
Final report

Impact of more effective use of the fridge and freezer



Estimating the benefits and costs of more effective fridge and freezer use by consumers, in order to reduce the amount of household food waste.

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where resources are used sustainably.

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benefits of reducing waste, developing
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Front cover photography: Freezing at home (Love Food Hate Waste Partners)

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Executive summary

WRAP research¹ has revealed which types of food and drinks are thrown away in the home. One of the largest contributors to the 4.4 million tonnes of avoidable household food waste thrown away each year is perishable food that requires, or benefits from, refrigerated storage e.g. fresh / raw meat and fish, dairy products, fruit and vegetables etc.

WRAP has also estimated that around 800,000 tonnes of food is thrown away due to it 'not being used in time', which could be frozen to eat later rather than spoiling or passing its 'use by' date.

This prompted further detailed research into how consumers use their fridges² and freezers³, how effective domestic fridge thermometers are⁴, and a literature review⁵ to identify 'best practice' in terms of home freezing a range of foods. Key findings from this research include domestic fridges running at an average of 6.6°C (rather than below 5°C), only 24% of consumers storing apples in the fridge (where they will last much longer), 59% believing food should be frozen on the day of purchase, and only 60% who would freeze unopened packs a few days after shopping. There is clearly scope to reduce food waste through optimising the temperatures at which domestic fridges are operating, and consumers making more effective use of both fridges and freezers.

These insights have informed how WRAP, through Love Food Hate Waste⁶, and food industry partners communicate to consumers about using their fridges and freezers to make their food last longer and waste less, and how WRAP has worked to improve on-pack storage guidance.

Through clear labelling and communications activities, WRAP and the food industry are helping consumers:

- store the right foods in the fridge, in the right way (i.e. in original packaging / additional wrapping);
- run the fridge at temperatures below 5°C; and
- use the freezer more interactively to manage foods that aren't going to be eaten before they pass their 'use by' date.

However, it is recognised that lower fridge temperatures can only be achieved with additional energy consumption as the refrigeration systems run for longer to maintain the colder temperatures and to reduce the temperature of added food to a greater extent. Equally, assuming that a freezer will maintain or eventually return to the same temperature (e.g. -18°C) after warm food is added, it is logical that there will be an energy penalty to remove the heat. The additional heat load on a freezer during food addition comes from a combination of heat from the warm food added and heat gained through having an additional door opening.

1 <http://www.wrap.org.uk/content/new-estimates-household-food-and-drink-waste-uk> (These data will be updated in 2013.)

2 <http://www.wrap.org.uk/content/insights-around-domestic-refrigerator>

3 <http://www.wrap.org.uk/content/understanding-consumer-use-freezer>

4 <http://www.wrap.org.uk/content/performance-assessment-domestic-fridge-thermometers>

5 <http://www.wrap.org.uk/content/review-literature-about-freezing-food-home-0>

6 <http://www.lovefoodhatewaste.com>

The potential environmental and cost savings from using the fridge and freezer to reduce food waste must, therefore, be balanced against the environmental and cost impact of the increased energy consumption. However, no published data were found to allow assessment of the scale of this energy penalty in comparison with baseline energy consumption.

Experimental trials were therefore devised to measure the impact on energy consumption of:

- lowering fridge temperatures and adding additional foods which are normally kept at ambient; and
- adding chilled and ambient food to a freezer, with increased door opening.

To assess the waste saving and energy impacts associated with using domestic fridges and freezers more effectively, this report details:

- A literature review designed to assess the potential for increased storage life of chilled foods at lower fridge temperatures.
- Results from experimental measurement of the energy impact of lowering fridge temperatures and of adding additional foods which are normally kept at ambient.
- Results from experimental measurement of the energy impact of adding chilled and ambient food leftovers to a freezer.
- A comparison of the CO₂e emissions and costs associated with the saved waste and the additional energy.

Findings

Impact of temperature on storage life

Although the quantity and quality of references varied between products, the literature review suggested that storage lives of the majority of chilled foods would be increased if fridge temperatures could be lowered (e.g. from 7°C to 4°C). Where possible, the food types reviewed were used to represent wider categories e.g. the results for cod and salmon were taken to be applicable to all fresh fish. Storage life extensions for the selected categories ranged from 26% to 59%, typically equivalent to an additional 3 days of storage life.

Lowering fridge temperatures

Lowering average fridge air temperatures from 7°C to 4°C was conservatively estimated to offer the potential for savings in annual UK food waste of around 70,000 tonnes, worth £160 million and associated with 270,000 tonnes of CO₂e emissions. Balanced against this, the additional energy required to achieve the lower fridge temperature was estimated to have an annual UK cost⁷ of £71 million and associated emissions of 321,000 tonnes CO₂e. This suggests that although there is a potential financial benefit to consumers, this may come at the cost of an increase in emissions. The potential food waste savings were, however, based on conservative assumptions around how much food would be consumed as a result of the additional life, and did not include estimates for all foods that might benefit from lower fridge temperatures. In order to 'break even' in terms of CO₂e an additional 13,000 tonnes of food waste savings would be required, equivalent to around 3% of the current waste levels for foods stored in the fridge, and thrown away due to having 'gone off'. In addition, further savings in food waste could result from manufacturers increasing 'given life' (i.e. extending 'use by' and 'best before' dates) if there is confidence that UK domestic fridges are operating at or nearer recommended temperatures⁸.

⁷ All costs are at 2011 prices.

⁸ Food business operators (FBO) would need confidence that domestic fridges were achieving these temperatures, at the time of determining product life. NOTE EU guidance on shelf life (challenge testing) for *Listeria* states "If the actual storage temperatures are not known for the product in question, the FBO may use e.g. 8-12 °C for the storage temperature for the shelf-life studies.

However, the FBO must justify which temperatures are used for the shelf-life setting, taking into account the data from temperatures during distribution and storage by consumers.

Refrigerating foods which are not always stored in the fridge

The potential annual UK waste savings resulting from following manufacturers' guidance⁹ on the storage of fresh fruit and vegetables (refrigerating or not) was estimated to be worth £120 million and associated with 308,000 tonnes of CO₂e emissions. Even at the more energy intensive 4°C, the extra energy required to refrigerate the additional foods was only estimated to have an annual UK cost of £10 million and associated emissions of 47,000 tonnes CO₂e. Both financially and environmentally, the case for refrigerating such foods seems compelling.

Lowering fridge temperature and adding additional foods

The combined estimates for potential annual UK waste savings resulting both from lowering fridge temperature and also refrigerating foods which are predominantly stored at ambient are together worth £280 million and associated with 580,000 tonnes of CO₂e emissions. To achieve the lower temperature and add the additional foods the additional energy was estimated to have an annual UK cost of £81 million and associated emissions of 367,000 tonnes CO₂e. Combining the benefits of the two measures allows the considerable financial savings on offer from lowering temperature to be achieved (a net benefit of around £200 million) at the same time as an overall reduction in emissions (a net reduction of around 210,000 tonnes).

It is worth stating that any associated food safety benefits, for example reductions in the incidence of food borne illness and associated costs to the health service and business in terms of lost working days, of running fridges at the recommended 'below 5°C'¹⁰ temperature have not been estimated, and would be in addition to the food waste savings.

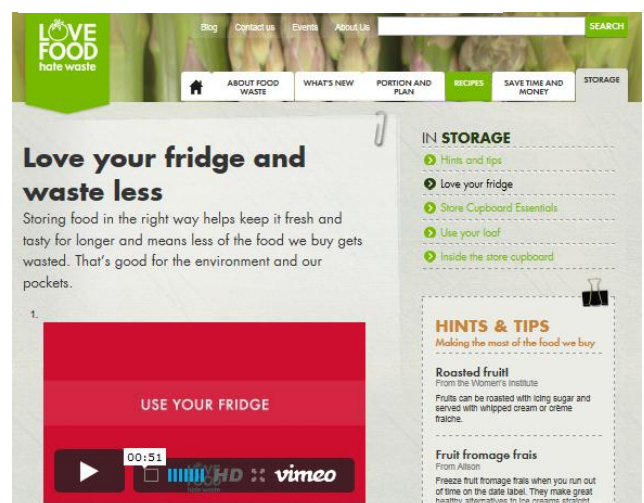
Estimating the impact of improved freezer use

The additional energy consumed by a typical stand-alone freezer while freezing a selection of foods was measured under controlled test room conditions. The extra energy required by the freezer was found to be 0.154 kWh (an additional 26.7%) in the 24h period during which the food was added, after which the energy use returned to normal. The financial value of the food items added and their embodied CO₂e emissions were over 100 times higher than the cost and CO₂e emissions associated with this extra energy. WRAP has estimated that at least 800,000 tonnes of food is thrown away each year that could have been frozen to eat at a later date. This is associated with over 3 million tonnes of CO₂e and has a value of over £2 billion.

Given the findings from this work, together with an increasing trend towards more energy efficient domestic appliances, the recommendations to avoid household food and drink waste through improved domestic fridge temperature control, greater use of the fridge to store fresh fruit and vegetables and more interactive use of the freezer have been strengthened.

Therefore, Love Food Hate Waste and its partners should continue to reinforce the effective use of domestic fridges and freezers, and WRAP will continue to work with the food industry to:

Source: www.lovefoodhatewaste.com



The screenshot shows the 'Love Food Hate Waste' website. The main heading is 'Love your fridge and waste less'. Below this is a video player with the title 'USE YOUR FRIDGE' and a duration of 00:51. To the right of the video is a 'STORAGE' section with a list of links: 'Hints and tips', 'Love your fridge', 'Store Cupboard Essentials', 'Use your loaf', and 'Inside the store cupboard'. Below this is a 'HINTS & TIPS' section with the sub-heading 'Making the most of the food we buy'. It features two items: 'Roasted fruit' from the Women's Institute, which can be roasted with honey and served with whipped cream or orange fraiche; and 'Fruit fromage frais' from Alison, which are frozen fruit fromage frais that can be run out of time on the label and are a healthy alternative to ice cream.

⁹ WRAP conducts a survey of factors, such as presence of on-pack storage guidance, for a range of products. The latest results are from 2011 and available at: <http://www.wrap.org.uk/content/helping-consumers-reduce-food-waste-retail-survey-2011>

¹⁰ <http://www.nhs.uk/Livewell/homehygiene/Pages/how-to-store-food-safely.aspx>

- Provide clear storage guidance to ensure the right products are stored in the fridge.
- Use recommended wording 'keep refrigerated below 5°C' within on-pack storage guidance, for temperature-sensitive products that benefit from refrigeration in the home.
- Provide clear freezing and defrosting guidance¹¹ for all freezable products, as part of the on-pack storage guidance or in other consumer-facing communication materials e.g. point of sale, online recipes etc.
- Continue the move away from 'freeze on day of purchase' labelling.
- Make available, in-store, tools that help optimise fridge and freezer use in the home e.g. air-tight storage containers, freezer bags, fridge thermometers and bag clips.
- Use Love Food Hate Waste materials to raise awareness of the benefits of reducing food waste and engaging consumers to act.
- Improve fridge design e.g. to include relevant functionality such as built in thermometers / external temperature displays, harmonising settings on temperature control dials (and how they relate to actual temperatures in the fridge), the sensitivity and effectiveness of the temperature setting / thermostats, and options to better maintain fridge temperatures based on the relatively high (compared to freezers) number of door openings. Consideration should also be given to the continued use of single thermostats in combined fridge freezers (only 35% have dual thermostats currently).

¹¹ <http://www.wrap.org.uk/sites/files/wrap/Info%20Sheet%20Freezing%20final.pdf>

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Glossary

- Greenhouse gases (GHG) – gases present in the Earth’s atmosphere which can absorb and emit infra-red radiation, contributing to global warming. These include carbon dioxide (CO₂), a major by-product in energy production.
- Carbon dioxide equivalent (CO₂e) – a measure used to compare the emissions from various greenhouse gases based upon their global warming potential, so that a combined effect of for example energy use and refrigerant leakage can be estimated. For typical food groups, the total CO₂e figure might include such components as CO₂ from direct energy use and from burning of fossil fuels for transportation, leakage of refrigerant, nitrous oxide (N₂O) from use of nitrogen fertiliser in agriculture and methane (CH₄) emissions from cattle.
- Practical Storage Life (PSL) – the period of storage at a given temperature during which a food product retains its characteristic properties and remains fully acceptable for consumption or processing.
- Coefficient of determination (R² value) – the R² value ranges from 0 to 1 and denotes how well a trend-line fits the data on which it is based, in other words, the closer the R² value is to 1, the better the fit of the trend-line to all of the data on the chart.

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1.0 Introduction

1.1 Effect of fridge temperature on food storage lives

Keeping refrigerated food cold (typically below 5°C) is important to ensure the safety and quality of the food up to the end of its stated shelf life. From the point of manufacture, through distribution and in in-store display cabinets, there are strict guidelines for the control of temperature. It is important that consumers take similar care from the point of purchase, through transportation home and in the domestic fridge.

If the air temperature in the fridge is lower than 0°C for prolonged periods, there is a risk that foods such as salad would be rendered unpalatable, for example, if they became partially frozen or sustain a chilling injury. For example, if chilled meat begins to freeze the ice crystals cause cell damage and increase loss of fluid ('drip loss') once the meat is thawed. If on the other hand food product temperatures rise above 5°C, they are likely to spoil more quickly through the growth of microbes and the development of rancid flavours.

