown in Fig. 2. Although each cabinet type is of similar size and therefore can be directly compared in terms of functionality, there is a large difference in energy consumed by each type of CSC.

There are over 4 million refrigerated vending machines in the USA consuming 12 billion kW h of electricity per year (Refrigeration Technology & Test Centre (RTTC), 2009a). They consume between 7 and 16 kW h per day, which is typically five times more electricity than a domestic refrigerator. Ambient temperature has a substantial affect on energy consumption. An 8 °C rise in ambient from 24 to 32 °C resulting in a 40% increase in energy consumption.

Table 3
Energy consumed by each cold store.

Refrigeration plant	kW h/ year	kW h/ year/m^3	kW h/ year/m^2
Cold store 1 (3 frozen chambers 1550 m^2)	710,335	57.3	458.3
Cold store 2 (1 frozen chamber 910 m^2)	652,573	71.1	710.6
Cold store 3 (3 chilled and 1 frozen chamber total 2458 m^2)	1138,178	57.9	463.1

Stores 1 and 3 were operated by a direct expansion refrigeration system with single stage reciprocating compressors and evaporative condensers. Store 2 was operated from a low pressure receiver system with a twin screw economized compressor and an air cooled condenser. All stores were operated on R22.

Fig. 2. Energy consumed by different types of CSCs in different types of catering establishments.

3.5. Retail

In 2002 it was estimated that there were 322,000 supermarkets and 18,000 hypermarkets worldwide and that the refrigeration equipment in these supermarkets used on average 35–50% of the total energy consumed in these supermarkets (United Nations Environment Programme, 2002). In a US survey of a store (Refrigeration Technology & Test Centre (RTTC), 2009b) 68% of its total annual electric use was attributed to refrigeration, with only 8% to heating, ventilation and air conditioning, and 23% to lighting. For a typical size food retail store, 3500 MW h of electrical energy will be consumed in a year, of which 2100 MW h can be due to the refrigeration systems (Evans et al., 2007). In the retail environment the majority of the refrigeration energy is consumed in chilled and frozen retail display cabinets (James et al., 2009).

3.6. Domestic

Domestic refrigerated storage is an often-unregarded part of the food cold-chain by the food industry. However, from an environmental point of view this sector is important. There are approximately 1 billion domestic refrigerators worldwide (International Institute of Refrigeration (IIR), 2002). At present, most of these are in industrialized countries. However (as noted by Billiard, 2005), production in developing countries is rising steadily (30% of total production in 2000). When the environmental impact of these refrigerators is considered using a LCCP (Life Cycle Climate Performance) approach, the emissions of refrigerant in a domestic HFC-134a refrigerator represent only 1–2% of the total contribution to global warming while emissions due to energy consumption represent 98–99% (Billiard, 2005). Therefore, energy consumption is the most significant issue with regards to global warming. In a study on ketchup, Anderson, Ohlsson, and Olsson (1998) found that energy used in long-term storage in home refrigerators can dwarf energy use in any other sector of the ketchup life cycle by a factor of two or more, and fuel used for consumer shopping can be as much as fuel used in all other transportation earlier in the life cycle, on a per kg basis.

3.7. Overall

On the best available data, James et al. (2009) identified the top ten processes, excluding domestic systems, in the UK cold-chain in terms of energy saving potential as shown in Table 4. The saving potential within the top five consuming operations in the UK

Table 4
Best estimate of the top ten food refrigeration processes ranked in terms of their potential for total energy saving (basis of estimations provided on www.grimsby.ac.uk/documents/defra/usrs-top10users.pdf).

	Sector	Energy		Saving	
		'000 t CO_2/year	GW h/year	%	GW h/year
1	Retail display	3100–6800	5800–12,700	30–50	6300
2	Catering – kitchen refrigeration	2100	4000	30–50	2000
3	Transport	1200	4800	20–25	1200
4	Cold storage – generic	500	900	20–40	360
5	Blast chilling – (hot) ready meals, pies	167–330	309–610	20–30	180
6	Blast freezing – (hot) potato products	120–220	220–420	20–30	130
7	Milk cooling – raw milk on farm	50–170	100–320	20–30	100
8	Dairy processing – milk/cheese	130	250	20–30	80
9	Potato storage – bulk raw potatoes	80–100	140–190	~30	60
10	Primary chilling – meat carcasses	60–80	110–140	20–30	40

(retail, catering, transport, storage and primary chilling) was estimated to lie between 4300 and 8500 GW h/year in the UK.

As yet few other studies appear to have looked at the cold-chain. Work in Germany on the fish cold-chain found that retailing consumed over six times the energy of the next most energy-intensive operation of spiral freezing (Meurer & Schwarz, 2003). While Ramirez, Patel, and Blok (2006) reported that the specific energy consumption required to produce frozen carcass meat was far higher than for chilled (Table 5). Further processing the meat to produced cut up and deboned products further increased the energy required. In Europe the amount of energy required to produce a tonne of meat has increased by between 14% and 48% between 1990 and 2005 (Ramirez et al., 2006).

