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Temperature and energy performance of domestic cold appliances in households in England

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Highlights

- Temperatures and energy consumed by 998 cold appliances in households are reported.
- Mean refrigerator temperature was 5.3°C; the mean freezer temperature was -20.3°C.
- Mean electricity consumption was 354 kWh per year.
- Differences between cold appliance types were determined from statistical analysis.

Abstract

This paper reports the results of a large-scale survey in which 998 cold appliances were monitored in 766 properties in England. No surveys published to date analyse such a large dataset, which includes data on ambient temperature, cold appliance temperature (refrigerator and/or freezer) and electricity consumption of the cold appliance.

Simultaneous measurements of the temperature inside and outside of the cold appliances and the electricity consumption were taken over a period of seven days during a nine-month period in 2015. An interview was also conducted with the householders to collect further information about the cold appliances and their usage patterns.

The cold appliances monitored in the work included fridge-freezers (52%), refrigerators with ice-box (6%), larder fridges (14%), chest freezers (9%) and upright freezers (19%). It was found that for all monitored cold appliances with valid data that: the mean ambient temperature was 18.5°C; the mean refrigerator temperature was 5.3°C; the mean freezer temperature was -20.3°C; and the mean electricity consumption was 354 kWh per year. Significant differences between the electricity consumption of different types of cold appliance were determined from statistical analysis.

Keywords: Survey, Domestic households, Refrigerator, Freezer, Temperature, Electricity consumption, England

Nomenclature

n/a	not available
se	standard error
σ	standard deviation
ANOVA	analysis of variance
HRP	household reference person
N	number of samples
RSL	registered social landlord

1. Introduction

Domestic refrigerators and freezers are generally operated using a vapour compression thermodynamic cycle and many researchers have focused their work on increasing the energy efficiency of these appliances. The main parameters affecting the electricity consumption of cold appliances can be divided into two main groups: (1) technical features, for example air flow distribution, type of thermodynamic cycle, type of refrigerant, type of insulation used to reduce the heat gains, etc.; (2) cold appliance operation, for example number of door openings, ambient temperature, thermostat set point, and quantity/temperature of products placed in the appliance, etc.

1.1 Technical features

Concerning the first group, studies by researchers such as Avci et al. (2016), Belman-Flores et al. (2014), Kumlutaş et al. (2012), Laguerre et al. (2010), Amara et al. (2008), Gupta et al. (2007) and Laguerre et al. (2007) have used CFD (Computational Fluid Dynamics) models to identify and optimise the main design parameters, thermal stratification and air flow issues so as to improve the energy efficiency of domestic cold appliances. Other researchers such as Yang et al. (2015) have developed new refrigeration cycles based on a 2-stage vapour compression cycle. Yoon et al. (2013) showed that the choice of insulation, in terms of type of material and thickness, enabled high energy savings to be achieved. For example, by using vacuum insulated panels instead of standard polyurethane foam insulation, 5-10% of the energy could be saved as reported by Hammond and Evans (2014).

Regarding different types of refrigerants, new European regulations of the European Parliament and Council (2014) restrict the use of high GWP (Global Warming Potential) refrigerants. Although the majority of refrigerated appliances in Europe operate using hydrocarbon refrigerants (e.g. R600a) there is still ongoing work to replace R134a as a refrigerant in locations where hydrocarbons are not generally accepted, with work being undertaken by Aprea et al. (2016), Joybari et al. (2013) and Mohanraj (2013) to investigate replacements for R134a. Most refrigerants used in domestic refrigerators are azeotropes (they boil at a constant temperature) but it has been suggested that zeotropic refrigerants that have a wide temperature glide (they boil over a wide temperature range) could have advantages in domestic refrigerators, particularly in providing different temperatures in specific compartments. Mohanraj et al. (2009) showed a reduction of around 12% in electricity consumption when using a zeotropic mixture composed of R290 and R600a instead of R134a.

Research is also increasing into developing new refrigeration systems able to exploit the use of an ejector in a refrigeration cycle for domestic appliances, so as to improve cycle performance. The ejector is a component that expands a high-pressure primary substance to absorb a secondary substance at a pressure slightly above the low pressure reached by the primary substance. In refrigeration cycles, the two substances are identical, so both flows mix together leading to mixture pressure increase due to the change of the flows momentum. For example, Liu et al. (2015), Wang and Yu (2015) and Wang et al. (2014) have proposed a modified ejector-expansion refrigeration cycle for domestic appliances; the results showed that the new system could reduce the electricity consumption compared to the conventional domestic refrigerator-freezer by 5-7%.

Other important technical features of a domestic appliance that may impact the electricity consumption, are the evaporator defrosting cycle and the design of the door gaskets. Automatic defrosting of domestic refrigerated appliances is normally fixed, for example after a certain number of on-cycles of the compressor. However, the need for defrosting can be predicted and initiated only when required, thus leading to the avoidance of excessive defrosting and electricity consumption associated with defrost cycles. For example, Modarres et al. (2016) showed that an adaptive defrost when compared to a fixed defrost cycle could reduce the electricity consumption by up to 12.5%. Door gaskets for refrigerators are generally based on magnetic strips encased in flexible plastics such as polyvinyl chloride (PVC). The magnetic strip is attracted to the metal outer case of the refrigerator and pulls the soft flexible plastic against it to form a seal. Inefficiencies include air gaps where the seal is not well formed, heat conduction through the plastic and metal, and over time damaged or stressed areas of the seals can fail. Also Gao et al. (2017) investigated the total effective heat leakage at the refrigerator gasket with the average effective heat leakage at the door gasket region estimated to be 0.2 W/m.K, which corresponded to 14% and 17% of the total energy used by the fresh food and freezer compartments respectively.

1.2 Cold appliance operation

Real operating conditions of appliances are difficult to test in the laboratory as the behaviour of householders is quite varied. Limited information is available on the number of times appliance doors are opened, the types and temperature of the food placed in the appliance and the ambient temperature around the appliance (which does not remain constant over time). According to Gilbert et al. (2007) the temperature of food stored in refrigerators should be in the range of 1-5°C. Over the past 30 years there have been a large number of surveys on temperatures in domestic refrigerators. In some cases, it is very clear how temperatures were measured, which sensors were used, the position of the sensors and for how long the measurements were carried out. In other cases, insufficient information is available to adequately compare information. James et al. (2008) reviewed available information from 20 papers on temperatures in domestic refrigerators. They concluded that many refrigerators were running at higher than recommended temperatures. Since 2008, there have been several papers published on temperatures in domestic refrigerators (James et al. (2017), Roccato et al. (2017), Hassan et al. (2015), Evans et al. (2014), Geppert (2011), Landfeld et al. (2011) and WRAP (2009)). These generally concur with the results from the James et al. (2008) review. An average temperature in UK refrigerators of 5.2°C was obtained in a survey reported by Geppert (2011). In the same survey the authors found higher mean refrigerator temperatures in France (6.7 °C) and Germany (6.2 °C) but lower mean refrigerator temperatures in Spain (4.1 °C). Roccato et al. (2017) presented data from previously published surveys but divided the data into northern and southern Europe. In southern Europe the mean refrigerator temperature was 7°C whereas in southern Europe the mean refrigerator temperature was 6.1°C. Temperature measurements in domestic refrigerators and freezers were reported in the work of Evans et al. (2014). The overall mean refrigerators temperature was 4.4°C while the minimum and the maximum mean were -0.6°C and 10.4°C. Overall the refrigerators spent 58% of the time above the reccomended temperature of 5°C. The overall mean temperature in the freezers was -20.1°C while the minimum and the maximum mean were -41.1°C and -11.1°C respectively, with 32% of the time spent over the recommended temperature of -18°C.