One of the largest contributors to the 4.4 million tonnes of avoidable household food waste thrown away each year¹² is perishable food that requires, or benefits from, refrigerated storage e.g. fresh / raw meat and fish, dairy products, fruit and vegetables etc. WRAP has estimated that around 800,000 tonnes of this food is thrown away due to it 'not being used in time', which could be frozen to eat later rather spoiling or passing its 'use by' date. Temperature is the prime factor controlling bacterial growth on foods. In foods such as meat the storage life is highly related to bacterial growth. 'Off' odours and slime caused by microorganisms are detected when populations reach ca. 10^7 to 10^8 organisms.cm⁻². For example, in trials on beef carried out by Ingram and Roberts (1976), storage life could be extended from 1 week to almost 3 weeks by reducing the storage temperature from 10°C to 0°C. WRAP and Campden BRI undertook preliminary work in 2008¹³, to identify the shelf life benefits of optimal fridge temperatures, for a small number of products. The results suggested that there are potentially quite significant shelf life benefits for certain products of storing at fridge temperatures below 5°C. Section 2 of this report details the findings from this project to extend and build upon these initial findings.

A high proportion of food poisoning cases originate in the home (e.g. Perry, 1994 estimates the proportion to be around 50% of all sources) and if food is stored in less than optimal conditions, such as more moderate temperatures, the potential for growth of pathogenic organisms exists.

1.2 Temperature control in domestic fridges and freezers

Temperatures in domestic fridges and freezers are controlled by thermostats which turn the refrigeration system on when temperatures are too warm and off when temperatures are satisfactory. The result is a cyclic on/off operation during which temperatures repeatedly pull down when the system is turned on and then rise again when the system is turned off. When the system is running, the peak power consumed is generally very similar regardless of the heat load, as the system always operates close to its maximum power while switched on. However, under greater heat loads, it is the length of time for which the system runs which increases, meaning that power is used for longer until the added heat is removed. During this time it is also likely that temperatures will rise above their stable values if there is too much heat for the refrigeration system to extract.

¹² <http://www.wrap.org.uk/content/new-estimates-household-food-and-drink-waste-uk> (These data will be updated in 2013.)

¹³ These results were not published but fed in to subsequent WRAP research around fridge use (<http://www.wrap.org.uk/content/performance-assessment-domestic-fridge-thermometers>; <http://www.wrap.org.uk/content/insights-around-domestic-refrigerator>)

In a fridge-freezer the impact on energy would be likely to be masked by the slow reaction of the thermostat and the impact would be likely to be smaller in magnitude but longer in duration¹⁴. This is because the fridge section of a fridge-freezer controls the temperature of the freezer (i.e. when the fridge is cooled the freezer is also cooled as the circuits are generally in series). This is why consumers often find that their frozen food thaws if they keep a fridge-freezer in a cold environment (e.g. a garage in winter) as the fridge does not require any cooling as the ambient temperature is similar or below that of the fridge. In this situation if large quantities of warm food are placed into a freezer the freezing times may be extended as the freezer will not operate for any longer that it would have done without the added food.

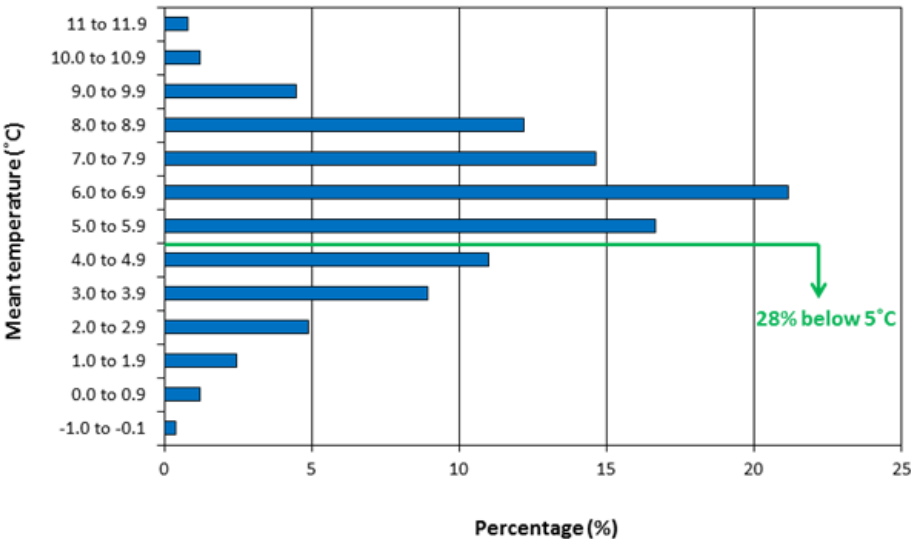
This understanding of how temperature is controlled in domestic appliances informed the methodology for the experimental trials undertaken through this project. For example, in relation to Section 4 where trials were used to assess the additional energy used to freeze food, an upright freezer was used for the trials to make any additional energy used when freezing product visible.

1.3 Temperature variation in domestic fridges

In the past decade there have been at least 15 surveys of temperatures in domestic fridges (reviewed by several authors, including Nauta et al, 2003 and James et al, 2008). Although in some cases the details of the measurement methods are not completely clear, the reported results are very similar with overall mean temperatures ranging from 4.5 to 6.6°C and maximum temperatures from 11 to 14°C. These results are worrying since they imply that the average temperature of at least 50% of domestic fridges is above 4.5°C.

To evaluate temperatures within UK fridges Evans et al. (1991) used miniature data loggers with three air and two product sensors to monitor temperatures continuously for a period in excess of seven days. Air temperature sensors were positioned in the top, middle and bottom sections of the fridge and in a simulated food product. The mean temperature over 7 days (evaluated from top, middle and bottom sensors) ranged from -1°C to 11°C. The overall mean of all fridge air temperatures in the survey was 6°C, with 72% of fridges operating at average temperatures at or above 5°C (Figure 1).

Figure 1 Overall mean temperatures for all fridges in survey (source: Evans et al., 1991)



¹⁴ Please note, this has not been tested through this research and no evidence has been found in the literature.

In analysing data from most of the surveys reported over the 30 years prior to 2006, Peck et al. (2006) concluded that 61% of fridges throughout the world run at mean¹⁵ temperatures above 5°C.

The last available survey in the UK was carried out by WRAP¹⁶ and consisted of a survey of 50 fridges in consumers’ homes. Results demonstrated that a proportion of the fridges tested (14 fridges, 29% of the sample) were operating at mean air temperatures of 9°C or above. 34 fridges (70%) operated below 8°C. Only 14 of the 48 fridges (29% of the sample) were found to be at mean air temperatures of 5°C or less.

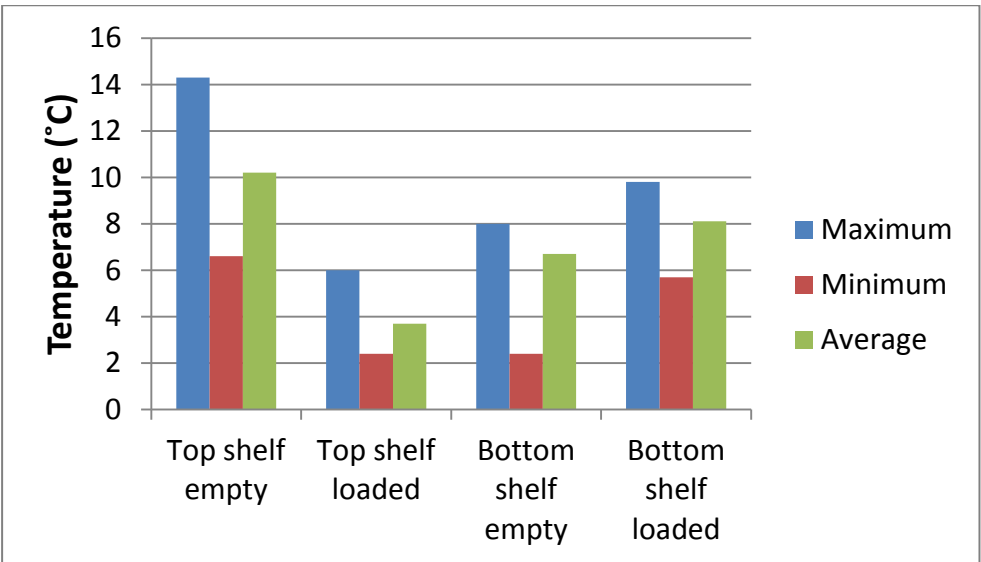
Temperatures in fridges are neither static nor uniform. Numerous studies, such as Koutsoumanis and Taoukis (2005), note major temperature variations throughout a fridge. This can be a variation between locations within a fridge and also fluctuation in temperature in a single position in the appliance.

The WRAP study (2010) showed that large variations in temperature occurred in the fridge section of fridge-freezers. For example, in one fridge, during the simulated night time operation (no door opening), average values of the temperature ranged from 1.4°C (middle shelf, back) to 9.1°C (top of door). The study found that variation existed not only at one location, but between different positions within the appliance.

1.4 Affecting temperature through usage

The temperature within a fridge not only varies with time (due to the compressor cutting in and out), but it is also affected by usage. Loading can have a large influence on temperatures and can increase or decrease temperatures (Figure 2). This is primarily due to air circulation within the appliance that is predominantly buoyancy driven. Buoyant flow can easily be disrupted and placing food in a fridge can radically change the air flow pattern in an appliance. This in turn affects air and product temperatures (Table 1).

Figure 2 Temperatures in a fridge-freezer when empty and loaded (source: Evans et al., 1991).



¹⁵ It is important to note that within any fridge there will be a range of temperatures, and the mean will not reflect the scale of that range.

¹⁶ <http://www.wrap.org.uk/content/insights-around-domestic-refrigerator>

Table 1 Maximum, minimum and mean temperatures on shelves and in door of fridges (source: Evans et al., 1991)

Position		Ice box		Fridge-freezer no. 1		Fridge-freezer no. 2	
		Empty	Loaded	Empty	Loaded	Empty	Loaded
Top shelf	Maximum	2.1	1.2	14.3	6.0	10.7	11.1
	Minimum	0.7	-1.2	6.6	2.4	4.7	5.2
	Mean	1.5	0.3	10.2	3.8	7.3	8.0
Middle shelf	Maximum	2.2	0.4	8.0	6.9	5.4	4.9
	Minimum	-1.0	-2.6	1.7	4.3	0.9	-0.1
	Mean	1.4	-0.6	6.3	5.5	3.6	2.9
Bottom shelf	Maximum	1.6	4.0	8.0	9.8	5.0	3.7
	Minimum	-1.4	-3.0	2.4	5.7	-6.7	-5.8
	Mean	0.7	-0.6	6.7	8.1	2.1	1.0
Door	Maximum	5.9	3.3	8.0	8.4	6.5	6.7
	Minimum	0.9	-0.4	5.3	0.8	2.2	0.5
	Mean	3.2	2.0	6.9	3.8	4.2	3.7

Door openings can have a significant effect on energy use depending on frequency and duration. Böhmer and Wicke (1998) stated that 3% of the total energy consumption of a fridge was due to door openings. Peart (1993) stated that 40 door openings per day could add 50-120 kWh per year to the energy used by a fridge. Lepthien (2000) found that 20 door openings per day increased energy by 1-6%. Liu et al (2004) found that 50 five-second door openings within 10 hours increased energy consumption by 5-10% in an ambient temperature of 15°C. At an ambient of 30°C, 15 door openings within 10 hours increased energy by 0.5-4%. Graham (1997) found that vinyl flaps installed to prevent cold air escaping from fridges saved 10-20% of the energy.

In a study by Laguerre et al (2002) 19% of consumers claimed that they opened their fridge less than 10 times per day, 43% opened their fridge 10-20 times per day and 38% opened their fridge more than 20 times per day. In a Malaysian study Rahman et al (2005) found that 8% of households opened their fridge less than 10 times per day, 73% opened the door 10-20 times and 19% opened the door more than 20 times. Thomas (2007) found that in Europe each person in a household opened the fridge door an average of 8.2 times per day.

An unpublished study of door openings in consumers' homes was carried out by Evans (1991). Fridge usage varied widely with 65% of households opening their fridge less than 30 times per day and 70% opening the door for less than 4 minutes per day. On average, fridge doors were opened for 7.3 seconds with a mean of 39 door openings and a total door opening time of 3.1 minutes per day. There were found to be poor correlations between either the average temperature at any position or the overall average temperature in the fridge and the number of door openings or total duration of door openings per day.

The effects of degree of loading and door openings on upright freezers follow similar patterns to those for fridges. However, there are some differences – while the air inside the freezer is colder and would tend to fall out of an open door more quickly, freezers tend to be compartmentalised using boxes and trays, and these help to keep air inside when the door is opened. In addition, freezers tend to be opened less frequently than fridges as the products inside are accessed less often. This understanding of consumer behaviour informed the methodology for the experimental trials undertaken through this project.

2.0 Estimating storage life extension due to lower storage temperatures

2.1 Literature review

Food products were chosen to be included in the literature review based on their potential for waste savings. Factors included their perishability at chilled temperatures, their sales volumes and the proportions reported to be wasted (WRAP 2009). An initial list of 10 products was agreed, made up of the following: cod, salmon, chicken, pork, strawberry, cherry, salad, broccoli, cream, milk.

For each product, a literature review of reported practical storage life (PSL) values at chilled temperatures (e.g. -2°C upwards) was carried out. The sources used included peer reviewed academic journal papers, conference publications, reference text books and information from trade, professional associations and non-governmental organisations e.g. IIR (International Institute of Refrigeration).