3.8. Refrigerants

About 20% of the global-warming impact of refrigeration plants is due to refrigerant leakage (March Consulting Group, 1998). However, it depends of course on the applications: for domestic refrigerators, for example, the figure is 2%; while for mobile air conditioning, the figure is 37%. Refrigerant leakage can be up to 15% per year in commercial refrigeration plants (Coulomb, 2008), and leakage varies greatly from one system to another.

The dominant types of refrigerant used in the food industry in the last sixty years have belonged to a group of chemicals known as halogenated hydrocarbons, e.g. chlorofluorocarbons (CFCs) and the hydrochlorofluorocarbons (HCFCs). Scientific evidence clearly shows that emissions of CFCs have been damaging the ozone layer and contributing significantly to global warming. Consequentially the Ozone Depletion Potential (ODP), the Global Warming Potential (GWP) and the Total Equivalent Warming Impacts (TEWI) have become the leading criteria in the choice of refrigerants today (Duiven & Binard, 2002).

The importance of these criteria has changed over the years. Initially the greatest concern was stratospheric ozone protection, with the Vienna Convention and resulting Montreal Protocol forcing the abandonment of Ozone-Depleting Substances (ODSs), resulting in the replacement of CFCs by HCFCs (Calm, 2008). This has broadly shown some success and there is evidence of ozone recovery (Calm, 2008). More recently climate change has become the prime motivator for concern and change and thus the GWP and TEWI of refrigerants has become important. The Kyoto Protocol, pursuant to the international Framework Convention on Climate Change, sets binding targets for greenhouse gas (GHG) emissions based on calculated equivalents of carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride. National laws and regulations to implement the Kyoto Protocol differ, but they typically prohibit avoidable releases of HFC and PFC refrigerants and in some countries also control or tax their use (Calm, 2008). Within the European Union these are generally referred to as "F-gas" regulations.

Table 5
Specific energy required (MJ/t) to chill, freeze and process (cutting and deboning) meat (adapted from Ramirez et al., 2006).

Product	Whole and chilled	Whole and frozen	Cut, deboned and frozen
Beef, veal and sheep	1390	2110	2866
Pork	2093	3128	3884
Poultry	3096	4258–5518	5014–6274

The retail sector, including supermarkets, is one of the largest users of F-gas (fluorinated greenhouse gas) refrigerants. In the UK, emissions due to leakage of HFC refrigerants from all types of stationary refrigeration was estimated to be equivalent to 1740,000 tonnes of CO_2 in 2005, with leakage from supermarket refrigeration systems contributing 769 tonnes (AEA Technology, 2004).

The first reaction of the refrigeration and chemical industries to the Montreal Protocol was to look for interim refrigerants, most based on R22, with friendlier environmental properties that could be used until optimum alternatives could be developed. Interim replacements for R502 for example were Isceon 69S and 69L, Suva HP80 and HP81 and Atochem FX10. Suva MP39 and MP66 were interim replacements for R12. Hydrofluorocarbon R134a has been the popular choice to replace R12 in a wide range of food refrigeration and air conditioning applications. These include most of the commercial applications that used R12 and in domestic refrigerators. R134a does not contain chlorine and, therefore, has an ODP of zero and, similarly to R12, has low toxicity levels and a low boiling point. However, 134a has a global warming potential (GWP) of 1300 while European rules require any new refrigerant to have a GWP of less than 150.

Further developments have produced refrigerants with lower GWP. Hydrofluorocarbon R152a is almost a straight drop-in substitute for R134a (Mohanraj, Jayaraj, & Muraleedharan, 2008) and has a GWP of 120, which is ten times less. It has similar operating characteristics to R134a, improved cooling ability, and typically only requires two-thirds the charge of R134a (AA1car, 2009). HFO-1234yf is another new replacement for R134a and has a GWP of only 4. A report produced by SAE International (2008) claims that HFO-1234yf is the best replacement refrigerant for R134a.

R502 is the preferred refrigerant in supermarket and food transport systems. Many chemical companies have worked on a long-term alternative to R502 with a zero ODP. Dupont produced Suva 62, ICI Klea 60, Rhone-Poulene Isceon RX3 and Atochem. Solkane507, with an ODP of 0 and a GWP of 0.84, now claims to be 'in practice' the optimal replacement for R502 (Solpac, 2009).

Many non-CFC alternatives including ammonia (R717), propane (R290), isobutane (R600a), carbon dioxide (R744), water and air have been used in the past in food refrigeration systems.