Higher temperatures in refrigerators may have an impact on food quality and safety. Surveys on the hygienic status of domestic fridges have found that 52% of refrigerators contained at least one pathogen (Kennedy et al. (2005)). A higher general incidence of pathogens and higher APCs (total aerobic plate counts) were found in the refrigerators of urban consumers than those of rural consumers, and consumers under 25 were more likely than older consumers to have one or more pathogens present in their refrigerators.

The internal compartment temperature of a domestic refrigerator not only affects the quality of the food stored in the appliance but also the electricity consumed by the appliance. Several regulations have been put into place over the last 25 years by the European Commission related to appliance electricity consumption (ecodesign and energy labelling Directives) but it is not known whether these translate energy savings in a laboratory environment into savings in the home.

There is very limited published information detailing comprehensive information on temperature control in appliances, and ambient temperature conditions combined with electricity consumption in real life conditions. In this paper, results from a recent survey in England are reported (Gemmell et al. (2017)). The survey involved 998 domestic refrigerators and freezer appliances and the following were monitored: (1) ambient temperature of the room where the appliance was installed; (2) internal appliance compartment temperature; (3) power consumption. Householders were also questioned about the management of their appliance with respect to door openings, quantity of food loaded in the appliance and shopping habits. Appliance models were also recorded in order to evaluate storage volume and surface area of the appliances. Using this detailed information, analysis was completed to assess the relationship between temperature control and electricity consumption, by investigating the impact of appliance features and occupant behaviour.

2. Materials and methods

2.1 Overview of field trial design

A large-scale survey was conducted across England in which 998 cold appliances were monitored in 766 properties. Data was collected over a period of 9 months, from March to November 2015. There were four waves of data collection, each lasting between three and five weeks: (1) Wave 1 - March; (2) Wave 2 - from April to June; (3) Wave 3 - from July to August and (4) Wave 4 - from October to November.

Simultaneous measurements of the temperature inside and outside of the cold appliances, as well as the electricity consumption were taken over a period of seven days. The cold appliances monitored in the work included: (1) Fridge-freezers; (2) Refrigerators with an ice-box; (3) Larder fridges; (4) Chest freezers and (5) Upright freezers. A diagram showing the types of cold appliance assessed is shown in Fig. 1. Table 1 presents the numbers of each type of cold appliance with valid monitoring data. In addition to data collection, an interview was conducted with the householders to collect information to understand how cold appliances were used and maintained.

2.2 Data collection method

The sampling frame used was formed from cases originally surveyed as part of the English Housing Survey (EHS). This replicates a well-established and successful procedure used for previous similar surveys, such as the Energy Follow-Up Survey conducted in 2011 (Hulme et al. (2014)).

Interview and monitoring data was collected by interviewers. On the first visit to each property the interviewers installed the monitoring equipment and conducted the householder interview. One week later they returned to remove the equipment and data was downloaded ready for analysis. The appliances were monitored for seven days to ensure the data reflected the performance of the cold appliances as accurately as possible.

2.2.1 Data monitoring equipment used: Temperature

The temperatures both inside and outside the appliance were monitored using TinyTag Transit 2 data loggers with a monitoring range of -40°C to 70°C, a reading resolution of 0.01°C and a reading accuracy of <0.8°C between -40-0°C, and <0.4°C between 0-50°C. One data logger was placed on the middle shelf of each appliance compartment in a plastic bag and one was attached to the outside of the door of the appliance. A photograph of one of these loggers is shown in Fig. 2a.

2.2.2 Data monitoring equipment used: Electricity consumption

The electricity consumption data of each cold appliance was collected using a Watts Up PRO monitor and data logger with an accuracy of +/- 1.5%. Each appliance was connected to the data logger, which itself was plugged into the wall socket. The electric power in Watts was monitored every 30 seconds for the period the appliance was plugged in. A photograph of a Watts Up logger is shown in Fig. 2b.

2.2.3 Data monitoring: Cleaning phase

The data collected from the TinyTag and Watts Up logger for every appliance monitored were examined in detail and, where necessary, the data was cleaned to ensure that only valid and reliable data were included in the analysis. Any data which did not accurately reflect the performance of the appliance was removed prior to analysis. In addition, the data cleaning was always applied to give the longest possible period of continuous data within the profile. Only appliances for which there was at least 24 hours of continuous valid and reliable data were included in the analysis.

Cleaning of the temperature profiles was necessary where: (1) the appliances had been turned off and/or (2) the loggers had been removed from the appliances.

Cleaning of the consumption data recorded by the Watts Up monitors was required in some cases due to: (1) monitors being unplugged and plugged back in and/or (2) appliances being switched off and on by the occupant and (3) occasional faulty periods of monitoring. Faults in monitoring were evident in the data as periods where the consumption profiles recorded extreme values or zeros for portions of the data.

2.2.4 Householder interview

The householder interviews were conducted face-to-face and the occupant responses were collected on a tablet PC using a Computer Aided Personal Interviewing (CAPI) system. The interview collected data on: (1) number of occupants; (2) number, type, location and age of the cold appliances in the property; (3) how often the appliances were opened per day; (4) how full the appliances were kept; (5) how often occupants introduced warm food into the appliances; (6) how often the occupants maintained their appliance (if at all); (7) make and model of the appliances where possible; (8) energy label and size of the appliances where available. If the householders were not able to remember the exact age of the appliance an estimate was made to the nearest 5 years.

2.2.5 Participants

Data was collected at 766 households across England. Table 2 shows the sample breakdown by tenure, number of occupants, age of household reference person (HRP), and household type. It can be observed that the majority of households (56%) were owner occupied and 79% of them had 3 or less occupants with an average number of occupants per household of 2.43. The age of the householders was relatively well distributed across the age groups with an age range between 16 to over 65. The majority of participants were couples with no dependent children (34%), or couples with dependent children (20%).

2.2.6 Statistical analysis

Statistical analysis was conducted on temperature and electricity consumption data using IBM SPSS Statistics program (version 21). Data was tested for normality using a Kolmogorov-Smirnov test, and if normal parametric statistical analysis was performed by using Analysis of Variance (ANOVA). Where data was not normally distributed, non-parametric statistical analysis was used in the form of a Kruskal-Wallis test. Post-hoc tests were conducted using a Tukey test for parametric analysis, and a Mann-Whitney tests for non-parametric analysis. Significance was reported at the 95% confidence level (when $p<0.05$).

3. Results and discussion

3.1 Characteristics and use of monitored cold appliances

Monitoring data was collected from a total of 998 cold appliances, with valid temperature data for 938 cold appliances and valid consumption data for 665 cold appliances. Table 3 shows the breakdown of the monitored appliances monitored by: type; age; number of door openings; fill level; whether warm food was added to appliances; and the cleaning and maintenance of cold appliances.

3.1.1 Sample of monitored cold appliances

The majority of cold appliances monitored were fridge-freezers (52%), followed by upright freezers (19%) and larder fridges (14%). The vast majority of the cold appliances (75%) were located in the kitchen/kitchen-diner. Only 7% of appliances were located in the utility room and 6% in garages. In total, 89% of the appliances monitored were free standing and 11% were built-in. The majority of appliances were bought new (78%) while the remaining 22% includes appliances that were bought second-hand or received as a present or came with the property. Around 7% of the monitored cold appliances with a known age were less than 1-year-old while the majority had an age between 1 and 5 years (45%). Of the appliances that were greater than 5 years old, 27% were between 6 and 10 years and 19% were greater than 10 years old. The average age of the appliances in the survey was 7 years. This was lower than indicated by Cravioto et al. (2017) who found the average age of refrigerators in 5 developed countries to be 12.7 years. However, the age of appliances in the survey was quite similar to that presented by the NSW Food Authority (2009) who stated that 32% of appliances in a survey were 5 years or less, 34% were between 5 and 10 years old and 34% were older than 10 years. This compared to equivalent figures of 45% less than 5 years old, 27% between 5 and 10 years and 28% greater than 10 years old for the survey results.