For each reference found, the reported PSL and storage temperature(s) were recorded, together with relevant product details such as packaging and previous treatment. Details of the method used to judge the end of the storage period (sensory e.g. panel scoring of taste, odour; chemical e.g. thiobarbituric acid levels for detection of rancidity; microbiological e.g. total viable counts of bacteria, numbers of spoilage bacteria etc.) were also recorded.

Very few results were found for strawberry, cherry and cream so these products were excluded from the detailed analysis below. It should be noted that exclusion does not mean that such products would not benefit from reduced storage temperatures, merely that the available data do not allow storage life estimates to be derived in the same way.

The PSL values for each product for which sufficient data were found, were tabulated and plotted against storage temperature. Exponential curve-fitted trend-lines were then added, and the resulting equations and their coefficients of determination (R^2 values) noted. The R^2 value ranges from 0 to 1 and denotes how well a trend-line fits the data on which it is based, in other words, the closer the R^2 value is to 1, the better the fit of the trend-line to all of the data on the chart. For those products with acceptable curve-fits, the exponential equations were used to determine storage lives at 7°C and 4°C¹⁷.

For the products reviewed, the PSL values plotted against temperature are shown below, and the tabulated data and full list of references used for the literature review are available from WRAP on request.

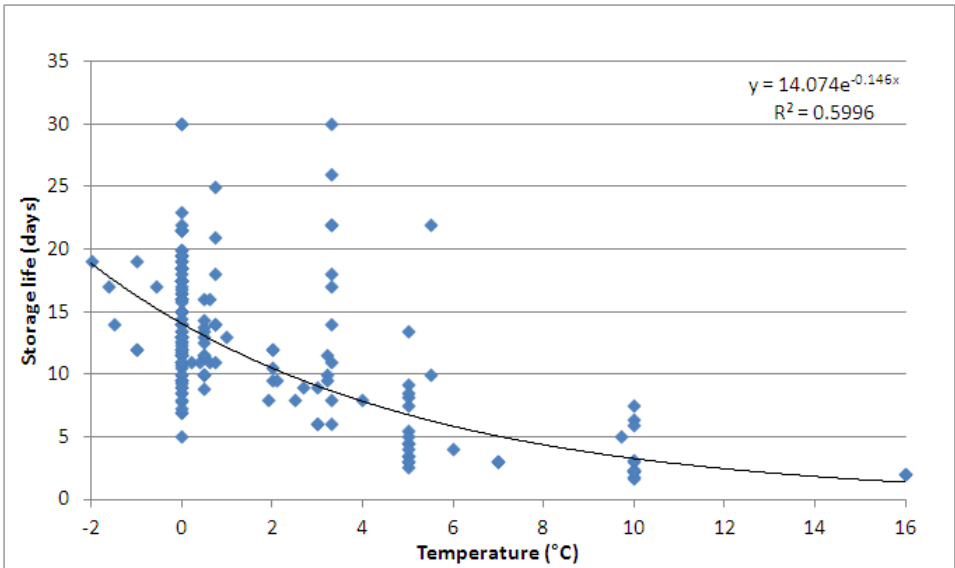
¹⁷ Four degrees was selected as the current FSA guidance for storage within the fridge is 'below 5'.

2.2 Results

2.2.1 Cod

References for PSLs of cod were numerous, with the majority being for storage at 0°C, reflecting the traditional ‘storage on ice’ temperature for fish. As can be seen in Figure 3, considerable scatter was found at individual temperatures. Reasons for scatter include ‘product factors’ such as method of catch and processing, chilling method and speed, time to shore, transport time, condition of fish (whole / gutted / fillets), packaging material, and use of modified atmosphere in some packs. There were also ‘experimental factors’, such as measurement type (sensory, chemical, microbiological) and storage life cut-off criteria e.g. different levels of bacteria, different sensory scoring.

Figure 3 Practical Storage Life versus temperature for cod



The coefficient of determination (the R² value) for the exponential curve-fitted line was not high but was considered acceptable. Using the equation for the line gave the following storage life values at 4°C and 7°C (Table 2).

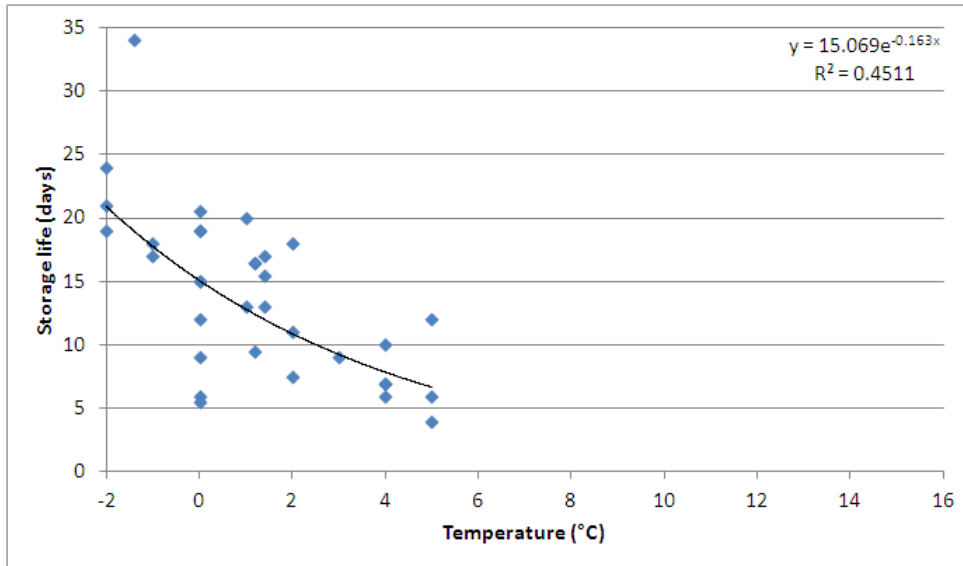
Table 2 Storage lives of cod at 4°C and 7°C

<i>Temperature (°C)</i>	<i>Storage life (days)</i>
4	7.8
7	5.1

2.2.2 Salmon

References for salmon were less numerous and covered a narrower temperature range (Figure 4). As with cod, there was considerable scatter at some temperatures, and reasons for the scatter were similar to those for cod.

Figure 4 Practical Storage Life versus temperature for salmon



The R^2 value for the salmon curve-fit was lower than that for cod, indicating a slightly worse fit. It was, however, considered acceptable to use the curve-fit equation to generate the values shown in Table 3.

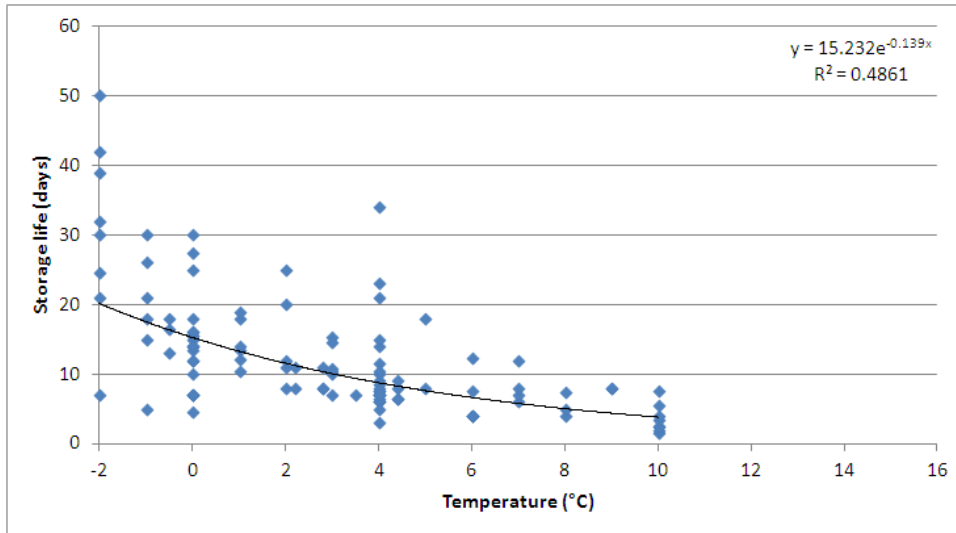
Table 3 Storage lives of salmon at 4°C and 7°C

<i>Temperature (°C)</i>	<i>Storage life (days)</i>
4	7.9
7	4.8

2.2.3 Chicken

Chicken references were also reasonably numerous, but again showed considerable scatter (Figure 5). Reasons for scatter other than experimental factors were predominantly thought to be packaging and processing factors, including some references related to mild chemical treatments.

Figure 5 Practical Storage Life versus temperature for chicken



The R^2 value for chicken reflected the scatter, but was considered acceptable for the purposes of determining the following storage lives (Table 4).

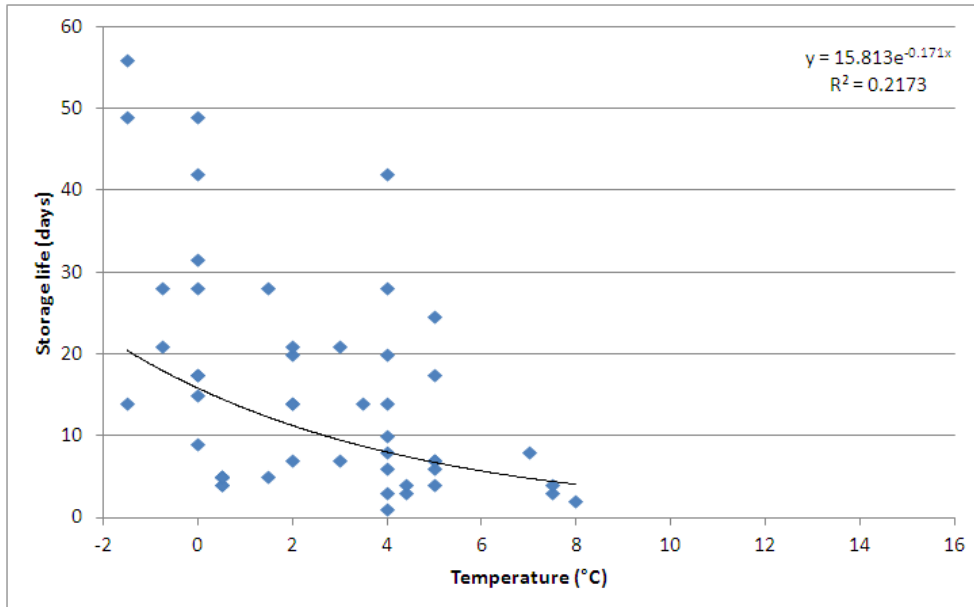
Table 4 Storage lives of chicken at 4°C and 7°C

<i>Temperature (°C)</i>	<i>Storage life (days)</i>
4	8.7
7	5.8

2.2.4 Pork

A reasonable number of references were found, but PSL values were relatively scattered as a result of factors such as inclusion of different cuts of meat, packaging, experimental methods, etc. as shown in Figure 6.

Figure 6 Practical Storage Life versus temperature for pork



The acceptability of the R^2 value for the curve-fit was questionable, but use of the curve-fit equation generated storage lives which appeared logical and within the expected range (Table 5).

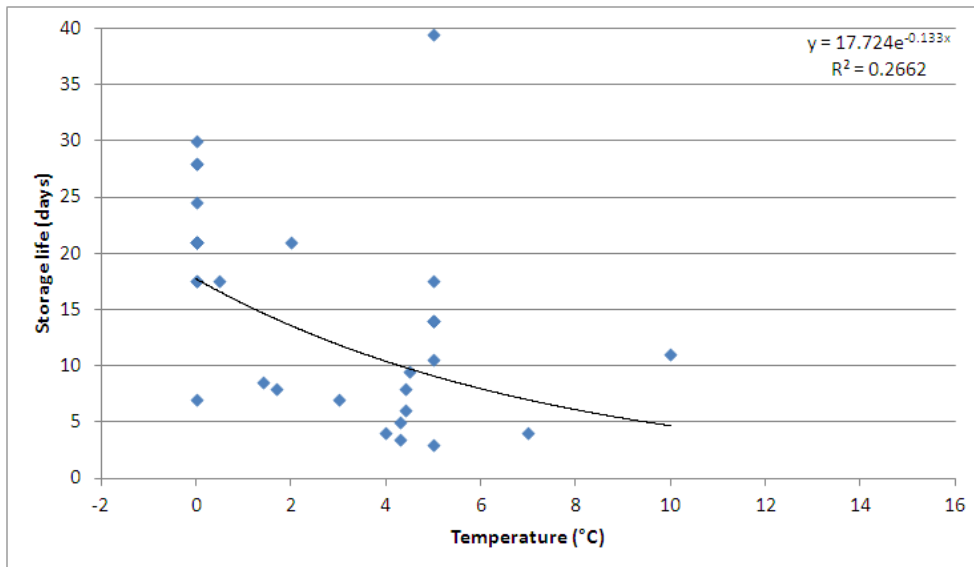
Table 5 Storage lives of pork at 4°C and 7°C

<i>Temperature (°C)</i>	<i>Storage life (days)</i>
4	8.0
7	4.8

2.2.5 Salad

The literature search for bagged leafy salad produced limited data (Figure 7), with scatter being due mainly to type of leaves, packaging and use of modified atmosphere.

Figure 7 Practical Storage Life versus temperature for leafy salad



As with pork, the acceptability of the R^2 value for the curve-fit was questionable, but use of the curve-fit equation generated storage lives which appeared logical and within the expected range (Table 6).