Ammonia is the common refrigerant in large industrial food cooling and storage plants. It is a cheap, efficient refrigerant whose pungent odour aids leak detection well before toxic exposure or flammable concentrations are reached. The renewed interest in this refrigerant has led to the development of compact low charge systems, which significantly reduce the possible hazards in the event of leakage. Ammonia also has a role in more sensitive areas where a leak, however small and safe, is considered unacceptable, such as supermarkets. It can be used in remote plants as a primary refrigerant to cool secondary refrigerants such as water, brine or glycol. These secondary refrigerants can then be pumped round the stores to provide the cooling required in air conditioning units and chilled and frozen stores and display cabinets. However the energy consumption may be up to 10% higher than other systems (Duiven & Binard, 2002). Ammonia/Carbon dioxide cascade systems are showing great promise with energy consumption figures being reported to be either the same or even lower than conventional systems (Duiven & Binard, 2002).

Environmental groups, Greenpeace in particular, have championed the use of hydrocarbons, particularly propane and isobutane or mixtures of both, for domestic refrigerators and freezers. Studies have shown that propane or butane in the quantities required within domestic systems result in a minimal risk of fire or explosion, although there have been reports in the UK press recently of explosion problems with hydrocarbon fridges (Fox, 2009). Greenpeace (2009) claims that there are now over 400 million hydrocarbon refrigerators in the world today, and that of the 100 million domestic refrigerators and freezers produced annually globally between 35% and 40% of the production now use hydrocarbons. Due to concerns over the safety risk of the larger quantities of hydrocarbons required in commercial or industrial food refrigeration plants their use in these applications is less common. However, hydrocarbon use is expanding beyond domestic applications with the UK supermarket Waitrose recently claiming to be the first supermarket to develop propane based refrigeration technology, which it claims will dramatically reduce its carbon footprint by 20% (Waitrose, 2009). It is planning on introducing this technology to it's new Waitrose Altrincham branch in 2010 and "in every new and major refitted branch thereafter".

4. Improving the energy efficiency of the cold-chain

Refrigeration has been identified as an area where dramatic emission cuts could be made relatively easily, by using and maintaining energy-efficient equipment correctly (International Institute of Refrigeration (IIR), 2003).

It is clear that maintenance of food refrigeration systems will reduce energy consumption (James et al., 2009). Repairing door seals and door curtains, ensuring that doors can be closed and cleaning condensers produce significant reductions in energy consumption. In large cold storage sites it has been shown that energy can be substantially reduced if door protection is improved, pedestrian doors, liquid pressure amplification pumps fitted, defrosts optimised, suction liquid heat exchangers fitted and other minor issues corrected. Also, it is well known that the insulation efficiency of insulated panels can reduce by 5–12% per year (Estrada-Flores, 2009).

Better design of facilities can also reduce energy consumption. Among the suggested improvements (Duiven & Binard, 2002) are: thicker floor, wall and roof insulation; use of in-feed and out-feed conveyors with lock gates instead of doors; selection of the right compressor and refrigerant; appropriate selection of components of the refrigeration process; application of speed control for compressors to achieve full-load during refrigeration, as well as speed control of fans; electronic expansion valves; adequate pipe dimensions and insulation; advanced lighting methods; defrosting using hot gas; computer control systems, monitoring and data processing.

4.1. Primary and secondary cooling operations

To be able to calculate the energy efficiency of current primary chilling processes data are required on the measured energy consumption of industrial systems for a known throughput of the raw material being chilled. Swain et al. (2009) located very few publications that contain both measured energy and throughput data. However, five publications were located that provide some relevant data on milk (Legett, Peebles, Patoch, & Reinemann, 1997; Milk Development Council, 1995), potatoes (Devres & Bishop, 1992) and meat (Collett & Gigiel, 1986; Gigiel & Collett, 1989), which are three of the key primary raw materials in terms of a high primary chilling energy requirement.

There are a number of stages in quantifying the potential to save energy in different primary chilling operations. The first stage is a simple technology transfer exercise in which the most energy efficient current industrial process is identified.

With milk and carcass meat, data exist that allow a first attempt at calculating the energy reduction potential of a simple technology transfer exercise (Fig. 3). In the 1980s Gigiel and Collett (1989) measured the energy consumption, cooling rates and weight loss in 14 commercial beef chillers. The average energy consumption in beef chilling was 116 kJ kg^{-1} and the total annual UK consumption 113 TJ. It was estimated that if UK plants reduced their consumption to that of the best measured then the country would save 42 TJ of energy and the industry would increase its profits by 26%.

A second stage of the process is to see if a simple technology transfer between sectors would be beneficial. The cooling of a liquid product such as milk is a very different process to that of cooling solids such as potatoes and meat carcasses. However, since both meat carcasses and potatoes are cooled in air based systems it should it be possible to make potato cooling as efficient as the best of the measured carcass cooling plants. This would improve the efficiency of potato cooling from 0.313 to 1.725, which would result in a potential annual saving of 154 GW h in the UK.