3.1.2 Use of cold appliances

Householders were also asked how often they opened their appliance, how full the appliance was kept and how frequently the temperature was adjusted. These three questions were asked for each of the monitored appliances in a household, as well as the individual compartments (fridge and freezer) in the case of a fridge-freezer. Householders reported that most appliances (40%) were opened 1-4 times a day while 11% of appliances were opened less than once a day. The majority of appliances that were opened less than once per day were freezers or the freezer section of fridge-freezers. The remainder of appliances were opened more than 5 times a day; these were generally fridges or the fridge section of fridge-freezers.

With regards to how full appliances were kept, 40% of appliances were kept completely full, 35% were kept three quarters or half full, 19% were kept half full while only 6% were kept a quarter or less full (Table 3). Usually, freezers were more commonly reported to be completely full and fridges, three quarters full. Concerning how often householders modify their appliances setting, the temperature setting was never adjusted for 68% of appliances, while it was adjusted occasionally in 24% of appliances and in 6% of appliances it was adjusted every six months. Only 1% of householders reported adjusting the temperature setting of their appliances weekly or monthly.

Householders were asked how frequently they put warm food in their cold appliances. The majority of householders (91%) said they 'never' added hot food, 8% said they did occasionally and just 1% said they did often or always.

3.1.3 Cleaning and maintenance of cold appliances

Fig. 3 shows the frequency with which households cleaned and maintained their cold appliances. Over half the households (56%) said they regularly or occasionally defrosted their appliances, however, almost a third (32%) said they never carried out defrosting (most likely due to the appliance being frost-free). A large proportion (42%) of households said they regularly cleaned the door seals on their appliances, compared with 14% who regularly unblocked the drains and 7% who removed dust from the back of the appliance (where the condenser was located in the majority of cases). Almost half the households (45%) said they never unblocked the drains and about 60% of households said they never removed dust from the back of the appliance.

3.2 Ambient temperature

Based on 900 samples with valid ambient temperature data, the mean ambient temperature of the room in which the appliances were located was 18.5°C, the maximum mean temperature was 29.6°C and the minimum mean temperature was 5.6°C.

The ambient temperature was found to vary significantly according to the wave of the survey. The lowest mean temperatures were observed in wave 1 (16.1°C), higher mean temperatures were observed in wave 2 (18.5°C) and wave 4 (18.5°C) with the highest mean temperatures being observed in wave 3 (20.4°C). These differences were due to the waves being carried out at different times of the year (Table 4). Mean ambient temperature in wave 1 (early spring time) was significantly lower than in waves 2 (late spring to summer time), 3 (summer time) and 4 (autumn/winter time). The mean temperatures in wave 3 were significantly higher than in all the other waves. There was no significant difference between mean temperatures in waves 2 and 4.

The frequency distributions of the time spent at 2°C mean ambient temperature intervals are shown in Fig. 4. Overall the mean ambient temperatures in the survey were between 18 and 22°C for 35% of the monitoring time in wave 1, 52% in wave 2 and 4 and 65% in wave 3. A low mean ambient temperature (<16°C) was registered for 38% of the time in wave 1, 18% in wave 2 and 4 and only 4% in wave 3. It should be noted that, during spring and summer seasons, the low ambient temperatures were primarily related to chest freezers and upright freezers which were often installed in the garage or in the cellar where there was no heating.

3.3 Cold appliance temperature data

3.3.1 Refrigerator temperature

The overall mean internal temperature of all refrigerators (671 appliances) measured in the survey was 5.3°C. The maximum overall mean temperature in a single refrigerator was 14.3°C and the overall minimum mean temperature was -4.1°C.

Based on the 671 appliances, the mean internal refrigerator temperature was not found to vary according to the study wave. However, the appliance type was found to have a significant effect on the refrigerator temperature. The refrigerator sections in fridge-freezers were found to be significantly lower in mean temperature than refrigerators with an ice-box and larder fridges. Statistically significant differences are shown in Table 5.

The mean temperature of each refrigerator type was ranked in order of increasing temperature as presented in Fig. 5. This shows clearly that there was a trend for temperatures in larder fridges and refrigerators with an ice box to be higher than the temperature in fridge-freezers. The frequency distribution at 1°C intervals based on absolute values for temperature over the survey period is shown in Fig. 6.

Overall the fridge-freezers in the survey operated between 0 and 5°C (recommended zone) for 45% of the time, while 51% of the time was spent at temperatures above 5°C. In the case of refrigerators with an ice-box and larder fridges 32% of the time was spent between 0 and 5°C and 64% of the time was spent above 5°C. It can be noted in Fig. 6 that within the range of temperatures 0-6°C, the temperature frequency distribution of fridge-freezers was always higher than that of refrigerators with an ice-box and larder fridges. When the temperature was above 6°C the fridge-freezer temperature frequency distribution was always lower than that one of the other refrigerators. Overall, 108 fridge-freezers, 18 refrigerators with an ice-box and 48 larder fridges operated for 100% of the time at a temperature higher than 5°C. Only 30 fridge-freezers, 3 refrigerators with an ice-box and 4 larder fridges operated for 100% of the survey period within the recommended temperature of 5°C.

3.3.2 Freezer temperature

The overall mean temperature of freezers in the survey (745 appliances) was -20.3°C. The maximum mean temperature was -5.6°C and the minimum mean temperature was -37.0°C.

The mean temperature of freezers was found to be significantly different according to the wave of the survey, with the lowest mean temperature being observed in wave 3, the highest mean temperature in wave 1 and intermediate mean temperatures observed in wave 2 and 4. Statistically significant differences are shown in Table 6. The mean freezer temperature in the different waves shown by rank order is presented in Fig. 7.

As the survey waves were carried out at different times of the year it was possible that the differences in freezer temperature could be related to ambient temperature. Fig. 8 shows a graph of mean freezer temperature plotted against mean ambient temperature. No clear relation between freezer and ambient temperature was demonstrated apart from in the case of chest freezers where the correlation coefficient (Pearson's coefficient) was found to be -0.265, thus showing a slight reverse correlation. This was because there was a larger range in ambient temperature for these appliances. For most appliances the range in ambient temperature was probably not large enough to show any influence on performance.

Freezer temperature was found to also depend on the appliance type. The main difference in freezer temperature between appliances was observed between refrigerators with an ice-box and all other types of appliance (Table 7). The overall mean freezer temperature of refrigerators with an ice-box was higher than the recommended temperature of -18°C, whereas all other freezer appliances operated at a mean temperature below -18°C. This was most likely due to the ice-box appliances being rated as 2 star appliances whereas other appliances were most likely rated as 3 or 4 star appliances. The number of stars indicates the operating temperature of the appliance; 3 or 4 stars is normally referred to as operation below -18°C while 2 stars is operation below -12°C.