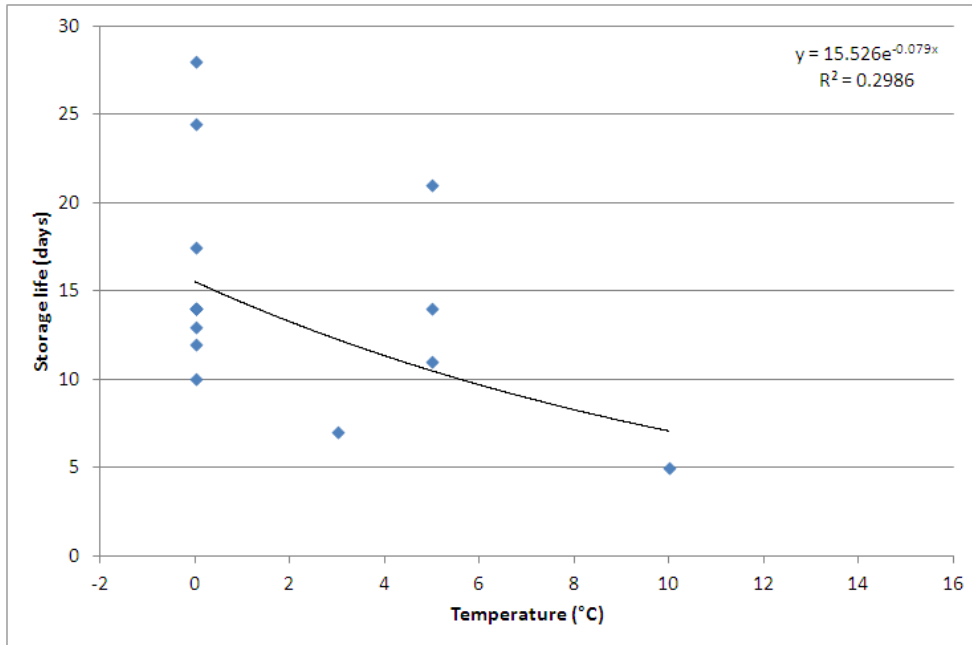
Table 6 Storage lives of salad at 4°C and 7°C

<i>Temperature (°C)</i>	<i>Storage life (days)</i>
4	10.4
7	7.0

2.2.6 Broccoli

References for broccoli were relatively scarce and concentrated mainly on storage lives at 0°C (Figure 8). Scatter at this temperature was partly due to packaging and use of modified atmospheres (but note that modified atmospheres are not used for broccoli in the UK).

Figure 8 Practical Storage Life versus temperature for broccoli



The curve-fit R^2 value was not high, but use of the equation gave the following logical results (Table 7).

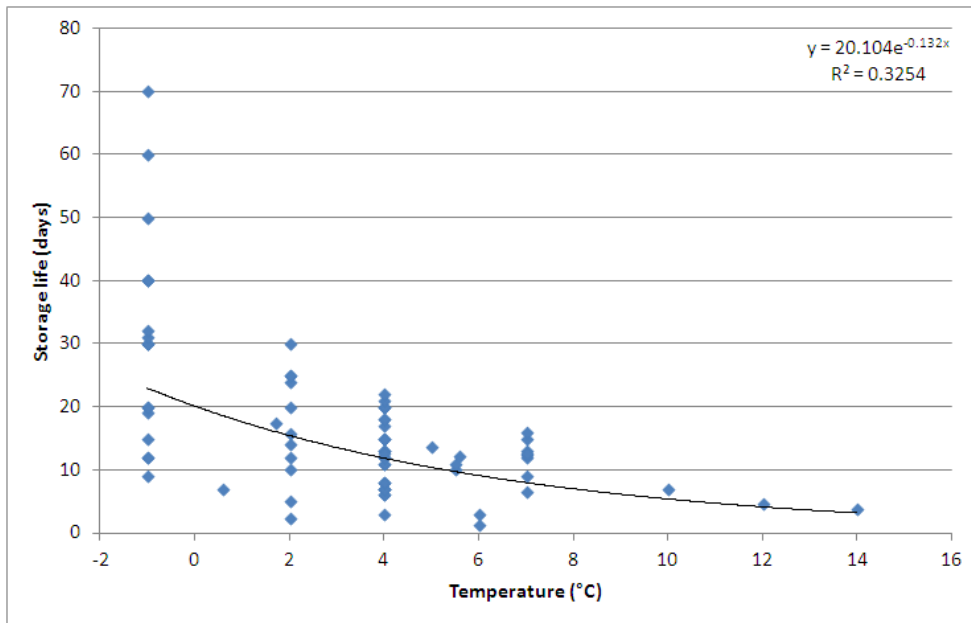
Table 7 Storage lives of broccoli at 4°C and 7°C

<i>Temperature (°C)</i>	<i>Storage life (days)</i>
4	11.3
7	8.9

2.2.7 Milk

The literature search for milk storage lives was originally focused on semi-skimmed milk, but this severely limited the number of references. Other types of milk were therefore included, which gave far more references but at the same time added an additional reason for scatter in the data, which together with use of pasteurisation and homogenisation resulted in considerable scatter (Figure 9).

Figure 9 Practical Storage Life versus temperature for milk



Although the R^2 value was still relatively low, use of the curve-fit equation gave logical and expected values (Table 8).

Table 8 Storage lives of milk at 4°C and 7°C

<i>Temperature (°C)</i>	<i>Storage life (days)</i>
4	11.9
7	8.0

2.3 Summary of estimated extensions

A summary of the percentage extensions in storage life is shown in Table 9. Extensions to storage life resulting from storage at 4°C rather than 7°C ranged from 26 to 67%, corresponding to varying time extensions depending on the sensitivity of the food type.

Table 9 Calculated storage life extensions due to lower fridge temperatures

Product	Storage life at 7°C	Storage life at 4°C	Difference	Difference
			(days)	(% extension)
Cod	5.1	7.8	2.7	53
Salmon	4.8	7.9	3.1	65
Chicken	5.8	8.7	2.9	50
Pork	4.8	8.0	3.2	67
Salad	7.0	10.4	3.4	49
Broccoli	8.9	11.3	2.4	26
Milk	8.0	11.9	3.9	49

2.4 Developing estimates

2.4.1 Waste reduction due to storage life extension

The project team devised a method by which to estimate the amount of food and drink waste that could be saved as a result of extending storage life through optimum in-home storage temperatures, based on previously reported reasons for waste (WRAP 2009). WRAP data distinguishes between food waste which is avoidable and unavoidable e.g. bones, some peelings. The reasons why different foods are wasted tends to vary with the degree of perishability, in other words foods which spoil more quickly are more likely to be disposed of due to reasons such as 'going off' or 'going past the date'.

A method of estimation was constructed, based on the total tonnage of reported avoidable waste for each type of food reviewed. The total for each food type was first multiplied by the proportion wasted because it was 'not used in time' (as opposed to being thrown away due to 'cooking, preparing or serving too much', which would be unaffected by any change in shelf life). This figure was then multiplied by the proportion reported to be thrown out due to 'going off' (i.e. where judgement is used to determine whether to discard food, rather than making use of a date label. For the purposes of this study it was assumed that the shelf life set by the manufacturer would reflect the current higher than recommended fridge temperatures, and therefore whilst optimising fridge temperatures might extend life beyond the date on the label, there would be no benefit in terms of waste reduction if the date is still used to determine whether or not to discard the food).

The assumption was then made that extending storage life allowed more time for the food to be used, and that the additional amount which would be used would be proportional to the increase in storage life e.g. 50% more storage life could allow up to 50% of waste previously classed as 'gone off' to be saved. This figure was taken as an estimate of the maximum potential saving due to extended storage life, for these foods. It was considered unlikely that the maximum potential would be realised, so a final adjustment was applied to account for food which might still be discarded during the extended storage life (based on insights about consumer behaviour around specific types of food from other WRAP research), to arrive at a conservative estimate for potential savings.

It is important to stress that whilst the theoretical storage life might be increased through improved storage temperatures, many consumers would still use the 'use by' or 'best before'

date to judge when it is safe or acceptable to eat a product (the percentage of consumers who do this will vary by product type). Therefore, in some cases, there may be no food waste saving from improved storage temperatures because the actual shelf life, indicated by the date mark, would be unchanged (this has been taken in to account in the development of the estimates of potential waste savings reported in this report, as described above). There is, therefore, potential to achieve further food waste savings, over and above the ones estimated in this work, if the food industry could extend shelf life in response to more optimal domestic fridge temperatures.

For some products, the findings from the literature review were used as representative storage life extensions for wider food groups for which food waste tonnages were known. These were:

- cod and salmon shelf lives were used to represent 'all fresh fish', and the average storage life extension for these two products was applied in the calculation;
- chicken and pork were used to represent 'all fresh meat';
- broccoli was used to represent a range of other vegetables, accepting that perishability will vary within these (including whole heads of lettuce, leeks, cucumber, spring onions, peppers, tomatoes, cabbage, cauliflower, mushrooms, but excluding root vegetables, which on the whole will be less perishable);
- bagged leafy salad and milk were retained as separate categories.

In addition, it was felt that excluding an estimate of the potential benefits on fresh fruit and root vegetables (e.g. carrots) stored in the fridge would give an unduly conservative estimate, and so, in the absence of specific shelf-life data, but drawing on the above and on other published work¹⁸, it was assumed that there would be a 10% benefit in terms of added life.

An example of the calculation for leafy, bagged salad is as follows:

- Avoidable waste is 36,000 tonnes p.a.
- Of this, 'not used in time' waste is 22,000 tonnes p.a.
- Proportion of this due to 'going off' = 30% or 6,600 tonnes p.a.
- Storage life extension from lower temperature = 49%, so maximum potential saving is 49% of 6,600 tonnes p.a. = 3,225 tonnes p.a.
- Apply a cautious estimate that 50% of this will still be discarded, as salad has 'use by' date and some rejection based on circumstances or habit is likely.
- Final saving estimate is thus 1,613 tonnes p.a.

2.4.2 Benefits of reduced fridge temperatures

Tabulating the results for the wider food groups gives the UK-wide tonnage savings shown in Table 10. For the included categories of food which are normally kept in the fridge, the estimated waste saving resulting from storage at the lower fridge temperature is around 71,000 tonnes per year. Savings of milk and vegetables make up the majority of the savings in tonnage partly due to their high sales volumes.

There are other categories of food that are likely to benefit from lower fridge temperatures, such as chilled juices, yoghurts, cheese, pre-prepared foods etc. but data is not available to enable a robust estimate of potential waste savings arising for these as a result of lowered fridge temperatures.

¹⁸ <http://www.wrap.org.uk/content/helping-consumers-reduce-fruit-and-vegetable-waste> for example

Table 10 Estimates of annual UK waste reduction due to extended shelf lives

Product	Avoidable waste (t)	'Not used in time' (t)	Thrown away "going off" (%)	Thrown away due to "going off" (t)	Storage life difference (%)	Potential saving realised (%)	Waste saved (t)
Leafy/salad vegetables	270,000	201,000	80	160,800	26.5	75	31,959
Milk	360,000	200,000	50	100,000	48.8	50	24,400
Fresh meat	200,000	130,000	20	26,000	58.3	50	7,579
Bagged salad	36,000	22,000	30	6,600	48.9	50	1,613
Fresh fish	9,600	7,200	20	1,440	58.8	25	212
Root vegetables*	51,000	40,500	80	32,400	10	50	1,620
Fruit*	99,150	91,300	80	73,040	10	50	3,652
Total	1,025,750	692,000		400,280			71,035

* These are the tonnages related to the % of the relevant foods currently stored in the fridge by consumers (e.g. 26% of apples)

The financial value of avoided food waste and its embodied CO₂e emissions (Table 11) were derived using the average costs per tonne of each food category (Defra Family Food, 2011¹⁹) and the average emissions conversion factor of 3.8 tonnes of CO₂e per tonne of food produced (WRAP 2009, Appendix E).

Table 11 Value and embodied CO₂e emissions in annual UK waste savings

Product	Estimate of tonnage saving (t)	Cost per tonne (£)	Estimated value of waste saved (£m)
Normally refrigerated			
Leafy/salad vegetables	31,959	2,590	82.8
Milk	24,400	620	15.1
Fresh meat	7,579	6,300	47.7
Bagged salad	1,613	3,930	6.3
Fresh fish	212	9,570	2.0
Root vegetables*	1,620	1,154	1.9
Fruit*	3,652	1,910	7.0
Total	71,035		162.9

The potential food waste savings associated with a reduction in fridge temperature are therefore around 70,000 tonnes, with a value of £163 million. This would equate to preventing almost 270,000 tonnes of CO₂e.

2.4.3 Benefits of more effective use of the fridge

Some categories of food are predominantly not stored in fridges, but would have increased storage lives if they were, primarily many examples of fresh fruit and vegetables. A large proportion of fresh fruit is not refrigerated e.g. only 26% of surveyed consumers store apples refrigerated, and 36% of carrots were stored outside of the fridge²⁰. There are also products stored in the fridge that would potentially have longer life stored elsewhere, for example bread (11% stored this in the fridge where it can stale up to six times faster) and bananas (4% in the fridge). For the purposes of this study we have estimated the potential waste savings of storing fruit and vegetables as recommended based on comparisons of shelf-life at different storage temperatures in previous WRAP research (2008). Storage in the fridge increased shelf-life by between 7 and 17 days, and so it has been assumed that this could result in a reduction in waste of 50%.