There is little specific data on the energy use of specific cooling methods. Duiven and Binard (2002) cite figures of 70–130 kW h/ton of product for blast freezing in comparison to 60–100 kW h/ton of product for plate freezing. Pedersen (1979) calculated the relative costs of five different chilling methods for poultry. When only energy costs were considered, the cost of a counter-current water chilling system was one fifth that of an air chilling method. However, when the costs of the water and wastewater disposal

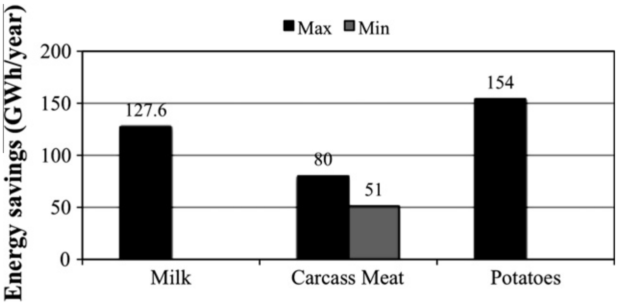

Fig. 3. Energy saving potential with existing technology transfer.

were added, the water chilling cost was over 50 times that of the air system.

The surface temperature of cooked products is very high when they leave baking ovens or deep fat fryers and consequently the difference between the surface and the ambient is very large at that time. To reduce energy usage and costs a number of food manufacturers have traditionally operated a two-stage cooling operation using ambient air followed by refrigerated air (James & James, 2002). However, the use of ambient cooling is not widespread within the food industry and in some cases it is not encouraged. This is due to belief that the slower cooling rate would encourage bacterial growth and that the distribution of ambient air over unwrapped products could increase bacterial contamination. James, Senso, and James (2010) have carried out investigations on the ambient cooling of hash browns prior to freezing and ambient cooling of meat and vegetable pries prior to blast chilling. Hash browns emerged from a fryer at 80 °C and had to be frozen to −12 °C before packaging at a process rate 4.5 tones/h. The existing spiral freezer was incapable of extracting the initial heat load and the moisture loss from the hash browns was causing ice to build up the evaporator. An initial 5 min of ambient cooling removed 562,500 kJ of heat energy from the 4.5 tonnes of hash browns every hour. It also prevented 60 kg per hour of water freezing on the evaporator. This reduction was achieved with insignificant increase in total freezing time.

Prechilling of Albacore tuna prior to freezing using a refrigerated seawater system (RSW) removed almost one third of the total heat load and improved the quality of the fish (Kolbe, Craven, Sylvia, & Morrissey, 2004). The RSW system operating more energy efficiently than a low temperature blast freezer (Kolbe 1990).

4.2. Distribution

For some foods the preferred storage temperature is still a matter for debate and needs further clarification. Heap (2006) used garlic as such an example, which "may be carried at a preferred temperature between −4 °C and 0 °C, or at ambient temperature with good ventilation". This has implications to the requirements for the use of refrigeration and energy consumption.

Providing the product is fully cooled prior to loading and the loading carried out in a refrigerated loading dock, the only heat load of consequence is infiltration through the structure. As already mentioned insulation materials deteriorate during use and containers are periodically tested to see if they are within thermal specifications. Currently the only system that is being considered to improve the insulation of containers is vacuum insulated panels. In practice these panels can be five times more efficient that insulated foam panels therefore wall thickness can be thinner and load capacity increased. However, currently they are expensive and problems occur at corners and junctions.

Many advantages are claimed for liquid nitrogen transport systems, including minimal maintenance requirements, uniform cargo temperatures, silent operation, low capital costs, environmentally acceptability, rapid temperature reduction and increased shelf life due to the modified atmosphere (Smith, 1986). Overall costs are claimed to be comparable with mechanical systems (Smith, 1986). However, published trials on the distribution of milk have shown that the operating costs using liquid nitrogen, per 100 l of milk transported, may be 2.2 times that of a mechanically refrigerated transport systems (Nieboer, 1988).

A review of food transport refrigeration (Tassou, De-Lille, & Ge, 2008) concluded that the Coefficient of Performance (COP) of transport refrigeration systems was low, ranging from 0.5 to 1.75 and that up to 40% of diesel consumed during transportation is used by the refrigeration system. However, the conclusions had to be based on theoretical and derived data due to the lack of any experimentally measured data on fuel consumption by refrigeration systems in commercial use.

Only one example has been located where the amount of fuel consumed by the refrigeration systems in different commercial refrigerated vehicles in the UK was actually measured (James et al., 2009). The data, transformed into kW h consumed on the day of measurement, are shown in Fig. 4. Again it is clear that there is a wide range of energies used, both between and within categories, and research is required to determine the reasons for the range and transfer the knowledge obtained to the industry.

