ENOUGH

EUROPEAN FOOD CHAIN SUPPLY TO REDUCE GHG EMISSIONS BY 2050

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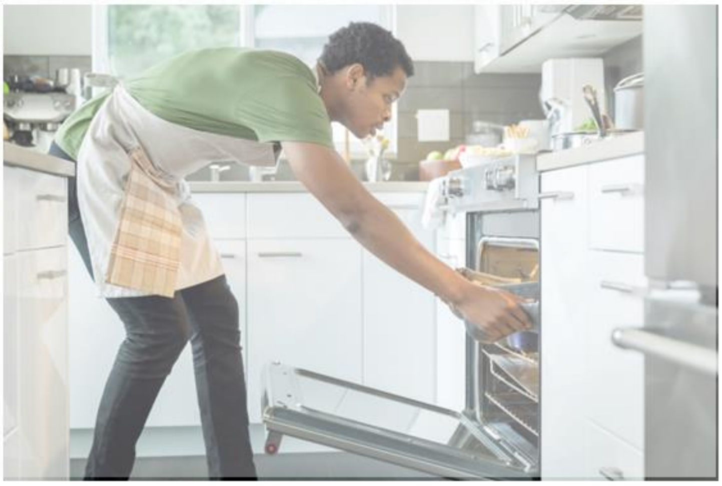

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588

1. NOMENCLATURE

AD	Anaerobic digestion
AI	Air impingement
ASHP	Air source heat pump
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAT	Best available technology
CFD	Computational fluid dynamics
CHTC	Convective heat transfer coefficient
CI	Carbon intensity (kgCO_2e/kWh)
CO_2	Carbon dioxide
COP	Coefficient of performance
DC	Direct current
DCKV	Demand control kitchen ventilation
DME	Di methyl ether
EC	European Commission
EEI	Energy efficiency index
EEV	Electronic expansion valve
ETS	Emissions Trading System
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FC	Frequency converter
FEA	Finite element analysis
GHG	Greenhouse gas
GWP	Global warming potential
HC	Hydrocarbon
HVAC	Heating ventilation and air conditioning
IR	Infra-red
kWh	Kilo Watt hour
LED	Light emitting diode
LULUCF	Land use, land-use change, and forestry
PCM	Phase change material
NG	Natural gas
NIST	National Institute of Standards and Technology
POE	Polyolester
PU	Polyurethane
PV	Photo voltaic
PVC	Polyvinyl chloride
RCP	Representative concentration pathway
RES	Renewable energy source

RH	Relative humidity
SEC	Specific energy consumption
SHGC	Solar Heat Gain Coefficient
tCO_{2e}	Tonnes of CO_2 equivalent
TE	Thermoelectric
TEC	Total energy consumption
TRL	Technology readiness level
UK	United Kingdom
UNRCCC	United Nations Framework Convention on Climate Change
US	United States
UV	Ultra-violet
VCHP	Vapor-compression heat pump
VFD	Variable frequency drive
VIP	Vacuum insulated panels

2. EXECUTIVE SUMMARY

In this roadmap we question how domestic food kitchens can decarbonise and rapidly reach zero carbon emissions. As part of the work, we provide independent reviews of 54 different technologies/strategies that could applied in domestic kitchens to reduce carbon emissions and energy consumption.

The reviews were used to identify the individual technologies/strategies that had the most potential in domestic kitchens. Only technologies with a high technology readiness level (TRL) were considered, as these technologies/strategies were already available on the market or possible to implement immediately. The carbon emissions from those that were not available were very difficult to quantify and often had very varied application times and the claimed savings often varied widely. Results were presented as potential carbon savings (high/medium/low) and payback time.

Mathematical modelling was then used to assess impacts from 2020 through to 2050 taking into account changes due to global warming and changes in the electrical grid carbon emission intensity as well as the impact of applying these technologies/strategies.