The potential for UK-wide waste saving is around 81,000 tonnes per year (Table 12).

¹⁹ <http://www.defra.gov.uk/statistics/foodfarm/food/familyfood/>

²⁰ <http://www.wrap.org.uk/content/helping-consumers-reduce-fruit-and-vegetable-waste>

Table 12 Estimates of annual UK waste reduction due to storing fresh fruit in vegetables in the correct location, due to extended shelf lives

Product	Avoidable waste (t)	'Not used in time' (t)	Thrown away "going off" (t)	% stored in the fridge	Tonnage that would benefit from being moved to or from the fridge	Potential saving realised (%)	Waste saved (t)
More stored in the fridge							
Apple	180,000	170,000	136,000	26	100,640	50	50,320
Citrus fruit	67,000	55,000	44,000	20	35,200	50	17,600
Carrots	46,000	40,000	32,000	64	11,520	50	5,760
Cabbage	53,000	23,000	18,400	60	7,360	50	3,680
Cauliflower	10,000	8,000	6,400	71	1,856	50	928
Peppers	16,000	13,000	10,400	89	1,144	50	572
Other root veg	22,000	14,000	11,200	81	2,128	50	1,064
Less stored in the fridge							
Bananas	83,000	78,000	62,400	4	2,496	50	1,248
Total	477,000	401,000	320,800		162,344		81,172

As above, the financial value of avoided food waste and its embodied CO₂e emissions (Table 13) were derived using the average costs per tonne of each food category (Defra Family Food, 2011²¹) and the average emissions conversion factor of 3.8 tonnes of CO₂e per tonne of food produced (WRAP 2009, Appendix E).

Table 13 Value and embodied CO₂e emissions in annual UK waste savings

Product	Estimate of tonnage saving (t)	Cost per tonne (£)	Estimated value of waste saved (£m)
More stored in the fridge			
Apple	50,320	1495	75.2
Citrus fruit	17,600	1660	29.2
Carrots	5,760	910	5.2
Cabbage	3,680	1350	5.0
Cauliflower	928	1780	1.7
Peppers	572	2950	1.7
Other root veg	1,064	1670	1.8
Less stored in the fridge			
Bananas	1,248	920	1.1
Total	81,172		121

The potential food waste savings associated with more effective use of the fridge to store fruit & vegetables are therefore around 80,000 tonnes with a value of £121 million. This would equate to preventing around 308,000 tonnes of CO₂e.

The combined benefits of a reduction in fridge temperature and using the fridge more effectively in storing fresh fruit and vegetables is shown in Table 14.

Table 14 Overall potential benefits of more optimal use of the fridge.

	Estimate of tonnage saving (t)	Estimated value of waste saved (£m)	Embodied emissions CO₂e (t)
Reductions in fridge temperature	71,035	163	269,930
More effective storage of fresh produce	81,172	121	308,454
Total	152,207	284	578,383

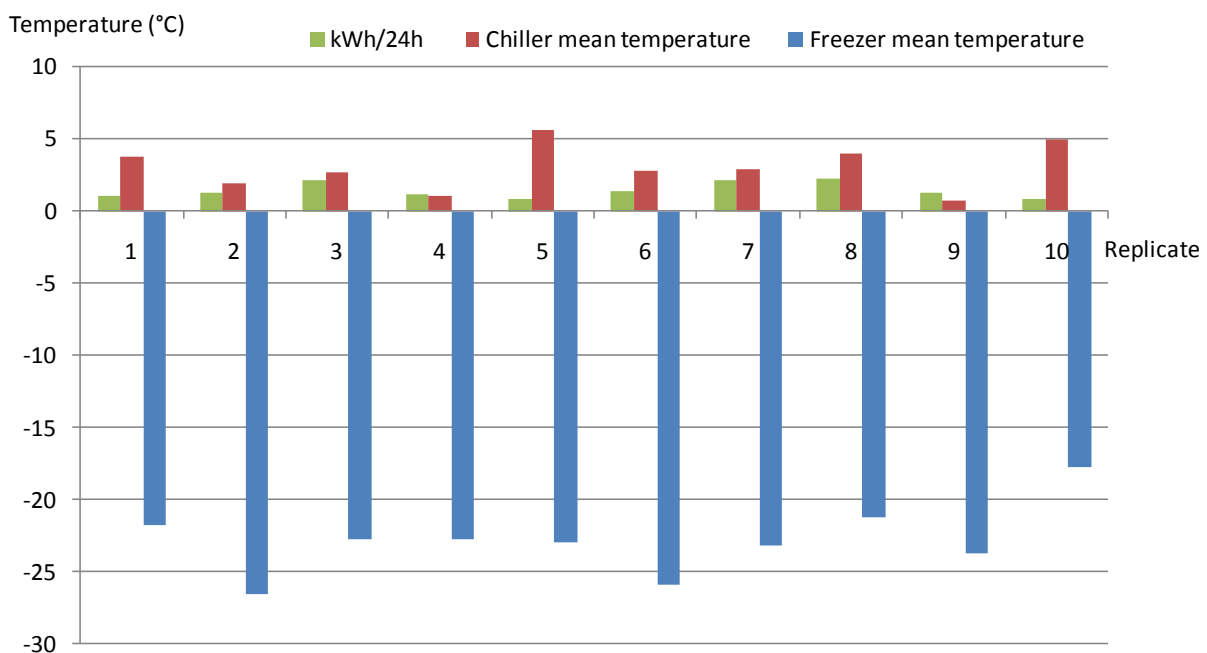
²¹ <http://www.defra.gov.uk/statistics/foodfarm/food/familyfood/>

3.0 Estimating the energy impact of improved fridge use

Typically a domestic fridge is major contributor to domestic electrical energy use. There is substantial information on energy used by domestic fridges under test conditions as all domestic fridges in Europe are energy labelled (and therefore need to be tested). The test conditions do not include simulated usage, as the tests are carried out with closed doors in a test environment. This project, therefore, generates new insights by measuring the energy impact of lowering fridge temperatures and of adding additional foods which are normally kept at ambient.

There is very little detailed information on energy use in real life situations. Limited information collected by Evans (unpublished) on a range of 10 fridge-freezers tested under simulated home usage conditions are presented in Figure 10. This shows a large variation in performance, both in terms of energy, but also temperature control.

Figure 10 Energy used by fridge-freezers under simulated usage conditions.



3.1 Method

3.1.1 Appliances and test methods

Three best-selling appliances were selected, all of which were A+ rated for energy – two stand-alone fridges (denoted Fridge 1 - the 130 litre net volume Beko CHILL53W and Fridge 2 - the 112 litre net volume Lec L5010W) and one fridge-freezer (denoted Fridge-Freezer 3 - the 150 litre net fridge volume Hotpoint RFAA52S).

All of the appliances had the more commonly used glass shelves which help to compartmentalise the internal volume²², and all (including the fridge-freezer) had single analogue dial thermostats. While the energy consumption of stand-alone fridges is directly related to the temperature of operation, consumption of fridge-freezers is complicated by the fact that, in most models, a single thermostat (sited in the fridge section) is used to control both the fridge and the freezer temperatures. Adjusting this thermostat therefore affects not only the fridge temperature but also the freezer temperature, compounding the energy impact.

²² <http://www.wrap.org.uk/content/insights-around-domestic-refrigerator>

The appliances were installed in a controlled environment test room running at $20.5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ to approximate typical domestic kitchen conditions in line with previous surveys of kitchen temperatures (e.g. James and Evans, 1992). Although little published work or data on kitchen relative humidity (RH) were found, it was decided to control RH at $50\% \pm 5\%$ to ensure that all appliances were subjected to the same steady ambient conditions. The kitchen is by far the most common site for fridges in the home (at 92.7%, WRAP 2010).

They were installed in a rigid metal frame at floor-level to which was attached an automatic door opening mechanism, which was in turn connected to the fridge doors. The mechanism was set to apply a simulated door opening pattern of a 10-second, 60 degree opening every 20 minutes between the hours of 08:00 and 22:00 each day. This pattern approximates to an average door opening behaviour found in previous domestic fridge surveys (James and Evans, 1992 and Laguerre, 2002).

Air temperatures in two positions on each of the fridge shelves, two positions in the crisper section and three in the door shelves were measured using calibrated t-type thermocouples connected to Datascan datalogging modules (Measurement Systems, UK). The positioning of the thermocouples is illustrated in Figure 11.

Figure 11 Photographs showing thermocouple positioning for air temperature measurement



Temperatures in samples of food were measured and recorded using similar thermocouples attached to portable Evo dataloggers (Comark, UK). Use of these loggers allowed continuous measurement of temperatures before loading (from either chilled storage or ambient), after loading and subsequent storage in the fridges. Although not strictly required for these trials, three further RH Evo loggers were used to measure RH on the middle shelf of each fridge section. Low RHs in fridges can result in excessive drying of unwrapped food products, as identified in previous WRAP research (WRAP, 2010). Such drying can be a source of waste both through direct loss of useable product weight and more importantly through disposal for reasons of appearance or texture.

The power used by each appliance was measured using calibrated power meters (Northern Design, UK). Period-averaged temperature and power values were recorded together with room temperature and RH every minute using Orchestrator software (Measurement Systems, UK). For the fridge-freezer, additional thermocouples were placed inside each shelf in the freezer to measure air temperatures.

Please note, the inclusion of a greater number of appliances, and in particular those equipped with more sophisticated controls, would be beneficial in checking that both the average measured figures and the assumptions applied are appropriate when considering national (and wider) fridge stocks.

3.1.2 Appliance temperatures and thermostat settings

The principal aim of the trials was to determine the energy impact of lowering average fridge air temperature from 7°C to 4°C. The positions included in this average were those on the shelves of the fridges. The appliances were first set to their manufacturer's recommended settings as detailed in the manual. These were as follows:

- Fridge 1 – thermostat range 0 (off) to 5 (coldest), initial setting 3
- Fridge 2 – thermostat range 1 (warmest) to 6 (coldest), initial setting 3.5
- Fridge-freezer 3 – thermostat range 1 (warmest) to 5 (coldest), initial setting 3

The fridge-freezer also had a 'fast freeze' switch designed to over-ride the thermostat and force continuous running – this was turned off for these trials. As its operation relied on forced air circulation, the fridge-freezer also had a fan which operated continuously.

As detailed in the results section, these 'default' settings were found to give average air temperatures close to 7°C during stable operation of all appliances and were therefore accepted as the settings for the first temperature level. A series of trials with different loadings was then carried out as described below. Once these nominal 7°C trials were complete, the thermostats were adjusted closer to their maximum setting, which forced the refrigeration systems to run for longer and reduce air temperatures. After considerable adjustment and fine tuning, the following settings were accepted as those giving the closest average air temperatures to the target of 4°C without forcing the refrigeration systems to run continuously:

- Fridge 1 – thermostat setting approximately 4.6 (out of 5)
- Fridge 2 – thermostat setting 5.5 (out of 6)
- Fridge-freezer 3 – thermostat setting approximately 4.25 (out of 5).

The series of trials with different loadings was then repeated.

3.1.3 Food loadings

At each temperature setting the appliances were loaded first with small amounts of food representing an 'empty' loading just before addition of a main shop. They were allowed to stabilise with this load and then run for at least 24 hours. Further items of food were then added to represent a 'normal' loading following a typical main shop. The appliances rose in temperature after addition of the food, and they were left to pull down in temperature back to stable operation, after which they were again run for at least 24 hours. These loadings were designed to approximate to the extremes of typical domestic fridge loading. A third loading level 'normal plus additional' was then added to assess the impact of refrigerating not just the normal main shop, but also additional items which are not always refrigerated but which might benefit from increased storage lives at refrigerated temperatures (e.g. fresh fruit). Again the appliances were allowed to pull down and left to run at their stable operating conditions for at least 24 hours. For comparative purposes, when loads of all types were added to the appliances, they were added at mid-day. Analysis of temperatures and energy was therefore based on 24 hour periods from mid-day to mid-day.

The types of food included in each loading level were as follows:

- 'empty' (approximately 15% full by volume) – representing a poorly stocked fridge just before a main shop is added. Products loaded were either chilled items (cabbage, margarine, cauliflower, sauce, ham, butter, fruit juice) or ambient items (small lemonade bottles, cans of beer, lemonade cans, eggs and bottled beer). Chilled items were taken from a refrigerated store at 5°C and held in the test room for 1 hour in carrier bags before loading to simulate the warming period following selection of shopping and transport to home. Items with thermocouples inserted to measure centre temperatures were cabbage, butter and margarine.
- 'normal' (approximately 70% full by volume) – representing the addition of products in a main shop which are normally refrigerated. Further products loaded were again either chilled (broccoli, ready meal, sausages, cheese, bacon, second pack of ham, second fruit juice, soup, sauces, milk) or ambient (grapefruit, melon, parsnips, more lemonade bottles, lemons, more lemonade cans). Items with thermocouples inserted to measure centre temperatures were ham, cheese and ready meals.
- 'normal plus additional' (approximately 85% full by volume) – representing the addition of products in a main shop which are normally refrigerated, plus some products which are not normally refrigerated but which would benefit from refrigeration. Additional products loaded were ambient items which are often not refrigerated but which could benefit from refrigeration (oranges, apples, carrots, additional grapefruit, swede) and some duplicate filler items (lemonade cans, bottled lemonade and cans of beer). Items with thermocouples inserted to measure centre temperatures were carrots, apples and grapefruit.