Spence, Doran, and Artt (2004) state that 'Through development work, an air-cycle system using optimised turbomachinery, heat exchangers, transmission and bearings would realise much better efficiency than the demonstrator plant. Consequently the efficiency could rival the efficiency of the standard vapour-cycle system at part-load operation, which represents the biggest proportion of operating time for most units.'

The application of photovoltaics (PV) to refrigeration for the distribution of chilled supermarket produce has been pioneered in the UK. In 1997 Sainsbury's, a major UK supermarket chain, commissioned the world's first solar powered refrigerated trailer (Bahaj & James, 2002; Tubb, 2001). The trailer operated for 4 years with the operating power being solely derived from solar energy. In further developments the performance was increased by 27% and the total cost claimed to be competitive with current competition. Operating in the UK it was stated that 'During most of the year there has been an excess of solar energy over daily demand'. It is not clear why commercial systems are not currently available, but it is possible that the high capital cost of current PV systems is limiting adoption. It is anticipated that with time the cost of PV systems should come down and payback times shorten (Bahaj & James, 2002).

4.3. Storage

In three cold stores investigated by FRPERC in the UK (James et al., 2009) a number of methods of reducing the energy shown in Table 3 were investigated. Predicted savings in energy assuming that door protection was improved, pedestrian doors and liquid pressure amplification pumps fitted, defrosts optimised, suction liquid heat exchangers fitted and other minor issues corrected would result in reductions in energy of 23% in cold store 1, 5% in cold store 2 and 39% in cold store 3. It was estimated that if cold store 2 were fitted with an evaporative condenser the savings would increase to 38%.

In recent years, energy conservation requirements have caused an increased interest in the possibility of using more efficient storage temperatures than have been used to date. Researchers, such as Jul (1982), have questioned the wisdom of storage below −20 °C and have asked whether there is any real economic advantage in very low temperature preservation. There is a growing

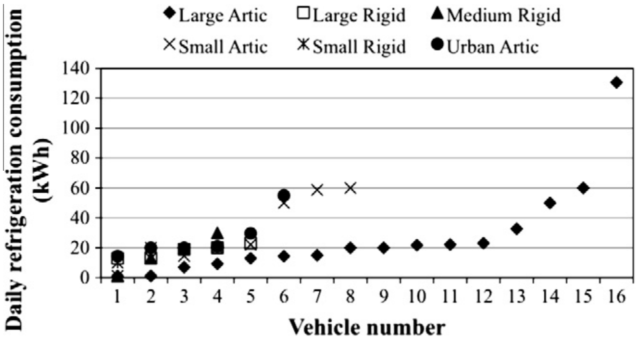

Fig. 4. Energy consumption of refrigeration systems of transport vehicles.

realisation that storage lives of several foods can be less dependent on temperature than previously thought. Since research has shown that many food products, such as red meats, often produce non-linear time–temperature curves there is probably an optimum storage temperature for a particular food product. Improved packing and preservation of products can also increase storage life and may allow higher storage temperatures to be used. The British Frozen Food Federation (2009) looked at the potential to reduce energy usage and CO_2 emissions by raising the temperature control set point of cold stores and also by raising the associated evaporating temperatures. They reported that 'Savings of over 10% will often be achievable with relatively little capital investment. Even larger savings of over 20% can be achieved in some situations'.

Cold storage refrigeration systems usually operate during the daytime when electrical costs and outdoor temperatures are highest and refrigeration system performance is at its worst. The feasibility of using the thermal mass of the items in storage as a means of decoupling the operation of the refrigeration system from the loads that it serves has been demonstrated by Altwies and Reindl (1999). In this case, refrigeration equipment operates during low utility cost hours (off-peak) to pre-cool the stored items. Then the refrigeration equipment can remain idle during high utility cost periods (on-peak) with minimal changes in the storage environment and product temperature. In many cases, little or no capital investment is required to implement this type of warehouse operating strategy. Although this strategy may save money it is unlikely to reduce energy consumption and may actually increase it if product is pre-cooled to a much lower temperature than the overall average required.

4.4. Catering

Simply replacing current CSC cabinets by the best available, in terms of energy consumption, could save 1000 GW h/year (James et al., 2009). In the USA, Sarhadian (2004) measured the energy consumption of refrigeration systems in a catering establishment before and after a refitting operation (Fig. 5). Over the period monitored energy reductions ranged from 10% to 53%. In the UK, a study carried out in a small catering operation showed that one upright frozen storage cabinet consumed over 40% of the energy used in refrigeration. Two small cost-effective changes, i.e. cleaning the condensing coil and resetting the thermostat, produced energy reductions of 8% and 11% respectively (James et al., 2009).

4.5. Retail display

Laboratory trials at FRPERC have revealed large, up to 6-fold, differences in the energy consumption of frozen food display cabinets of similar display areas. In chilled retail display, which accounts for a larger share of the market, similar large differences, up to 5-fold, were measured. A substantial energy saving can therefore be achieved by simply informing and encouraging retailers to replace energy inefficient cabinets by the best currently available. To quote from a recent article in the UK's Guardian newspaper "What's the biggest and easiest thing that supermarkets could do to cut their energy bills and reduce their carbon footprint? They all know the answer. Put doors on their fridges" (Pearce 2009).