The mean freezer temperature within the different types of appliance shown by rank order is presented in Fig. 9. The frequency distribution based on absolute values of time and temperature for fridge-freezers, refrigerators with an ice-box, chest freezers and upright freezers in the survey is shown in Fig. 10. In the case of fridge-freezers, chest freezers and upright freezers, 73% of the survey time was spent at a freezer temperature lower than -18°C (recommended zone) whilst in ice-box freezers 54% of the time was spent at a temperature higher than -18°C. It can be noted in Fig. 10 that the frequency for refrigerators with an ice-box at higher temperatures was greater than those for fridge-freezers, chest freezers and upright freezers. In total, 99 fridge-freezers, 28 chest freezers and 67 upright freezers always operated at a freezer temperature lower than the recommended zone, however no ice-box freezers were found to be in this category. In total, 39 fridge-freezers, 12 refrigerators with an ice-box, 15 chest freezers and 23 upright freezers always operated at a temperature higher than -18°C.

3.4 Electricity consumption

Electricity consumption data was collected from 665 cold appliances. Overall mean annual consumption was 354 kWh per year, based on the entire monitored period.

The average consumption was found to vary significantly according to the period when the survey was carried out. Table 8 illustrates that the lowest mean electricity consumption was monitored in wave 1 (310 kWh per year), intermediate electricity consumptions were observed in wave 2 (343 kWh per year) and 4 (349 kWh per year) whilst the highest consumption was registered in wave 3 (403 kWh per year). Mean electricity consumption divided into waves and plotted in rank order is shown in Fig. 11.

Warmer temperatures in the summer period may explain the higher energy consumption in wave 3; moreover, higher levels of electricity consumption match with colder freezer temperatures in wave 3 (Table 7). Fig. 12 shows a graph of mean electricity consumption plotted against mean ambient temperature. No marked relation between electricity consumption and ambient temperature was demonstrated. Only in the case of chest freezers and larder fridges the correlation coefficient (Pearson's coefficient) accounted for 0.287 and 0.497 of the variability respectively. The differences found did not appear to be related to the appliance types and appeared to be primarily due to the random nature of the appliance selection process where high or low energy using appliances were included by chance in certain waves.

Electricity consumption was also found to vary based on the appliance type (Table 9 and Fig. 13). Larder fridges had the lowest consumption (201 kWh per year) with chest freezers (420 kWh per year) and fridge-freezers (390 kWh per year) having the highest electricity consumption. The electricity consumption of larder fridges was significantly lower than other cold appliances. This is related to the thermodynamic cycle of larder fridges, which is more efficient since the appliance is designed to operate at a temperature above 0°C (whereas all other appliances need to operate at least one compartment as a freezer).

The frequency distribution for electrical power, based on absolute values, split by cold appliance type is shown in Fig. 14. The compressor cycled on and off during the operation of most appliances, however in a small number of appliances, the compressor operated constantly throughout the survey period. This state was observed in 3 fridge-freezers, 5 larder fridges, 12 chest freezers and 7 upright freezers. No refrigerators with an ice box operated continually in the survey. The appliances that operated for 100% of the time consumed on average, 81% more energy than the mean energy consumption of all cold appliances in the survey.

3.4.1 Specific energy consumption (SEC) of appliances

The internal volume of the appliances studied in the survey varied and this may contribute to the variation in electricity consumption. The electricity data was therefore analysed according to the electricity used per unit of net volume and per unit of external surface area. Accurate data on volume and surface area was not available for all appliances. Refrigerators with an ice-box were not considered in the statistical analysis since the SEC data that was available was not considered sufficient to conduct the analysis.

Results from the statistical analysis are shown in Tables 10 (for volume) and 11 (for surface area). Chest freezers were found to have the highest mean SEC value, both in the case of volume and of external area. Upright freezers also had a high mean SEC volume value while the mean SEC volume for fridge-freezers and larder fridges was significantly lower than those for chest freezers and upright freezers (Table 10). Considering the results reported in Table 11, fridge-freezers and upright freezers had similar SEC values in terms of electricity use per unit of external area. The lowest SEC per surface area was obtained in the case of larder fridges.

Fig. 15 shows the increase in specific energy consumption [kWh/m^3.year] for appliances as age of the appliance increased. There is a clear difference observed in the SEC between all appliances over 11 years (mean = 3660 +/- 399 kWh/m^3.year, and any younger than 11 years (mean of all = 1597 +/- 81 kWh/m^3.year).

4. Conclusions

This paper presents the results of a large-scale survey of domestic cold appliances in households in England. Simultaneous measurements of the temperature inside and outside of the cold appliances, as well as the electricity consumption, were obtained over a period of seven days for 998 cold appliances. Data was collected from March to November 2015. Moreover, an interview was conducted with the householders to collect information about how the cold appliances were used and maintained.

Results from statistical analysis have shown that temperatures and electricity consumption in cold appliances significantly varied according to the time of year and appliance type. The mean temperature in domestic refrigerators was found to be 5.3°C, slightly higher than the recommended range of 0 to 5°C. In particular, 174 refrigerators operated for 100% of the time at a temperature higher than 5°C, in contrast only 37 refrigerators were found to operate for 100% of the survey period within the recommended range of 0 to 5°C. The mean temperature in domestic freezers was found to be -20.3°C, lower than the recommended temperature of -18°C. In total, 194 freezers always operated at a freezer temperature lower than the recommended value (-18°C), while a temperature higher than -18°C was monitored in 89 freezers. Overall, the mean electricity consumption was 354 kWh per year. The compressor operated continually in 27 cold appliances and, on average, these appliances used 81% more energy than the mean energy consumption of all cold appliances in the survey. Such information could potentially be used to target the replacement of high consuming appliances.

The most common cold appliances that were monitored were fridge-freezers which were found to operate within recommended temperature levels more commonly than other appliance types. Mean temperatures in fridge-freezers were between 0°C and 5°C in 48% of cases whereas in other types of refrigerator this figure was 35%. In fridge-freezers, the freezer compartment temperature was on average above -18°C in 24% of cases whereas in other appliances this figure was 30%.

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Fig. 1. Different types of cold appliance monitored in the survey.

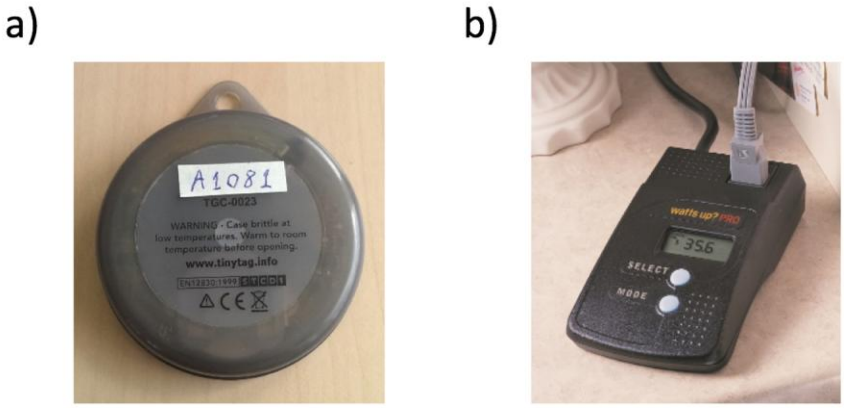


Fig. 2. TinyTag Transit 2 temperature data logger (a) and Watts Up PRO electricity consumption meter (b).