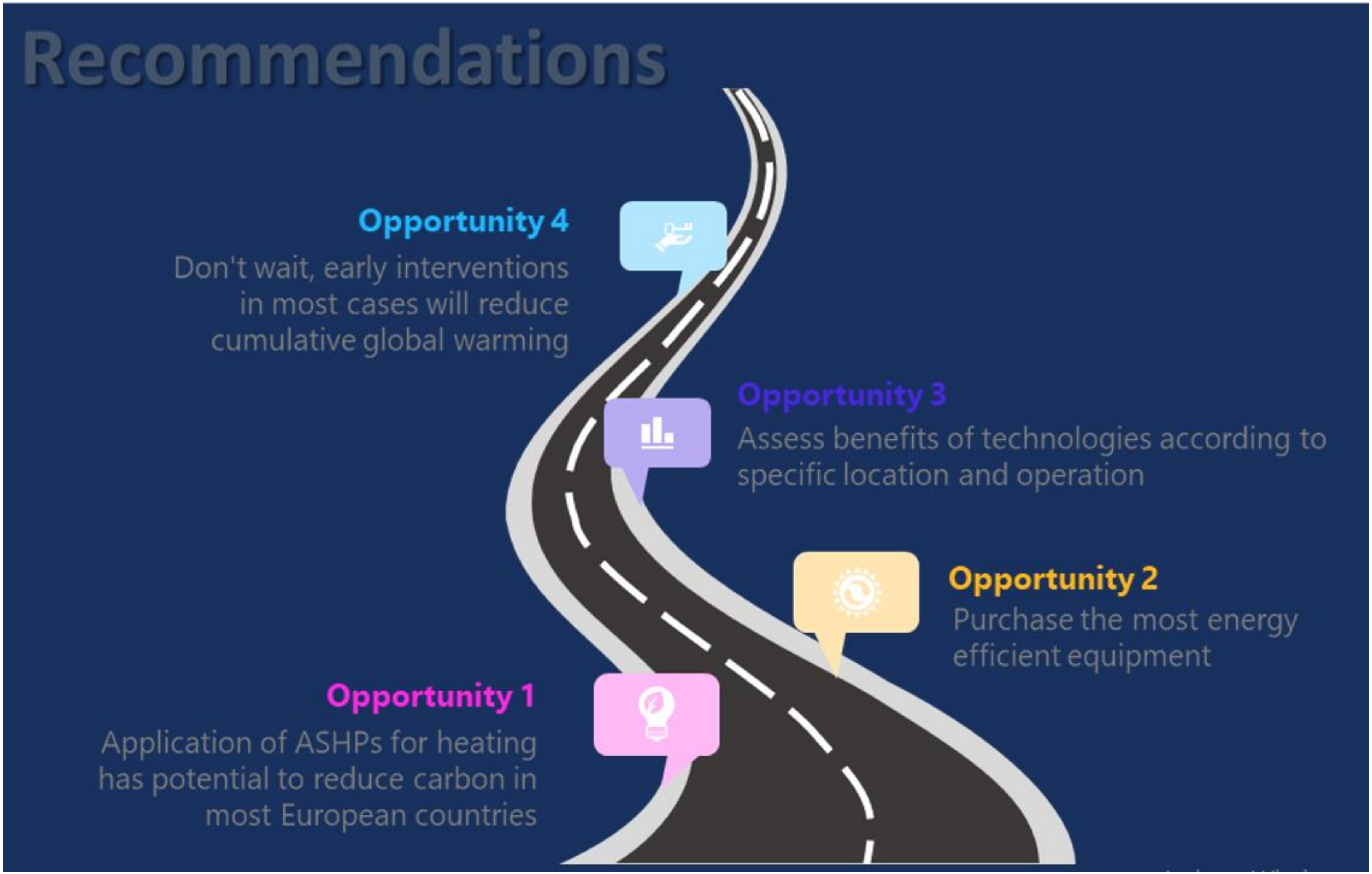
The following technologies/options were considered when applied to a typical kitchen in 6 locations (United Kingdom, France, Lithuania, Norway, Italy, Poland):

1. Move to air source heat pumps (ASHP) when not already installed
2. Move to resistive cooking when not already installed: it was assumed that resistive cooking was 73% more efficient than gas cooking (gas was 47% efficient).
3. Move to induction cooking: it was assumed that induction cooking was 84% more efficient than gas cooking (gas was 47% efficient).
4. More efficient cooking appliances (cooker, kettle and microwave: the cooking appliances (cooker, microwave and kettle) 10% less energy.
5. More efficient refrigeration: 10% less energy.
6. More efficient dishwasher: 10% less energy.
7. ASHP, induction cooking, more efficient cooking, refrigeration and dishwasher all combined.

Results indicated that carbon savings opportunities are available but that the savings depended very much on the baseline fuel applied in the country (for heating and cooking) and whether the carbon intensity of the electrical grid was equal or lower than the carbon intensities for these fuel sources. In countries where the carbon intensity of the grid is already low, applying electrically based equipment was always the lowest carbon option and ASHPs had benefits for heating the kitchen. For countries with high electrical grid intensities, or already used biomass for heating, the benefits of moving to electrical based technologies was less apparent in the short term. However, as the grid decarbonised the benefits would become greater.