Reducing energy consumption in a chilled multi-deck cabinet is substantially different to reducing it in a frozen well cabinet (James et al., 2009). Improvements can be made in insulation, fans and energy efficient lighting but only 10% of the heat load on a chilled multi-deck comes from these sources compared with 30% on the frozen well. Research efforts are concentrating on minimising infiltration through the open front of multi-deck chill cabinets, by the optimisation of air curtains and airflows, since this is the source of 80% of the heat load. In frozen well cabinets reducing heat radiation onto the surface of the food, accounting for over 40% of the heat load, is a major challenge. Traditionally open well cabinets were used to display frozen products but increasingly multi-deck cabinets are used because of their increased sales appeal. The rate of heat gain in a multi-deck cabinet and consequently the energy consumption is much higher than in a well cabinet. Due to the increased costs of energy multi-deck cabinets are now appearing on the market with double glazed doors that have to be opened to access the food on display.

The performance of an individual display cabinet does not only depend on its design. Its position within a store and the way the products are positioned within the display area significantly influences product temperatures. In non-integral (remote) cabinets (i.e. those without built in refrigeration systems) the design and performance of the stores central refrigeration system is also critical to effective temperature control.

Mitchell (2006) measured the energy consumption of the lights and refrigeration system in a retail display prior to and after the installation of fibre optic lights. The projected data showed an annual energy savings of 11,200 kW h (49.3%) from direct lighting (Fig. 6). Additionally, further analysis estimated an annual compressor energy savings of 11,800 kW h (16.7%). The estimated total annual energy savings was 23,000 kW h.

Studies carried out by the Refrigeration Technology and Test Centre (Refrigeration Technology & Test Centre (RTTC), 2009c) showed that retrofitting an old meat display cabinet with energy efficient lamps, ballasts and fan motors reduced the cooling load by 13% and the overall power consumption by 27%. Retrofitting a new more efficient meat display cabinet with electronic commutated fan motors (ECM) and a high efficiency coil reduced overall power consumption by 8% without affecting the meat temperature. Other studies carried out at the same test centre (Refrigeration

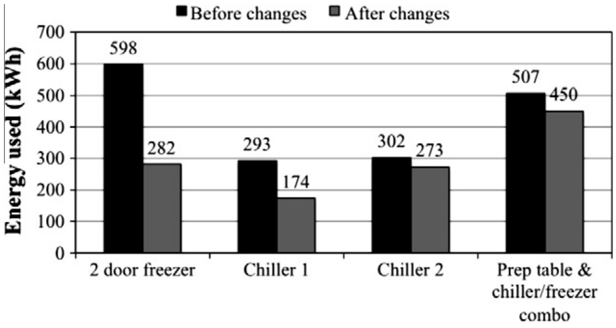

Fig. 5. Energy used in refrigeration systems in catering establishment pre and post refit (adapted from Sarhadian, 2005).

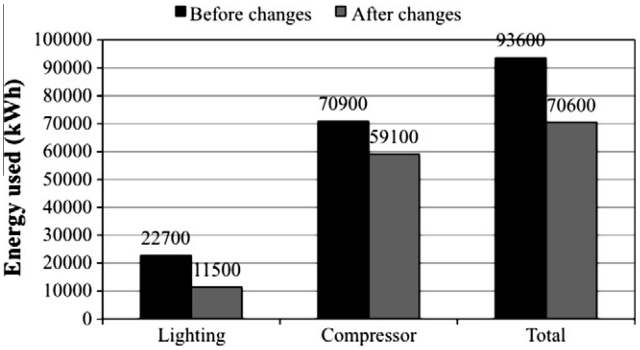

Fig. 6. Energy used prior to and after installation of fibre optic lighting on retail display. (adapted from Mitchell, 2006).

Technology & Test Centre (RTTC), 2009d) looked at the effect of different food loading scenarios including: blocking of return air, overloading above load line, non-uniform loading and disturbing the air curtain. Interestingly the overall energy consumption was not significantly changed by any of the loading scenarios. However, with a fully blocked return air grill, average food temperatures rose by up to 3.4 °C and the maximum food temperature rose from 2.9 to 11.3 °C.

Sarhadian (2004) showed that by installing more energy efficient lighting and replacing integral retail display cabinets in a small food store could produce significant reductions in energy usage. The total electricity demand was reduced by 18%, the refrigeration system by 22% while the overall illumination was increased by 40% and the power consumed by the lighting reduced by 22%.