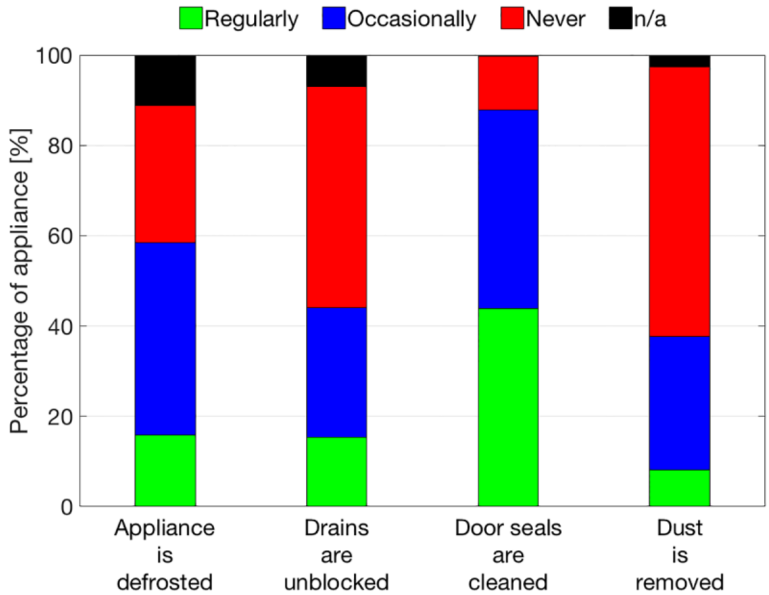


Fig. 3. Frequency of cleaning and maintenance of the cold appliances.

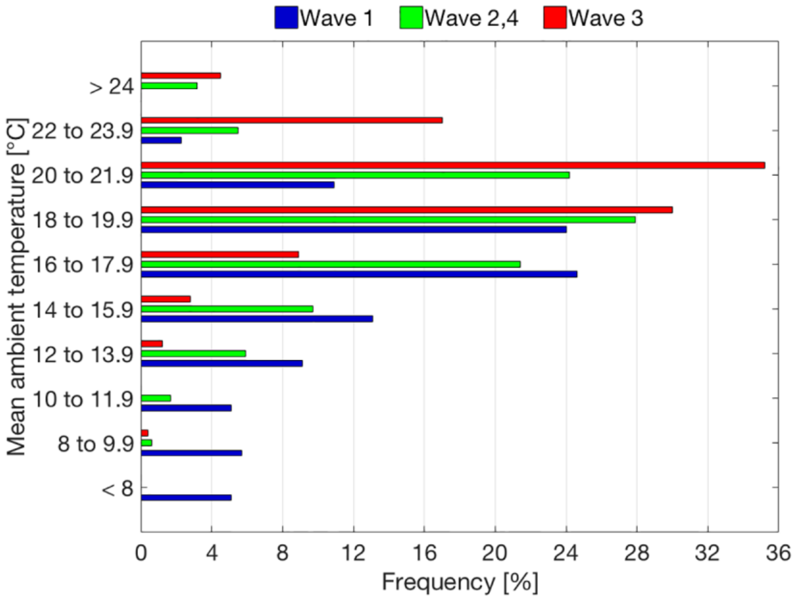


Fig. 4. Frequency distribution for time and mean ambient temperature [°C] during the survey.

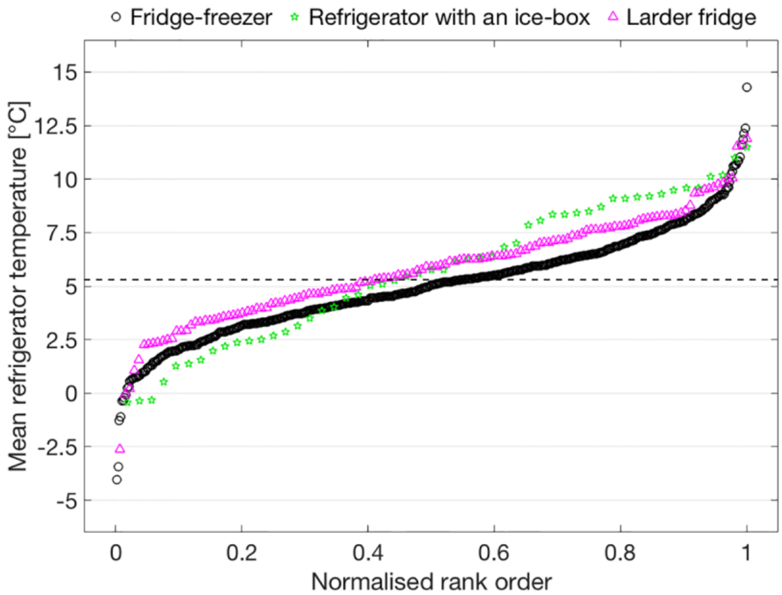


Fig. 5. Mean refrigerator temperature [°C] of each appliance. Overall mean refrigerators temperature [°C] in the survey is reported with a dashed line.

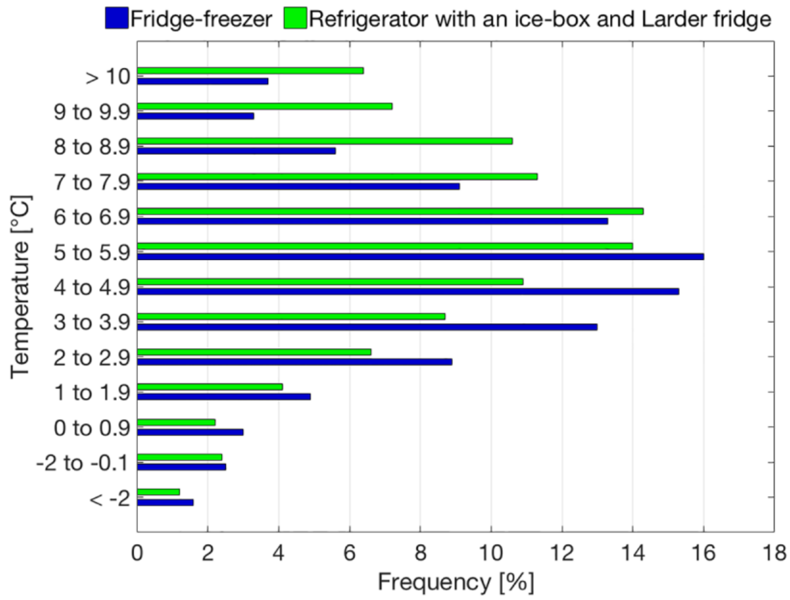


Fig. 6. Frequency distribution of time and temperature [°C] for refrigerators in the survey.

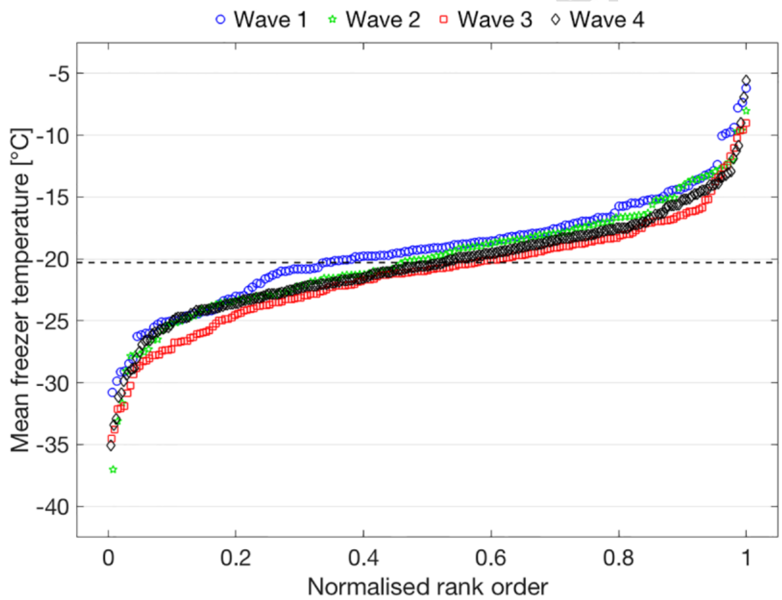


Fig. 7. Mean freezer temperature [°C] divided into waves. Overall mean freezers temperature [°C] in the survey is reported with a dashed line.