In 2050, less energy will be required in kitchens due to a reduced need for heating as the climate warms. Any impacts of increased energy used by appliances such as refrigerators (that would be negatively impacted by higher ambient temperature) was very low due to their low share of the total energy used in the kitchen (most energy was used for cooking and heating).

Results from the reviews and modelling identified routes for reduces emissions in domestic kitchens and enabled the creation of a roadmap though to 2050.


Recommendations
Opportunity 4
Don't wait, early interventions in most cases will reduce cumulative global warming
Opportunity 3
Assess benefits of technologies according to specific location and operation
Opportunity 2
Purchase the most energy efficient equipment
Opportunity 1
Application of ASHPs for heating has potential to reduce carbon in most European countries

3. ABOUT THIS ROAD MAP

Globally, greenhouse gas (GHG) emissions from the food chain are estimated to account for 33% of the total GHG emissions. Emissions from the food chain can emanate from direct or indirect sources. Emissions related to post farm gate (post-harvest/slaughter) which are the focus of the ENOUGH project are thought to account for around 20% of total emissions.

This road map focuses on the decarbonisation of domestic kitchens.

This road map presents quantified evidence on the levels of carbon that could be saved, the technologies and strategies that could be applied and looks forward to 2050 to predict whether a zero-carbon domestic kitchen is feasible.

4. INTRODUCTION

In June 2021, the European Union (EU) adopted a European Climate Law which aims to reach net zero GHG in the EU by 2050. In addition, the EU has a goal of reducing emissions by at least 55% below 1990 levels by 2030 (including land use, land-use change, and forestry (LULUCF)). This is implemented through the 'Fit for 55' package which is a set of policy proposals by the European Commission (EC) to achieve the 55% reduction target. To achieve this target the EU has proposed a number of measures which include:

- the strengthening of the emissions reduction targets for each Member State;
- a Carbon Border Adjustment Mechanism, putting a carbon price on imports of iron and steel, cement, aluminium, fertilisers and electricity;
- an increase of the target for renewable energy production to 40% by 2030;
- an update of energy efficiency targets for each Member State to 36-39% by 2030;
- a revision of the EU Emissions Trading System (ETS), and a new ETS for road transport and buildings;
- a revision of the Energy Taxation Directive, introducing an EU-wide minimum tax rate for polluting aviation and shipping fuels;
- higher carbon dioxide (CO_2) emission standards for cars and vans, requiring average emissions of new cars to come down by 55% from 2030 and 100% from 2035 compared to 2021 levels;
- an obligation for fuel suppliers at EU airports to blend increasing levels of sustainable aviation fuels in jet fuel through the ReFuelEU Aviation Initiative;
- a maximum limit on the GHG content of energy used by ships calling at European ports through the FuelEU Maritime Initiative;
- the introduction of an overall EU target for carbon removals by natural sinks, equivalent to 310 million tonnes of CO_2 emissions by 2030; and
- a new EU Forest Strategy, setting out a plan to plant three billion trees across Europe by 2030.

All this impacts the food cold chain which has significant emissions of carbon. In particular the domestic sector in Europe generates significant quantities of carbon emissions and so have a major role to play the aimed for 55% reduction target.

The focus of this report is to assess the technologies and strategies available for domestic kitchens to reduce their carbon emissions. This covers the emissions that they generate today and also how emissions moving forward 2050 could be reduced to ultimately assess how a food service outlet could become zero carbon. During the work 54 different technologies and strategies were reviewed in detail to assess their opportunities to reduce carbon. This covered technologies that could be applied to the refrigeration systems and cooking systems applied.

5. THE MARKET

5.1. Food consumption and waste

In 2021, households in the EU spent over €1,035bn (equivalent to 7.1% of the total EU GDP) on 'Food and non-alcoholic beverages'. This represents a share of 14.3% of total household expenditure. Compared with 2020 (14.8% share), this represents a decrease of 0.5 percentage points (pp)[1].

In 2021, the second year of the COVID-19 pandemic, around 131 kilogrammes (kg) of food waste per inhabitant were generated in the EU. Households generated 54 % of food waste, accounting for 70 kg per inhabitant[2].