4.6. Domestic storage

It has been reported that a 10-year old refrigerator uses 2.7 times as much energy per litre usable volume as a new A-class one (Carlsson-Kanyama & Faist, 2000). This has a clear effect on energy consumption. In Mexico Arroyo-Cabañas, Aguillón-Martínez, Ambríz-García, and Canizal (2009) evaluated the energy saving potential of replacing old, low efficiency domestic refrigerators with modern, high efficiency ones. They reported that total replacement would save 4.7 TW h/year, which represents 33% of the annual total consumption in Brazil of 14.1 TW h for such devices. In an example used by Carlsson-Kanyama and Faist (2000) the energy use for a 10-year old freezer, 0.029 MJ per litre net volume per day with only a 50% utilisation was 0.058 MJ per litre per day. Assuming a storage time of 90 days, then the energy use is 5.2 MJ per litre food. Using a new A-class freezer (0.012 MJ per litre net volume per day) with a 90% utilisation, the energy use during 90 days is only 1.2 MJ per litre. This is less than a fourth of the energy used in the first example, which shows the importance of both energy efficiency of the refrigerator and utilisation. However, considerable energy is needed to produce a new domestic refrigerator so there will be an increase in emissions in the short term.

Energy labelling is a valuable tool in reducing energy use. Energy labelling of domestic refrigerators, combined with minimum requirements, has led to a reduction of 26% in energy consumption per refrigerator over the last 10 years in the UK (DTI, 2002; Heap, 2001). In Brazil it was estimated that energy labelling of domestic refrigerators and freezers saved 1379 GW h in 2007 (Cardoso, Nogueira, & Haddad, 2010).

Several technological areas where improvements for efficiency enhancements are still possible are forced convection for evaporators and compressors; lower viscosity oils; reduction of temperature level inside the compressor; variable speed motors; linear compressors and improved insulation.

Some researchers (Estrada-Flores, 2008) have pointed out that the need for more energy-efficient domestic appliances will need to be balanced with the fact that food products will become more expensive and therefore, more valuable. Thus, consumers will demand that domestic refrigerators, freezers and other storage solutions maximise product shelf life. Garnett (2008a) also argues that efficiency improvements need to be also set in the context of behavioural trends that are hurrying us in ever more refrigeration dependent directions. Back in 1970, over 40% of the UK population did not have a fridge, and only 3% owned a freezer (Garnett, 2008b). Today, ownership of some sort of fridge-freezer combination is virtually universal in most of the developed world.

5. The use of alternative refrigeration systems in the cold-chain

Tassou, Lewis, Ge, Hadawey, and Chae (2009) reviewed the potential of new/alternative refrigeration technologies to reduce energy consumption in food refrigeration. Their review concentrated on seven systems: Trigeneration, Air Cycle, Sorption – Adsorption Systems, Thermoelectric, Stirling Cycle, Thermoacoustic and Magnetic refrigeration. Ground heat exchangers for heating and cooling and ejector refrigeration were also considered. Characteristics and potential applications of these systems are summarised in Table 6.

The majority of trigeneration systems in the food industry are large plants in the MW range in food factories where bespoke

Table 6
Characteristics and applications of new/alternative refrigeration technologies.

Technology	State of development	Cooling/refrig. Capacity of presently available or R&D systems	Efficiency/COP of presently available or R&D systems	Current/potential application area(s)
Trigeneration	Large capacity bespoke systems available. Smaller capacity integrated systems at R&D stage	12 kW–MW	Overall system efficiency 65–90%. Refrigeration system COP: 0.3 at −50 °C 0.5 at −12 °C	Food processing; cold storage; food retail
Air cycle	Bespoke systems available	11–700 kW	0.4–0.7	Food processing; refrigerated transport
Sorption-adsorption	Available for cooling applications > 0 °C. Systems for refrigeration applications at R&D stage	35 kW–MW	0.4–0.7	Food processing; cold storage; retail; refrigerated transport
Ejector	Bespoke steam ejector systems available	Few kW–60 MW	Up to 0.3	Food processing; refrigerated transport
Stirling	Small capacity 'Free' piston systems available. Larger systems at R&D stage	15–300 W	1.0–3.0	Domestic refrigerators; vending machines; refrigerated cabinets
Thermoelectric	Low cost low efficiency systems available	Few Watts–20 kW	0.6 at 0 °C	Hotel room mini bar refrigerators; refrigerators for trucks, recreational vehicles; portable coolers; beverage can coolers
Thermoacoustic	R&D stage. Predicted commercialisation: 5–10 years	Few Watts–KW capacity	Up to 1.0	Domestic and commercial refrigerators, freezers and cabinets
Magnetic	R&D stage. Predicted commercialisation 10 plus years from now	Up to 540 W	1.8 at room temperature	Low capacity stationary and mobile refrigeration systems

ammonia plant is linked to gas turbines, or internal combustion engines. More recently, the application of trigeneration has been extended to supermarkets with a very small number of installations in the USA, the UK and Japan.