During all of the trials, the freezer section of the fridge-freezer was kept loaded to approximately 70% by volume with the door remaining closed to avoid complication of the energy impact results from varying use of the fridge section. Items stored in the freezer were ice cream, lamb grills, pizza (all with thermocouple placed to measure centre temperatures) and ready meals, bread, and sausages.

3.2 Results

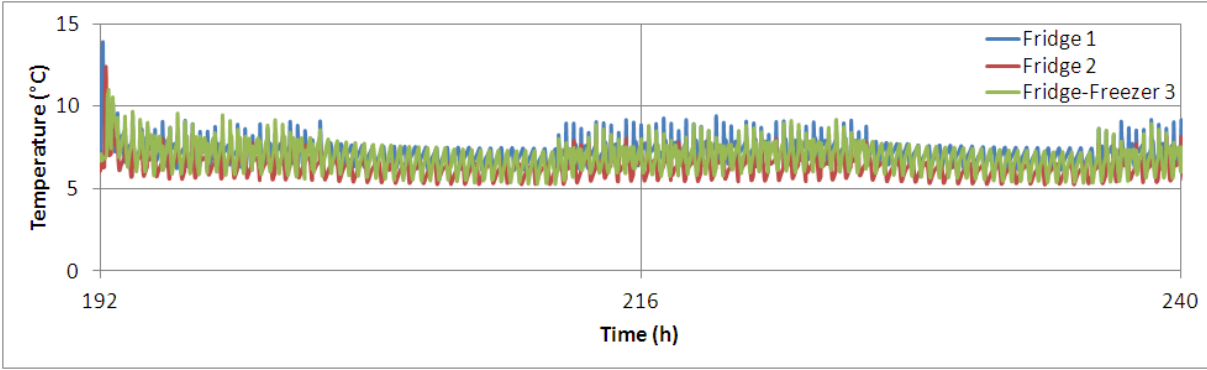
3.2.1 Test room conditions

The arithmetic mean air temperature in the test room throughout the experiments was 20.2°C (standard deviation 0.3°C) and the mean relative humidity was 51.6% (standard deviation 3.1%).

3.2.2 Fridge air temperatures

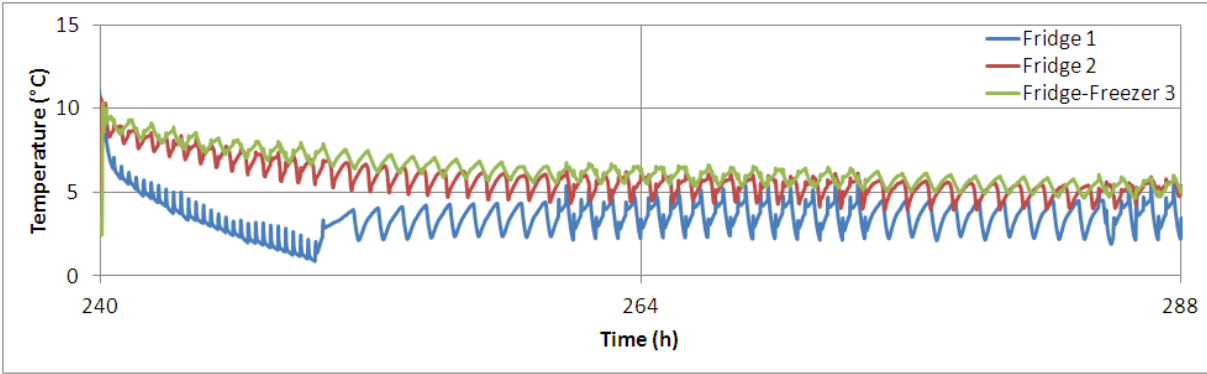
Air temperatures in the appliances followed typical cyclical patterns due to the on/off thermostatic control of the refrigeration systems. This can be seen in Figure 12, which shows average air temperatures above the shelves and in the crisper sections for an example period of 48 hours following loading to 70% full at 7°C. The initial rise in temperatures after loading can be seen, followed by pull-down within the first 24 hours and subsequent stable operation. The periods with greater oscillations result from the operation of the door opening regime, while those with lesser oscillations are periods with doors closed.

Figure 12 Average air temperatures above the shelves and in the crisper section of the three appliances after adding 'normal' loads at nominal 7°C settings



In comparison, air temperatures following loading to the 85% 'normal plus additional' level were complicated by two factors, as shown for nominal 4°C operation in Figure 13. The first factor, common to all appliances, was that temperatures were not fully pulled down during the first 24 hours. To account for this, the energy results were averaged over 48 hours rather than 24 hours. The second factor was specific to Fridge 1, which ran almost continuously to cope with the combined demands of low fridge temperature, high product load and the heat added by the experimental door opening regime. This continued until the end of the door opening regime (at around 249 hours on Figure 13), after which it reverted to a more typical cyclical operation similar to that for the other appliances. During the initial period, average air temperatures were reduced quickly (but too far for some individual air temperatures, resulting in partial freezing of food), and energy consumption was considerably greater than normal cyclical operation.

Figure 13 Average air temperatures above the shelves of the three appliances after adding 'normal plus additional' load at nominal 4°C settings



With re-adjustment of the thermostat to a warmer temperature, it may have been possible to avoid this behaviour. However, as the appliance had already functioned as normal with the two lighter food loadings it was decided to accept the result as being an occurrence which could happen in a domestic situation following adjustment to a setting close to maximum.

Average shelf and crisper box air temperatures (from 8 positions) over 24 hour stable periods for all loads are shown in Table 15 for both nominal temperature settings. Initial setup to achieve nominal average air temperatures of 7°C was relatively straightforward and the average shelf air temperatures achieved during all stages were within 0.6°C of the nominal temperature. However, achieving nominal average air temperatures of 4°C by adjusting the thermostat settings proved challenging and time consuming. The effect of

changes to the analogue dial settings was often not repeatable, and some changes made little difference to temperature, while others forced the fridges to run continuously and overshoot the desired temperature, resulting in partially frozen food and significantly higher energy consumption. The temperatures achieved and shown in Table 15, although not ideal, were the closest settings which allowed normal cyclical operation without forcing the refrigeration systems to run continuously and they were therefore accepted as the second nominal temperature settings.

The differences in achieved temperatures are presented at the bottom of Table 15, and these were used to scale energy results assuming a linear pro rata energy increase per degree of temperature reduction.

Table 15 Shelf air temperatures averaged over 24 hour stable periods at each nominal air temperature and food loading

Nominal Temperature °C	Load	Stage	Average shelf air temperature			
			°C			
			Fridge 1	Fridge 2	Fridge-freezer 3 fridge	Fridge-freezer 3 freezer
7	15%	Stable	6.8	6.7	6.5	-19.8
	70%	Stable	7.6	7.5	6.7	-19.6
	15%	Stable	6.9	6.9	6.6	-19.7
	85%	Stable	7.6	7.0	6.9	-19.6
	<i>Average</i>		<i>7.2</i>	<i>7.0</i>	<i>6.7</i>	<i>-19.7</i>
4	15%	Stable	3.9	5.1	4.5	-22.2
	70%	Stable	3.9	4.8	3.9	-23.0
	15%	Stable	3.7	5.1	4.1	-22.8
	85%	Stable	3.7	4.9	5.0	-22.4
	<i>Average</i>		<i>3.8</i>	<i>5.0</i>	<i>4.4</i>	<i>-22.6</i>
7 - 4	Diff		3.4	2.0	2.3	2.9

3.2.3 Product temperatures

Average product temperatures were calculated using a similar method to those for air temperatures, and are presented in Table 16. The values follow a similar trend to those for air temperatures, but a comparison of air and product temperatures for each temperature setting and load combination shows that some product temperatures were slightly warmer than air temperatures but others were slightly colder than air temperatures. The most likely explanation for such differences is that product thermocouples were necessarily sited in different positions to those used for air temperatures, and these positions could be warmer or colder than the air temperature sites.

Table 16 Product temperatures averaged over 24 hour stable periods at each nominal air temperature and food loading

Nominal Temperature °C	Load	Stage	Average product temperature °C			
			Fridge 1	Fridge 2	Fridge-freezer 3 fridge	Fridge-freezer 3 freezer
7	15%	Stable	6.5	6.6	6.3	-19.3
	70%	Stable	7.0	6.8	6.3	-19.5
	15%	Stable	6.5	6.6	6.3	-19.3
	85%	Stable	6.8	6.7	6.6	-19.3
	<i>Average</i>		<i>6.7</i>	<i>6.7</i>	<i>6.4</i>	<i>-19.3</i>
4	15%	Stable	3.5	5.8	3.6	-22.7
	70%	Stable	3.7	5.5	3.5	-22.3
	15%	Stable	3.5	5.8	3.6	-22.7
	85%	Stable	3.7	5.1	4.7	-22.0
	<i>Average</i>		<i>3.6</i>	<i>5.5</i>	<i>3.8</i>	<i>-22.4</i>
7 - 4	Diff		3.1	1.2	2.6	3.1

3.2.4 Fridge RHs

Relative humidities measured on the middle shelves of each fridge are presented in Table 17 as the averages of measurements taken during stable operation at the three different food loading levels, together with corresponding average air temperatures and calculated dewpoints.

Table 17 Average air temperatures, relative humidities and dewpoints measured on middle shelves during stable operation

Setting	Parameter (average of values measured on middle shelf)	Unit	Fridge 1	Fridge 2	Fridge-freezer 3
7°C	Air temperature	°C	6.4	5.9	6.5
	Relative Humidity	%	68.6	69.2	67.8
	Dewpoint	°C	1.0	0.6	0.8
4°C	Air temperature	°C	3.4	4.9	4.4
	Relative Humidity	%	70.3	68.1	69.3
	Dewpoint	°C	-1.9	-0.6	-1.1

Although not strictly relevant to the energy impact measurements, these results indicate the potential for the fridges to promote evaporation of water from unwrapped food products, which results in product weight loss and could also lead to waste due to perceived surface drying and its effects on appearance and quality.

3.2.5 Energy consumption data

For calculation purposes the use of energy by a fridge was considered as two components:

- the 'stable' energy required to hold the various food loads at their intended storage temperature; and
- the additional energy used by the fridge to reduce the temperature of added food to its storage temperature, referred to as 'pull-down' energy.

Table 18 shows the stable energy consumptions for each appliance at each nominal temperature setting. It was assumed that in practice fridge loading would reduce linearly from the loaded levels (either 70% or 85%) to the empty level (15%). The average stable energy consumptions were therefore calculated as the average of the loaded and empty energy consumptions (e.g. the 70% / 15% average stable values).

The additional pull-down energy consumption following loading of either the 70% or 85% loading was then determined as the difference between the increased energy consumption while food was being cooled and the stable energy consumption once stable storage temperatures were achieved.

Due to the thermostatic control issue described above, the pull-down energy for Fridge 1 at a nominal 4°C temperature and 85% loading (marked with * in Table 18) was considerably higher than other pull-down energies.

Table 18 Daily energy consumption and pull-down energies for the appliances measured at three loading levels

Nominal Temperature °C	Load	Stage	Energy consumption		
			kWh.day ⁻¹ (stable) or kWh (for pull-down)		
			Fridge 1	Fridge 2	Fridge-freezer 3
7	15%	Stable	0.261	0.224	0.686
	70%	Stable	0.236	0.219	0.675
	85%	Stable	0.249	0.215	0.680
	70% / 15%	Average stable	0.249	0.222	0.681
	85% / 15%	Average stable	0.255	0.220	0.683
	70%	Additional pull-down	0.025	0.025	0.021
	85%	Additional pull-down	0.043	0.046	0.039
4	15%	Stable	0.303	0.240	0.758
	70%	Stable	0.281	0.240	0.760
	85%	Stable	0.275	0.244	0.755
	70% / 15%	Average stable	0.292	0.240	0.759
	85% / 15%	Average stable	0.289	0.242	0.756
	70%	Additional pull-down	0.058	0.031	0.015
	85%	Additional pull-down	0.267*	0.061	0.033

3.3 Developing estimates

3.3.1 Annual energy consumptions for each appliance

To estimate the annual energy consumption for each appliance it was assumed that one large load of food (either the 70% 'normal' or the 85% 'normal plus additional' load) would be added once per week²³. Annual energy consumptions were therefore calculated as 365 days of stable energy consumption plus 52 additional amounts of pull-down energy. Table 19 shows the calculated stable and pull-down energy consumptions for each temperature and loading combination. It was considered that the high value measured for the Fridge 1 pull-down energy at a nominal 4°C temperature and 85% loading could also occur in a domestic situation where thermostat settings have been adjusted to achieve lower temperatures. Accordingly, the value was retained in the estimates for annual energy impact.

Table 19 Annual energy consumptions and increases due to lowering fridge temperatures and adding additional foods

Nominal Temperature °C	Load	Stage	Annual energy consumption		
			kWh		
			Fridge 1	Fridge 2	Fridge-freezer 3
7	70% / 15%	Stable	90.8	80.9	248.5
		Pull-down	1.3	1.3	1.1
		Total	92.1	82.2	249.5
	85% / 15%	Stable	93.1	80.3	249.4
		Pull-down	2.2	2.4	2.0
		Total	95.3	82.7	251.4
4	70% / 15%	Stable	106.7	87.6	277.0
		Pull-down	3.0	1.6	0.8
		Total	109.7	89.2	277.7
	85% / 15%	Stable	105.6	88.4	276.0
		Pull-down	13.9	3.2	1.7
		Total	119.5	91.6	277.7

For reference, the energy consumption values taken from the appliances' energy labels were as follows: fridge 1 was labelled at 116 kWh.annum⁻¹, fridge 2 at 117 kWh.annum⁻¹, and fridge-freezer 3 at 268 kWh.annum⁻¹.