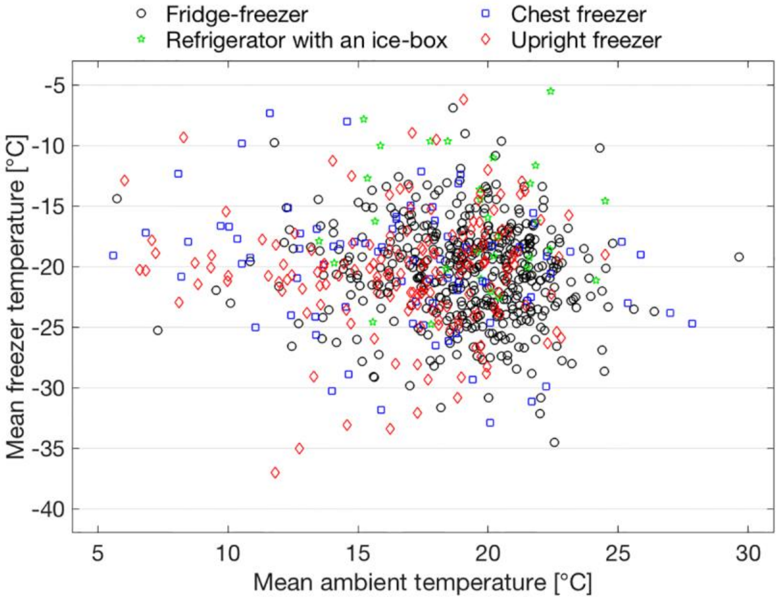


Fig. 8. Mean freezer temperature [°C] against mean ambient temperature [°C].

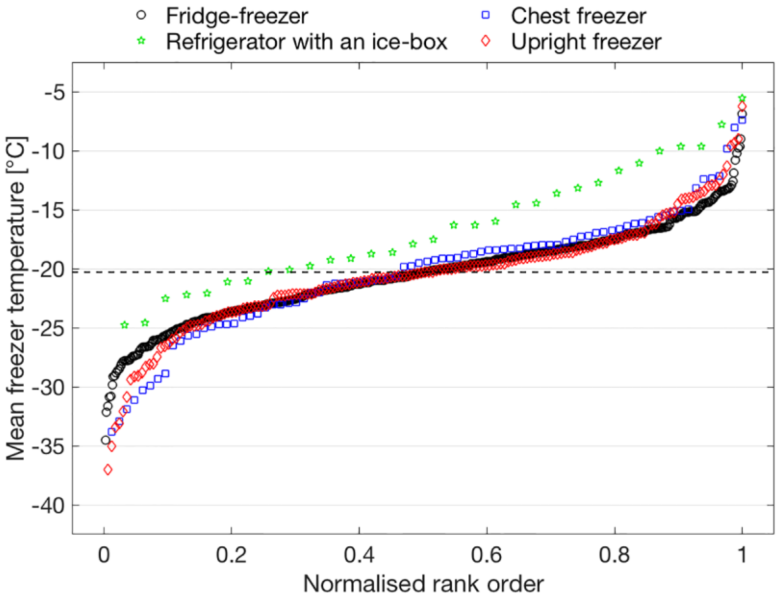


Fig. 9. Mean freezer temperature [°C] of each appliance. Overall mean freezers temperature [°C] in the survey is reported with a dashed line.

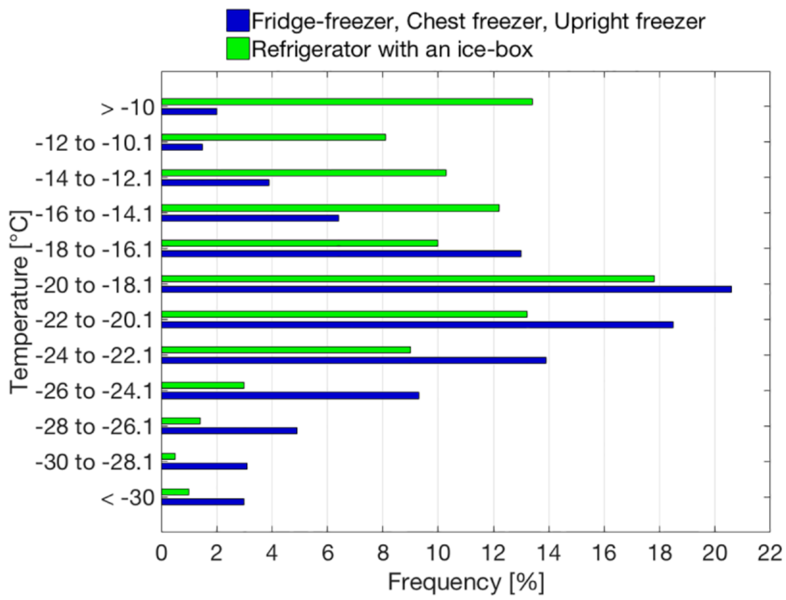


Fig. 10. Frequency distribution of time and temperature [°C] for freezers in the survey

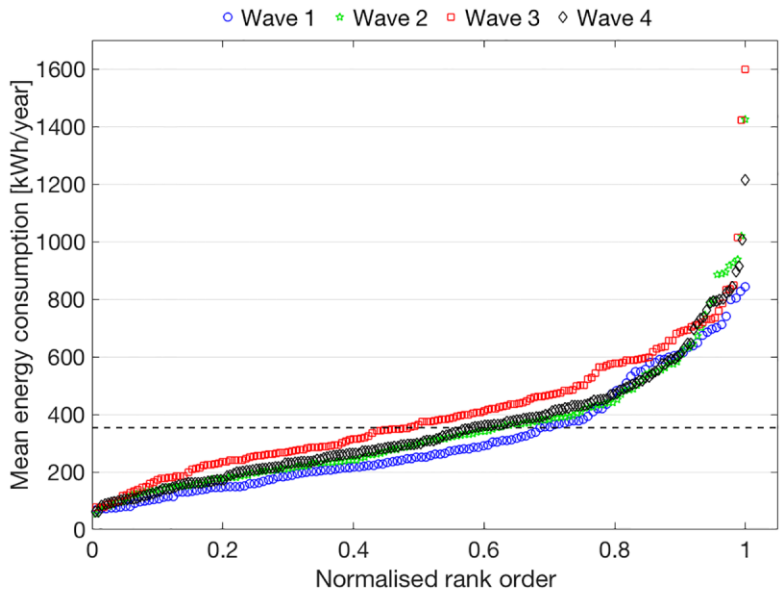


Fig. 11. Electricity consumption [kWh per year] of each cold appliance divided into waves. Overall mean energy consumption [kWh per year] in the survey is reported with a dashed line.