Air cycles generate high air temperatures, typically of over 200 °C, that can be used in combination with the low temperatures to integrate cooking and refrigeration processes. In the food sector air cycle technology can be applied to rapid chilling and/or freezing (including air blast, tunnel, spiral, fluidised bed and rotary tumble equipment); for refrigerated transport (trucks, containers, rail freight, ships, air cargo); and for integrated rapid heating and cooling (cook-chill-freeze or hot water/steam raising and refrigeration).

The application of sorption-adsorption systems in the food sector are likely to be in areas where waste heat is available to drive the adsorption system. Such applications can be found in food factories and transport refrigeration.

Current applications of thermoelectric refrigeration in the food sector include: hotel room (mini-bar) refrigerators; refrigerators for mobile homes, trucks and cars; portable picnic coolers; wine coolers; beverage can coolers; drinking water coolers. Other potential future applications include domestic and commercial refrigerators and freezers, and mobile refrigeration and cooling systems.

Stirling cycles have been evaluated experimentally for application to domestic and portable refrigerators and freezers as well as vending cold beverages. Values of COP between 2 and 3 have been reported for temperatures around 0 °C, and values around 1 for temperatures approaching −40 °C.

Magnetic refrigeration has the potential for use across the whole refrigeration temperature range, down to cryogenic temperatures but it is anticipated that the first commercial applications will be for low capacity stationary and mobile refrigeration system.

In addition solar powered, hydrogen and geothermal refrigeration may have applications in the food cold-chain. Solar powered refrigeration systems capable of providing temperatures as low as −23 °C have been demonstrated (Le Pierrès, Stitou, & Mazet, 2007). Metal hydrides absorb large amounts of hydrogen gas and provide significant cooling when hydrogen gas is removed from them. Conversely, when hydrogen is added to a hydride, heat is liberated. In the HyFrig system invented by Dr. Feldman of Thermal Electric Devices a compressor is used to pump hydrogen into one of two finned hydride reactors, while drawing it off the other. As a result heating and cooling is produced. Hydrogen is the most abundant element in the universe and poses no environmental threat. It is claimed that the system could be 15–50% more efficient than conventional systems. The total cost of a hydride heat pump is claimed to be less than £500 per ton of cooling. Feldman feels that the system is well suited to solar powered refrigerators and for electrical vehicle air conditioning. Geothermal cooling systems circulate water below ground through a series of pipes where it is cooled by the surrounding earth and subsequently pumped back to the surface (Masanet, Worrell, Graus, & Galitsky, 2007). Where feasible, such systems can replace or augment existing refrigeration systems, leading to significant energy savings. In 2005, Aohata Corporation, a jam manufacturer in Japan, began operating a new geothermal cooling system that provided its facility with 260 kW of additional cooling capacity. The company reported that the geothermal cooling system uses only about 25% of the electricity required by a traditional refrigeration system (Japan for Sustainability, 2006).

It is expected that many of these novel refrigeration technologies will find niche application in food refrigeration operations in the future. For example, one commercial company 'Camfridge' (http://www.camfridge.com/) hopes to have a commercial magnetic water cooler available in 3 years. However, none appear to be likely to produce a step change reduction in refrigeration energy consumption within the food industry within the next decade.

6. Conclusions

Any noticeable increase in ambient temperature resulting from climatic change will have a substantial effect on the current and developing food cold-chain. A rise in temperature will increase the risk of food poisoning and food spoilage unless the cold-chain is extended and improved. The little data that is available suggests that currently the cold-chain accounts for approximately 1% of CO_2 production in the world. However this is likely to increase if global temperatures increase significantly.

Until recently the major concern in the refrigeration industry regarding climate change has been the impact of refrigerants on the ozone layer and the replacement of current refrigerants with "greener" alternatives. Energy efficiency is increasingly of concern to the food industry mainly due to substantially increased energy costs and pressure from retailers to operate zero carbon production systems. Reducing energy in the cold-chain has a big part to play since worldwide it is estimated that 40% of all food requires refrigeration and 15% of the electricity consumed worldwide is used for refrigeration.

Simple solutions such as the maintenance of food refrigeration systems will reduce energy consumption. Repairing door seals and door curtains, ensuring that doors can be closed and cleaning condensers produce significant reductions in energy consumption. In large cold storage sites it has been shown that energy can be substantially reduced if door protection is improved, pedestrian doors fitted, liquid pressure amplification pumps fitted, defrosts optimised, suction liquid heat exchangers fitted and other minor issues corrected.

New/alternative refrigeration systems/cycles, such as Trigeneration, Air Cycle, Sorption-Adsorption Systems, Thermoelectric, Stirling Cycle, Thermoacoustic and Magnetic refrigeration, have the potential to save energy in the future if applied to food refrigeration. However, none appear to be likely to produce a step change reduction in refrigeration energy consumption within the food industry within the next decade.

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