The pull-down energies for the appliances were found to be relatively small compared to the differences in stable running energies. It is probable that this was partly due to addition of chilled food as a large part of the added loads. This food was equalised in a chilled store at 5°C before addition to the fridges, and was held at ambient for 1 hour before loading to simulate warming after purchase. However, much of the food would have entered the fridges at a temperature below the nominal 7°C setting and fairly close to the nominal 4°C setting. In the case of the 7°C setting, the added chilled food would actually reduce the energy consumption (although it would be balanced by the addition of the ambient food and

²³ While most consumers still carry out a main shop once a week, shopping frequency does vary so these results are indicative of what might be classed as traditional shopping routines.

the additional door opening time). In the case of the 4°C setting, the chilled food would have added only slightly to the heat load on the fridges.

The measured increases for the fridge-freezer were significantly higher than those for the stand-alone fridges, and this was because it was controlled by a single thermostat in the fridge section which meant that lowering the fridge temperature also reduced the freezer temperature by a similar amount. However, not all fridge-freezers are controlled in this way. Those with dual controls (and either dual compressors, refrigerant flow diverters or air baffles controlling air flow from the freezer to the fridge) would allow independent control of fridge temperature without the high energy penalty measured on the single thermostat appliance.

3.3.2 Energy impact of lowering temperature for each appliance

To determine the energy impact of lowering air temperature, the stable 70% / 15% values at 4°C nominal air temperature were compared with those at 7°C nominal air temperature to derive measured rises in energy consumption. However, as the actual achieved temperature drops were not exactly 3°C for each fridge, the increases in energy consumption were normalised to 3°C reduction equivalents. Although energy increases are not linear as temperature is reduced, the differences between achieved and target temperature reductions were considered to be small enough to allow linear scaling as follows:

Energy increase for 3°C reduction = Measured energy increase * 3°C / Actual temperature reduction.

Table 20 shows the measured energy impact of lowering temperature for each appliance, followed by the normalised impacts.

Table 20 Energy impact of lowering fridge temperature

Temperature °C	Load	Factor	Annual energy consumption kWh and temp. difference °C		
			Fridge 1	Fridge 2	Fridge-freezer 3
7	70% / 15%	Total	92.1	82.2	249.5
4	70% / 15%	Total	109.7	89.2	277.7
4-7		Measured increase	17.6	7	28.2
		Temp. difference	3.4	2	2.3
		Normalised increase	15.5	10.5	36.8

3.3.3 Energy impact of adding additional food

The energy impact of adding additional food which is not predominantly stored in the fridge was determined by comparing the 85% / 15% total energy values with the 70% / 15% total energy values. These comparisons are shown in Table 21 for nominal air temperatures of 7°C to illustrate the effect of adding foods at the current average fridge temperature, and at 4°C to illustrate the effect of adding additional foods to fridges which have been adjusted to an improved fridge temperature.

Interestingly for the fridge-freezer, although an increase in energy consumption due to adding additional food was measured at 7°C, there was no measured difference at 4°C. This may have been due to the interaction between the fridge section and the freezer section, although it would be expected that any such interaction would be similar at both temperatures.

Table 21 Energy impact of adding additional food items

Temperature °C	Load	Factor	Annual energy consumption kWh and temp. difference °C		
			Fridge 1	Fridge 2	Fridge-freezer 3
			7	85% / 15%	Total
	70% / 15%	Total	92.1	82.2	249.5
		Measured increase	3.2	0.5	1.9
		<i>Temp. difference</i>	<i>3.4</i>	<i>2</i>	<i>2.3</i>
		Normalised increase	2.8	0.8	2.5
4	85% / 15%	Total	119.5	91.6	277.7
	70% / 15%	Total	109.7	89.2	277.7
		Measured increase	9.8	2.4	0.0
		<i>Temp. difference</i>	<i>3.4</i>	<i>2</i>	<i>2.3</i>
		Normalised increase	8.6	3.6	0.0

3.3.4 Combined energy impact

If at the same time the fridge temperatures were lowered and the additional foods were refrigerated, their energy impacts would be combined, as would the potential waste savings. The combined energy impact can be estimated by comparing the energy use with 85% / 15% loading at 4°C with that for 70% / 15% loading at 7°C. These figures can be derived from the preceding tables, but are shown again for clarity in Table 22.

Table 22 The combined energy impact of lowering fridge temperature and adding additional food items

Temperature °C	Load	Factor	Annual energy consumption kWh and temp. difference °C		
			Fridge 1	Fridge 2	Fridge-freezer 3
			4	85% / 15%	Total
7	70% / 15%	Total	92.1	82.2	249.5
		Measured increase	27.4	9.4	28.2
		<i>Temp. difference</i>	<i>3.4</i>	<i>2</i>	<i>2.3</i>
		Normalised increase	24.2	14.1	36.8

3.3.5 Estimating energy impact on a national basis

The above figures for energy impact on individual appliances were expanded to national estimates for the UK based on the following assumptions, references and factors:

- Each of the approximately 26 million²⁴ households in the UK was assumed to have one main fridge or fridge-freezer (the WRAP 2010 study found that around 87% of respondents had one fridge, 12% had two and just over 1% had three fridges).
- 32% of these are fridges, 68% are fridge-freezers (based on 2010 sales data, GfK 2012). This gives 8.32 million fridges and 17.68 million fridge-freezers.

²⁴ <http://www.ons.gov.uk/ons/rel/family-demography/families-and-households/2012/rft-tables.xls>

- Up to 65% of fridge-freezers are single thermostat, 35% are dual control (Lot 13, 2005). It was assumed that energy impact on dual control appliances would be similar to that for fridges.
- Each kWh of domestic electricity costs on average 11.55p (DECC, 2011).
- UK conversion factor for electricity 0.5246 kg CO₂.kWh⁻¹ (Carbon Trust, 2011).
- The high pull-down energy behaviour observed for Fridge 1 was considered to be a possible consequence of consumer adjustment to low thermostat settings. In the experimental work it occurred in one out of two stand-alone fridges, so it was conservatively assumed that this ratio of occurrence is applicable to the national stock of stand-alone fridges.

Applying these assumptions and data gives the costs and emissions shown in Table 23.

Table 23 Increased energy and its costs and associated emissions resulting from lowering fridge temperature and adding foods which are normally not refrigerated

Scenario	Appliance type and loading level	Annual UK energy increase (1000 kWh)	Increased cost (£ m)	Increased emissions CO ₂ e (t)
Lowering fridge temperature 7°C to 4°C	Fridges	108,282	12.5	56,805
	Dual control fridge-freezers	80,535	9.3	42,249
	Single control fridge-freezers	422,706	48.8	221,751
	Total	611,523	70.6	320,805
Adding additional foods at 7°C	Fridges	14,866	1.7	7,799
	Dual control fridge-freezers	11,057	1.3	5,800
	Single control fridge-freezers	28,480	3.3	14,941
	Total	54,403	6.3	28,540
Adding additional foods at 4°C	Fridges	50,948	5.9	26,727
	Dual control fridge-freezers	37,892	4.4	19,878
	Single control fridge-freezers	0	0.0	0
	Total	88,840	10.3	46,606
Lowering temperature and adding additional foods at 4°C	Fridges	159,230	18.4	83,532
	Dual control fridge-freezers	118,427	13.7	62,127
	Single control fridge-freezers	422,706	48.8	221,751
	Total	700,363	80.9	367,411

4.0 Estimating the energy impact of improved freezer use

4.1 Method

Experimental trials were devised to measure the impact on energy consumption of adding chilled and ambient foods to a freezer. The trials were split into the following sections:

- stable operation (with two periods of automated door openings);
- stable operation as above, with ambient food added during an additional door opening; and
- stable operation as above, with a repeat of the additional door opening but no addition of ambient food.

In each of the sections, temperatures of freezer air and food were recorded together with power consumption until the freezer was either operating stably or had returned to stable operation after the addition of ambient food or the additional door opening.

4.1.1 Choice of appliance

An example of the current bestselling stand-alone freezer model, the Beko TZDA504FW upright freezer was purchased and installed in an environmental test room running at 20°C. An upright stand-alone freezer was chosen, rather than a fridge-freezer, because the impact of adding ambient food to a stand-alone freezer is likely to be more direct and, therefore, straightforward to measure. This is because the refrigeration systems on more common single-thermostat models of fridge-freezer are controlled based on temperatures in the fridge section not those in the freezer section. This means that the freezer section is only cooled when the thermostat senses that the fridge section is too warm. It can also mean that if large quantities of warm food are placed into the freezer section, the fridge-freezer may be slow to respond as the temperatures in the fridge section will not be directly affected by the heat from the added food and the thermostat will not immediately turn on the refrigeration system (to cool the freezer section). In this situation, the warm food will raise temperatures in the freezer section and freezing of the food will be slow. In a stand-alone freezer however, the thermostatic control is of course based on temperatures in the freezer, and the response to adding ambient food will be more immediate and temperatures are unlikely to rise as much.

4.1.2 Appliance setup and stable operation

The freezer was loaded to approximately $\frac{3}{4}$ full by volume in each compartment with a selection of typical frozen food items which acted as a base load. Calibrated t-type thermocouples were positioned to measure air and product temperatures at the top, middle and bottom sections of the freezer, which was connected to a power supply via a calibrated power meter (Northern Design, UK). All temperature and power data were recorded at 1-minute intervals using a Measurement Systems Datascan data logging system. A purpose-built door opening mechanism was attached to the freezer to automatically simulate a domestic door opening regime. The freezer door was opened during 2 one-hour periods each day to simulate breakfast and evening meal periods. In each of these periods the door was opened for a duration of 15 seconds every 10 minutes to an open angle of greater than 60 degrees.

The appliance was allowed to achieve stable operation at its default (as supplied) thermostat setting, but was then adjusted to achieve an approximate mean frozen food temperature of -16.7°C ($\pm 1^\circ\text{C}$) to match the European average freezer temperature defined in Lot 13 (2005)²⁵. As the freezer had an automatic on-demand defrost, which was initiated at varying intervals of up to 5 days apart, temperatures and power were recorded at each thermostat setting until at least a full day of stable operation had been achieved after defrost.

25 Lot 13 (2005). Refrigerators and freezers. Part 2 – present situation. Task 3: economic and market analysis, Rev 1.0. Preparatory studies for Eco-design requirements for EuPs.

4.1.3 Impact of adding warm food (plus additional door opening)

To assess the impact of adding a mixture of chilled and ambient food to the freezer, four typical products with a total weight of 2.302 kg were added:

- beef lasagne (enough for two people) in an air tight container, cooled to room temperature of approximately 20°C;
- beef cottage pie ready meal (approximately 400g two person portion) in original packaging of plastic tray with film lid and cardboard sleeve, cooled to room temperature of approximately 20°C;
- chicken breasts (two out of a pack of four) in a freezer bag, at fridge temperature of approximately 7°C; and
- half a loaf of white sliced bread in original packaging, at a temperature of approximately 7°C²⁶.

The addition of the food to the freezer was timed to be half way between two defrosts. The door opening mechanism was stopped and the freezer door manually opened to an angle of 90°. One of the portions of food was added to each of the drawers within the freezer and thermocouples were positioned in the centre and at the surface of each portion. The door was then closed and the automatic door opening mechanism re-started. The time required to add the food was approximately 2 minutes in total. The temperature and power data were again recorded until at least a full day of stable operation had been achieved after defrost to allow comparison with the stable operating period.

4.1.4 Impact of the additional door opening only

The additional heat load on the freezer during the time in which the food was added came from a combination of heat from the 'warm' food added and heat gained through having an additional (and relatively lengthy) door opening. To determine the relative amounts of these heat loads, a further consecutive trial was undertaken. A period of stable operation was monitored to ensure that temperatures were equivalent to those in the previous stable period i.e. the freezer had not become iced due to insufficient defrosting. The door opening part of the food addition trial was then repeated but this time without adding the food.

4.2 Results

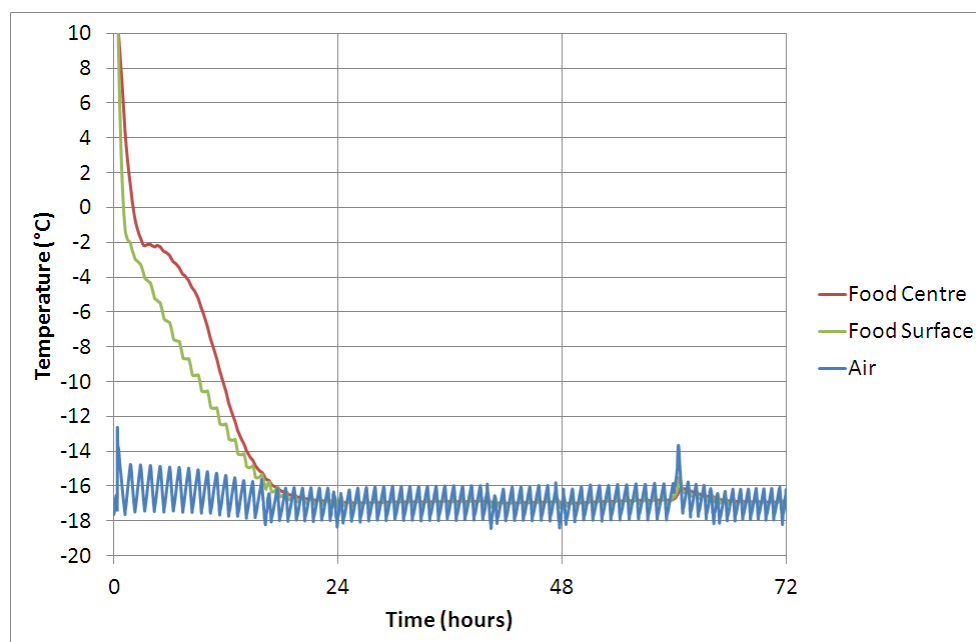
4.2.1 Air and product temperatures

Average air temperatures were calculated using the measurements from the three thermocouples positioned in the top, middle and bottom sections of the freezer. Averages were also calculated for the temperatures measured in the centres and at the surfaces of the four added food products. Figure 14 shows these average temperatures during the period following addition of the warm foods.