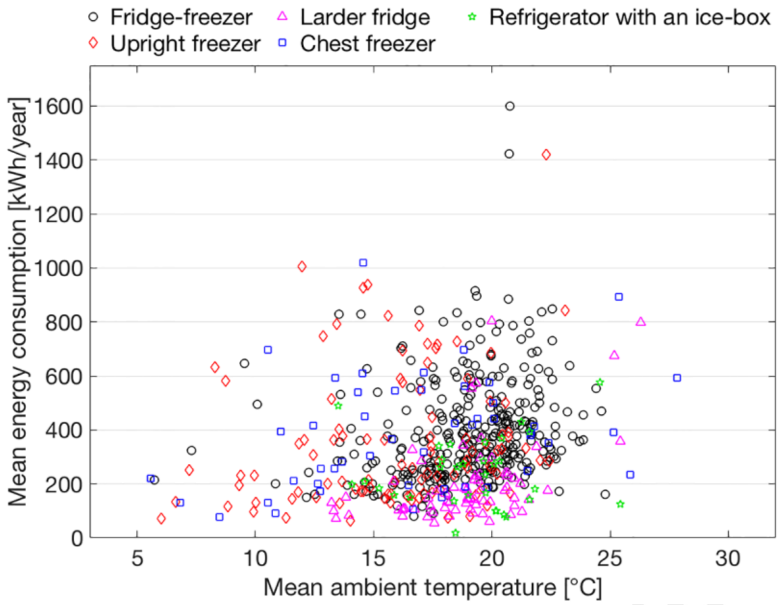


Fig. 12. Electricity consumption [kWh per year] against mean ambient temperature [°C].

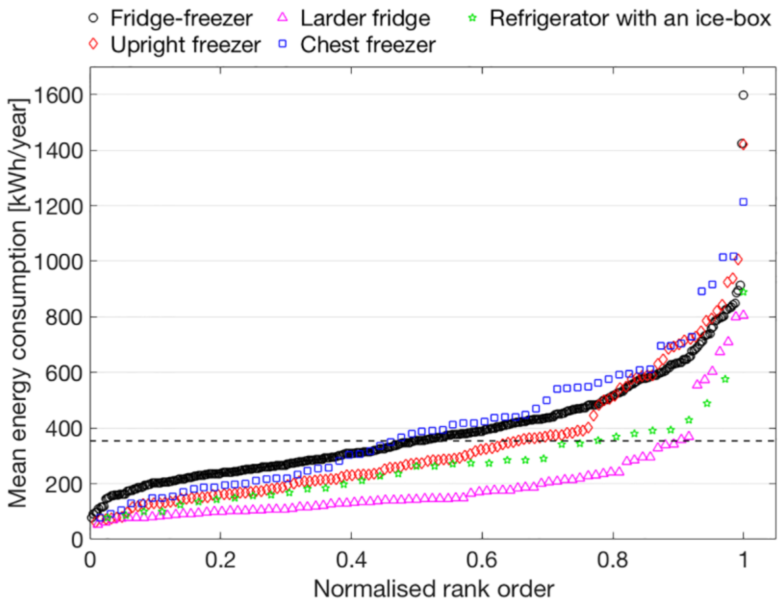


Fig. 13. Electricity consumption [kWh per year] of each cold appliance. Overall mean energy consumption [kWh per year] in the survey is reported with dashed line.

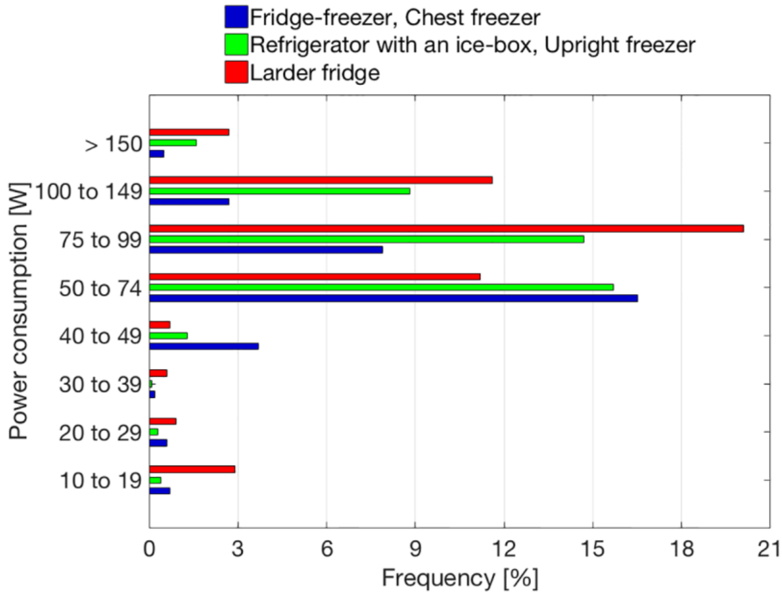


Fig. 14. Frequency distribution of time and power consumption [W] for cold appliances in the survey.

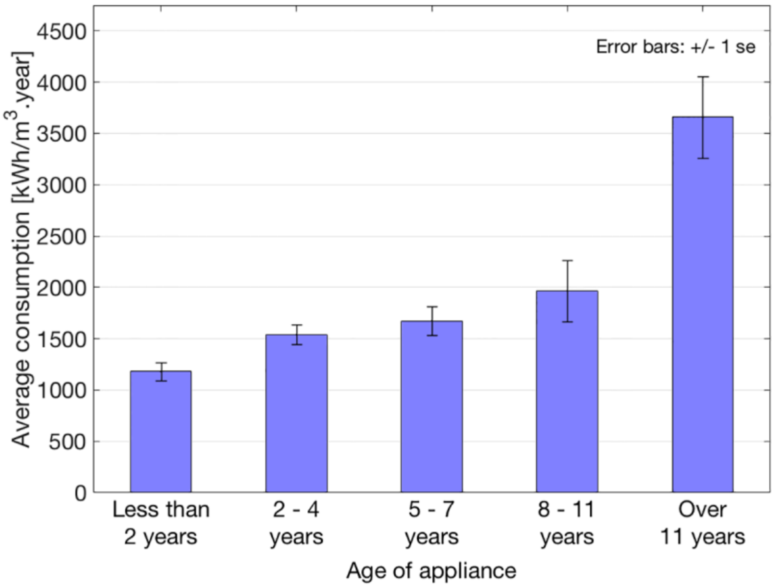


Fig. 15. Average specific energy consumption [kWh/m^3.year] by appliance age.

Table 1. Numbers of cold appliances in each wave of the survey (percentage values in brackets).

Appliance type	Wave 1			Wave 2			Wave 3			Wave 4		
	Rf sec [(a)]	Fz sec [(b)]	El [(c)]	Rf sec	Fz sec	El	Rf sec	Fz sec	El	Rf sec	Fz sec	El
Fridge-freezer	97 (77)	93 (60)	76 (56)	82 (67)	78 (55)	82 (51)	148 (74)	140 (69)	100 (60)	156 (70)	152 (62)	109 (55)
Refrigerator with an ice-box	11 (9)	5 (3)	6 (4)	12 (10)	8 (6)	13 (8)	18 (9)	11 (5)	11 (7)	11 (5)	7 (3)	6 (3)
Larder fridge	18 (14)	n/a	13 (9)	28 (23)	n/a	21 (13)	35 (17)	n/a	18 (11)	55 (25)	n/a	31 (15)
Chest freezer	n/a	18 (12)	12 (9)	n/a	19 (13)	15 (9)	n/a	18 (9)	12 (7)	n/a	27 (11)	18 (9)
Upright freezer	n/a	39 (25)	30 (22)	n/a	36 (26)	30 (19)	n/a	34 (17)	26 (15)	n/a	60 (24)	36 (18)
Total	126	155	137	122	141	161	201	203	167	222	246	200

[(a)] Refrigerator section temperature data

[(b)] Freezer section temperature data

[(c)] Electricity consumption data

Table 2. Data about participants (percentage values in brackets).

Tenure	N
Owner occupied	370 (56)
Private rented	53 (8)
Local authority	107 (16)
RSL	130 (20)
Total	660 [(a)]
Number of occupants	**N**
1	216 (28)
2	266 (35)
3	122 (16)
4	101 (13)
5+	61 (8)
Total	766
Age of HRP	**N**
16-34	93 (14)
35-44	106 (16)
45-54	122 (19)
55-64	141 (21)
65 or over	198 (30)
Total	660 [(a)]
Household type	**N**
Couple, no dependent child(ren)	228 (34)
Couple with dependent child(ren)	130 (20)
Lone parent with dependent child(ren)	57 (9)
Other multi-person households	60 (9)
One person under 60	70 (11)
One person aged 60 or over	115 (17)
Total	660 [(a)]

[(a)] Only 660 households agreed to allow the information collected to be published

Table 3. Characteristics and use of monitored cold appliances (percentage values in brackets).

Cold appliance type	N
Fridge-freezer	524 (52)
Refrigerator with an ice-box	57 (6)
Larder fridge	145 (14)
Chest freezer	86 (9)
Upright freezer	186 (19)
Total	998
Location of appliance	**N**
Kitchen/kitchen-diner	746 (75)
Utility room	69 (7)

Garage	57 (6)
Other	126 (12)
Total	998
Cold appliance age	**N**
< 1 yr	74 (7)
1 - 5 yrs	379 (38)
6 - 10 yrs	271 (27)
11 - 15 yrs	116 (12)
16 - 20 yrs	46 (5)
21 - 25 yrs	12 (1)
>25 yrs	11 (1)
n/a	89 (9)
Total	998
Number of door openings per day	**N**
< 1	163 (11)
1 - 4	619 (40)
5 - 9	275 (18)
10 - 14	255 (17)
15 - 20	88 (6)
20+	122 (8)
Total	1522 [a]
Fill level	**N**
0 - 25 %	86 (6)
26 - 50 %	290 (19)
51 - 75 %	539 (35)
76 - 100 %	607 (40)
Total	1522 [a]
Warm food added	**N**
Never	694 (91)
Occasionally	60 (8)
Often	10 (1)
Always	2 (<0.5)
Total	766

[a] This takes into account also the combined results from refrigerator, freezer and fridge-freezer openings

Table 4 – Statistical analysis results: mean ambient temperature [°C] and waves.

	N	Mean temperature [°C]	σ	se
Wave 1	175	16.1 [a]	4.0	0.3
Wave 2	181	18.5 [b]	2.9	0.2
Wave 3	248	20.4 [c]	2.4	0.2
Wave 4	296	18.5 [b]	3.1	0.2
Total	900	18.5	3.4	0.1

Table 5. Statistical analysis results: refrigerator temperature [°C] and appliance type.

	N	Mean temperature [°C]	σ	se
Fridge-freezer	483	5.0 [a]	2.4	0.1
Refrigerator with an ice-box	52	5.7 [b]	3.3	0.5
Larder fridge	136	5.8 [b]	2.5	0.2
Total	671	5.3	2.5	0.1

Table 6. Statistical analysis results: freezer temperature [°C] and waves.

	N	Mean temperature [°C]	σ	se
Wave 1	155	-19.3 [a]	4.4	0.4
Wave 2	141	-20.1 [a,c]	4.6	0.4
Wave 3	203	-21.1 [b]	4.4	0.3
Wave 4	246	-20.5 [b,c]	4.2	0.3
Total	745	-20.3	4.4	0.2

Table 7. Statistical analysis results: freezer temperature [°C] and appliance type.

	N	Mean temperature [°C]	σ	se
Fridge-freezer	463	-20.5 [a]	3.9	0.2
Refrigerator with an ice-box	31	-16.5 [b]	5.1	0.9
Chest freezer	82	-20.3 [a]	5.3	0.6
Upright freezer	169	-20.6 [a]	4.8	0.4
Total	745	-20.3	4.4	0.2

Table 8 – Statistical analysis results: Energy consumption [kWh per year] and waves.

	N	Energy consumption	σ	se
Wave 1	137	310 [a]	193	16.5
Wave 2	161	343 [a,b]	215	16.9
Wave 3	167	403 [c]	223	17.3
Wave 4	200	349 [b]	201	14.2
Total	665	354	211	8.2

Table 9. Statistical analysis results: Energy consumption [kWh per year] and cold appliance type.

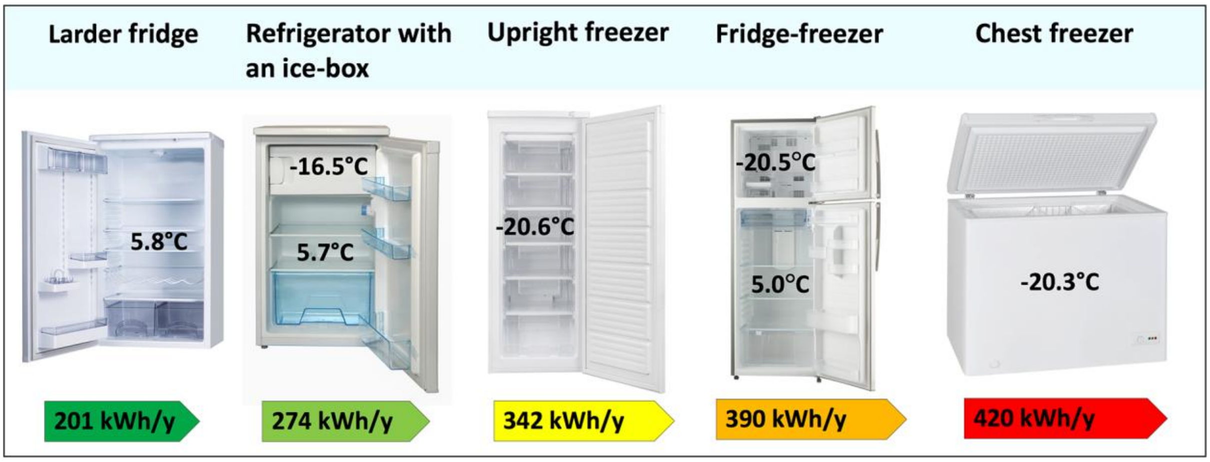
	N	Energy consumption	*σ*	*se*
Fridge-freezer	367	390 [a]	190	9.9
Refrigerator with an ice-box	36	274 [b]	159	26.5
Larder fridge	83	201 [c]	163	17.9
Chest freezer	57	420 [a]	249	33.0
Upright freezer	122	342 [b]	236	21.4
Total	665	354	211	8.2

Table 10. Statistical analysis results: Specific energy consumption [kWh/m^3.year] and appliance type.

	N	SEC (volume)	*σ*	*se*
Fridge-freezer	126	1575 [a]	965	86.0
Refrigerator with an ice-box	5	1585 [-]	722	322.9
Larder fridge	29	1257 [b]	971	180.3
Chest freezer	21	2997 [c]	2126	463.9
Upright freezer	40	2648 [c]	1772	280.2
Total	221	1863	1400	94.2

Table 11. Statistical analysis results: Specific energy consumption [kWh/m^2.year] and appliance type.

	N	SEC (area)	*σ*	*se*
Fridge-freezer	111	82 [a]	43	4.1
Refrigerator with an ice-box	5	63 [-]	8	3.6
Larder fridge	24	64 [b]	49	10.0
Chest freezer	12	109 [c]	57	16.5
Upright freezer	27	72 [a]	24	4.6
Total	179	79	43	3.2



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