During the first 24 hours the freezer air temperatures rose due to the added heat load from the additional door opening and the warm food added. By the start of the second 24 hours, the freezing process was complete and air temperatures returned to values which were similar to those in stable periods. During the third 24 hours the freezer initiated a defrost, causing a slight rise in the average temperatures, although these quickly dropped back to stable values. The period following the additional door opening without added food showed a similar pattern, but with less of an impact on temperatures in the first 24 hours. To make sure the freezer was not progressively icing up (which could affect its performance) the lengths of defrosts in each section of the trials were checked and found to be unaffected by the warm food or additional door opening, and temperatures recovered to the same values after defrosts.

²⁶ If the bread had been at room temperature it would have added around 3% more heat, i.e. not a significantly higher amount.

Figure 14 Average air, food centre and food surface temperatures in the freezer



4.2.2 Refrigeration system run time, power consumption and energy used

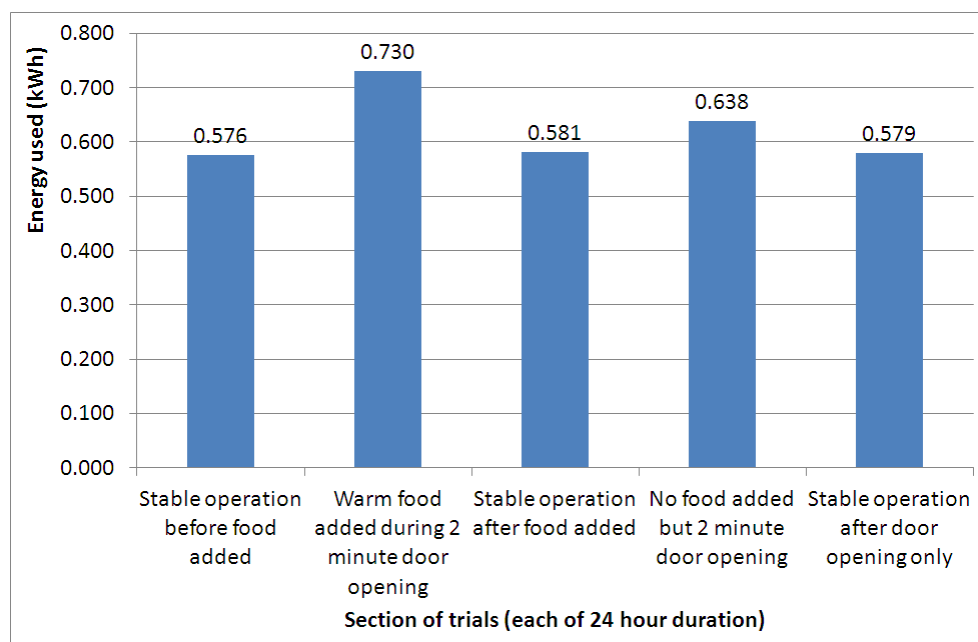
As described above, refrigeration systems on domestic freezers are generally controlled by a thermostat which switches the compressor off when it reaches its set temperature. Greater heat loads on the freezer, such as those from increased door opening or from the addition of ambient food, will result in the compressor having to run for longer periods. This is reflected in the run times, which are the percentage of time on each day for which the compressor ran. Table 15 shows the expected trend that adding a small amount of extra heat by opening the door increased the run time by a small amount (3.1 percentage points), and adding a greater amount of heat by opening the door and adding warm food increased the run time by a greater amount (8.2 percentage points).

Table 15 Refrigeration system (compressor) run time and average power during 24h test periods

Test period (<i>each of 24h duration</i>)	Run time (%)	Average power (W)
Stable operation before food added	30.0	24.0
Warm food added during 2 minute door opening	38.2	30.4
Stable operation after food added	30.2	24.2
No food added but 2 minute door opening	33.3	26.6
Stable operation after door opening only	30.1	24.1

As expected, the power consumed by the freezer closely aligned with its run times. For example, when warm food was added, the power consumption rose by 26.7% over the first 24 hours, and the run time increased by 27.3%. When only the additional door opening was applied without adding the food, these increases were 9.9% and 10.3% respectively. The extra power used when the freezer door was opened and warm food was added was 6.4W while that from door opening only was 2.4W. Converting the power values to the units of energy paid for by consumers (kWh) gives the figures shown in Figure 15.

Figure 15 Energy consumed by the freezer during each 24h test period



4.3 Comparison of costs and carbon dioxide emissions

As shown above, the additional power used by the freezer as a result of adding the warm food was an average of 6.4W over the first 24 hours, after which, power was equivalent to that during stable operation.

This gives an increase in energy of $6.4W * 24 / 1000 = 0.154$ kWh.

This can be split into the increase caused by adding the warm food (4.0W or 0.096kWh, equivalent to 62.3%) and that caused by the door opening (2.4W or 0.058kWh, equivalent to 37.7%).

The cost of this extra energy was 0.154 kWh * 11.55p/kWh (DECC, 2011) = £ 0.018.

The cost of the food was £5.36 (Asda, 2012).

The CO₂e emissions associated with the extra energy were 0.154 kWh * 0.5246 kg CO₂e / kWh (Carbon Trust, 2011) = 0.081 kg CO₂e.

The CO₂e associated with the food was 2.302 kg * 3.8 kg CO₂e / kg food = 8.75 kg CO₂e.

The financial and environmental benefits of avoiding waste by freezing leftover / part-used food, therefore, greatly outweighs the environmental and financial costs, by more than 100-fold, assuming of course that the food is eventually consumed and not disposed of at some future date.

On a UK level, the benefits depend on how many times such waste is avoided by the average household. Assuming that each of the UK's 26 million households saves the equivalent of the 4 small pieces of food used in the experimental trial over a period of a year, the financial saving equates to £139m and the CO₂e associated with the reduced waste is around 225,000 tonnes.

More broadly WRAP has estimated that at least 800,000 tonnes of food is thrown away each year that could have been frozen to eat at a later date. This is associated with over 3 million tonnes of CO₂e and has a value of over £2 billion.

5.0 Discussion

Several aspects of improved fridge use were assessed. These were:

- the potential for extension of storage life of typical chilled foods if lower fridge temperatures were used;
- estimates of reduced waste which might result from these extended storage lives;
- a comparison of the financial value and emissions associated with the waste saved and with the increased energy consumption when fridges are run at such temperatures;
- the savings in financial value and emissions resulting from storage of items which are not normally refrigerated but which store for longer at chilled temperatures; and
- the combined impact of using lower fridge temperatures and refrigerating the additional items which are not normally refrigerated.

In addition, a similar aspect of improved freezer use was assessed:

- freezing of food for later use rather than disposal.

Using the results from a literature review of food storage lives, it was estimated that lowering storage temperatures could result in considerable extensions to storage life for most chilled food products that were assessed, with typical extensions of around 3 days resulting from storage at 4°C instead of 7°C.

A method was devised to estimate the reductions in food waste which might result from such extensions, and the annual UK savings in waste were estimated to be worth £160 million and associated with 270,000 tonnes of CO₂e emissions. However, the costs and emissions associated with increased fridge energy consumption at lower temperatures must be balanced against these savings, and based on experimental measurements these were estimated at an annual UK cost of £71 million and associated emissions of 321,000 tonnes CO₂e. Comparing these figures suggests that although use of lower fridge temperatures would potentially reduce waste and save money, it might risk increased emissions. However, the estimates of waste savings were based on conservative assumptions around how much food would be consumed as a result of the additional life, and on a limited set of food types. Further savings would also result if manufacturers were able to extend the 'use-by' dates given for perishable foods, although to do this they would require clear evidence that fridges were operating at the lower temperatures needed to sustain extended storage lives.

Some foods (e.g. apples and carrots) which benefit from chilled storage are not always kept in the fridge. If these were refrigerated in the home, the potential annual UK waste savings were estimated to be worth £120 million and associated with 308,000 tonnes of CO₂e emissions. Even at the more energy intensive 4°C, the extra energy required to refrigerate such foods was only estimated to have an annual UK cost of £10 million and associated emissions of 47,000 tonnes CO₂e. Both financially and environmentally the savings far outweigh the energy penalty.

If the estimates for savings from lowering fridge temperature are combined with those for refrigerating the additional foods, food worth £280 million and associated with 580,000 tonnes of CO₂e emissions could be saved. The additional energy required to achieve this would have an estimated annual UK cost of £81 million and associated emissions of 367,000 tonnes CO₂e. Combining the two measures would therefore offer significant financial savings at the same time as reduced environmental impact.

Improved use of the freezer through freezing food for later use was assessed by measuring the additional energy consumed by a typical stand-alone freezer while freezing a selection of food left-overs. The extra energy required by the freezer was found to be 0.154 kWh (an additional 26.7%) in the 24h period during which the food was added, after which the energy use returned to normal. The financial value of the food items added and their

embodied CO₂e emissions were over 100 times the cost and CO₂e emissions associated with the extra energy.

These results should be interpreted as indicative in nature due to various factors, including availability of data in the literature review, the potential for inaccuracy in the method of storage life estimation, experimental accuracy of energy measurements and assumptions used in the expansion of individual daily appliance energy impacts to annual and national energy estimates.

The experimental measurements highlighted some practical issues with advising consumers to lower fridge temperatures. The first of these relates to the advice for single thermostat fridge-freezers. Adjusting the thermostat to achieve lower fridge temperatures for such appliances also has a similar effect on the freezer. This can result in unnecessarily low freezer temperatures and an amplified energy impact as the refrigeration system runs for longer to maintain the fridge and freezer sections at lower temperatures. The implications of advising lower temperatures for these appliances, therefore, need consideration.

A second practical issue was the difficulty experienced with setting inaccurate and / or poor sensitivity thermostats, and the ability of all appliances to achieve the lower temperature target. All of the appliances tested were equipped with analogue dial thermostats, for which adjustments often gave unpredictable and variable results, particularly at lower temperatures. Adjustment near to the lowest thermostat setting did not necessarily produce the target temperature of 4°C, and risked forcing the refrigeration system to run almost continuously with high energy consumption. Advice to consumers has previously stressed the importance of measuring fridge air temperatures with relatively cheap thermometers²⁷, and this could be even more important in detecting satisfactory operation at lower temperatures. This could also be assisted by checking energy use with plug-in energy meters, but the development of a simple-to-use method of identifying excessive running (perhaps based on comparison with energy label data) would be required.

A more general issue related to use of lower storage temperatures is the way in which consumers interpret (and use or ignore) 'use by' or 'best before' dates to inform their judgments on disposal of food²⁸. Whilst consumers who are willing to adjust their fridges to lower storage temperatures are likely to benefit from extended storage lives (particularly for products carrying a 'best before' date or that they currently dispose of before the 'use by' date due to early spoilage), food producers are not able to rely on such adjustments having been made. For food manufacturers to extend 'use by' dates, a significant improvement in current average domestic fridge temperatures would need to be evidenced. No such study is currently planned. Furthermore, food manufacturers may still need to plan for the worst case scenario; which is as previous studies have shown (e.g. WRAP 2010) that some domestic fridges run well above 8°C.

Some care and advice is also needed in advising addition of more foods to fridges. If fridges are loaded to increasingly full levels, gaps between products (which would normally allow air circulation) may become blocked. In such circumstances, temperatures of added food will be slow to reduce to acceptable levels and any benefit to storage lives may be limited. Advising careful loading could help to avoid this, and could be supplemented by advice on ensuring that items which do not need refrigeration are not placed in the fridge. These typically include bread, some preserves, many unopened drinks and other items which are either best stored, or which store equally well, outside the fridge.

²⁷ <http://www.wrap.org.uk/content/performance-assessment-domestic-fridge-thermometers>

²⁸ <http://www.wrap.org.uk/content/consumer-insight-date-labels-and-storage-guidance>

WRAP will use the findings from this research to continue its work with the food industry and white goods manufacturers, to help consumers get more out of the food they buy and waste less. For example:

- Develop in-store communications materials (posters, leaflets, in-appliance stickers) to promote good fridge and freezer use e.g. minimising door opening, cooling foods before adding them.
- Adopt consistent content within the fridge / freezer manual e.g. how to operate the thermostat.
- Stock items at point of sale e.g. fridge thermometers.
- Improve fridge design e.g. to include relevant functionality such as built in thermometers / external temperature displays, harmonising settings on temperature control dials (and how they relate to actual temperatures in the fridge), the sensitivity and effectiveness of the temperature setting / thermostats, and options to better maintain fridge temperatures based on the relatively high (compared to freezers) number of door openings. Consideration should also be given to the continued use of single thermostats in combined fridge freezers (only 35% have dual thermostats currently).

Appendix 1: References

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