5.2. Refrigerators

The Europe Household Refrigerator Market size is estimated at USD 15.69 billion in 2024, and is expected to reach USD 18.40 billion by 2029, growing at a compound annual growth rate (CAGR) of 3.23% between 2024-2029[3]. The retail share of these products is moving from shop to online sales. The market is fragmented with many companies having minor share of the market.

Almost all refrigerated domestic appliances are self-contained, ‘plug-in’ or integral appliances, in which the refrigeration system is built into the cabinet and the condenser heat is discharged into the surrounding area. Typically, integral appliances are factory assembled and have a refrigerant charge of less than 150 g.

5.3. Cookers/ovens

In 2024, the revenue in the Cookers and Ovens market in Europe is estimated to be US$6.38bn[4]. It is projected that the market will experience an annual growth rate of 4.71% (CAGR 2024-2028).

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[1] How much do households spend on food and alcohol? https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20230201-1#:~:text=In%202021%2C%20households%20in%20the,0.5%20percentage%20points%20(pp).

[2] Food waste and food waste prevention – estimates. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates

[3] https://www.mordorintelligence.com/industry-reports/europe-household-refrigerator-market

[4] https://www.statista.com/outlook/cmo/household-appliances/major-appliances/cookers-ovens/europe

5.4. Types of appliances

5.4.1. Domestic cookers

A cooker usually contains an oven at the bottom with hobs at the top. Although these can be purchased separately, especially for built-in appliances. For built-in cookers, the oven is usually beneath the worktop.

There are 3 main fuel types: gas, electric and dual fuel. Gas cookers are becoming less common. Gas hobs are popular due to the very fast and controllable heat. However, gas ovens suffer from high temperature gradients if they do not have fans to distribute the heat.

Electric cookers are popular where there is no gas connection. They take longer to heat than gas, however, fan assisted ovens give good temperature distribution.

In the EU cooking is generally based on the use of electricity (more than 50% of the needs in 13 Member States) and gas (more than 50 % in five Member States) with only Malta and Cyprus using petroleum products for that purpose (80 % and 59.3 % respectively). Energy consumption in households - Statistics Explained[5].

Ovens

Ovens, come as single, double, or even triple ovens. A grille is usually incorporated into the top oven. Ovens can either be natural convection or forced convection (fan assisted). Fan assisted ovens require less time for pre-heating and cooking, or lower temperature cooking. Dual fuel ovens combine a gas hob and electric oven, which some consider to give the most appropriate fuel for the hob and oven.

A pyrolytic oven is a self-cleaning oven. When activated the pyrolytic program produces high temperatures of up to 485°C to turn food residue and grease into ash that, once the oven has cooled, can simply be wiped away.

It is common for a cooker to have a hood above it. This extracts air through a filter and thus reduces grease, combustion products, fumes, smoke, heat, and steam from entering the kitchen.

Microwaves

Microwaves offer a fast method of cooking, although this is usually for a smaller amount of food. They are convenient for small kitchens and small families. Microwaves can be built-in or freestanding (counter-top). A convection microwave utilises oven-like heating elements and a fan to circulate heat around the microwave cavity. This allows some of the cooking methods which cannot be carried out in a traditional microwave, such as roasting and baking.

5.4.2. Domestic refrigerators

The main types of household refrigerators and home freezers in the market are:

- Top-freezer refrigerators: these are traditional refrigerators with the freezer compartment located at the top and the fresh food compartment at the bottom.

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[5]https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Energy_products_used_in_the_residential_sector

- Bottom-freezer refrigerators: these are similar to top-freezer refrigerators, but with the freezer compartment located at the bottom for easier access to fresh food items.
- Side-by-side refrigerators: these models have two vertical doors, with the freezer on one side and the fresh food compartment on the other.
- French door refrigerators: these have two narrow doors for the fresh food compartment, and a freezer drawer located at the bottom.
- Ice box refrigerators: these are generally small with a small evaporator freezer section (usually at the top).
- Chest freezers: a freezer with a horizontal top lid.

Appliances can be either built-in where the unit is integrated into a kitchen cabinet for a seamless appearance or free standing.

The vapour compression cycle is by far the most commonly applied cycle in domestic refrigerators. Other refrigerator types have/are applied. Absorption refrigerators were common in the past but are now only used in camping, leisure, hotels and off grid/semi off grid applications. Peltier or electronic coolers are applied in small appliances which are typically used for storing a small number of cans or in leisure/camping appliances.

The cycle used in domestic refrigerators is generally comprised of one fixed capacity compressor, one condenser, one or two evaporators and associated expansion devices, as shown in Figure 1.

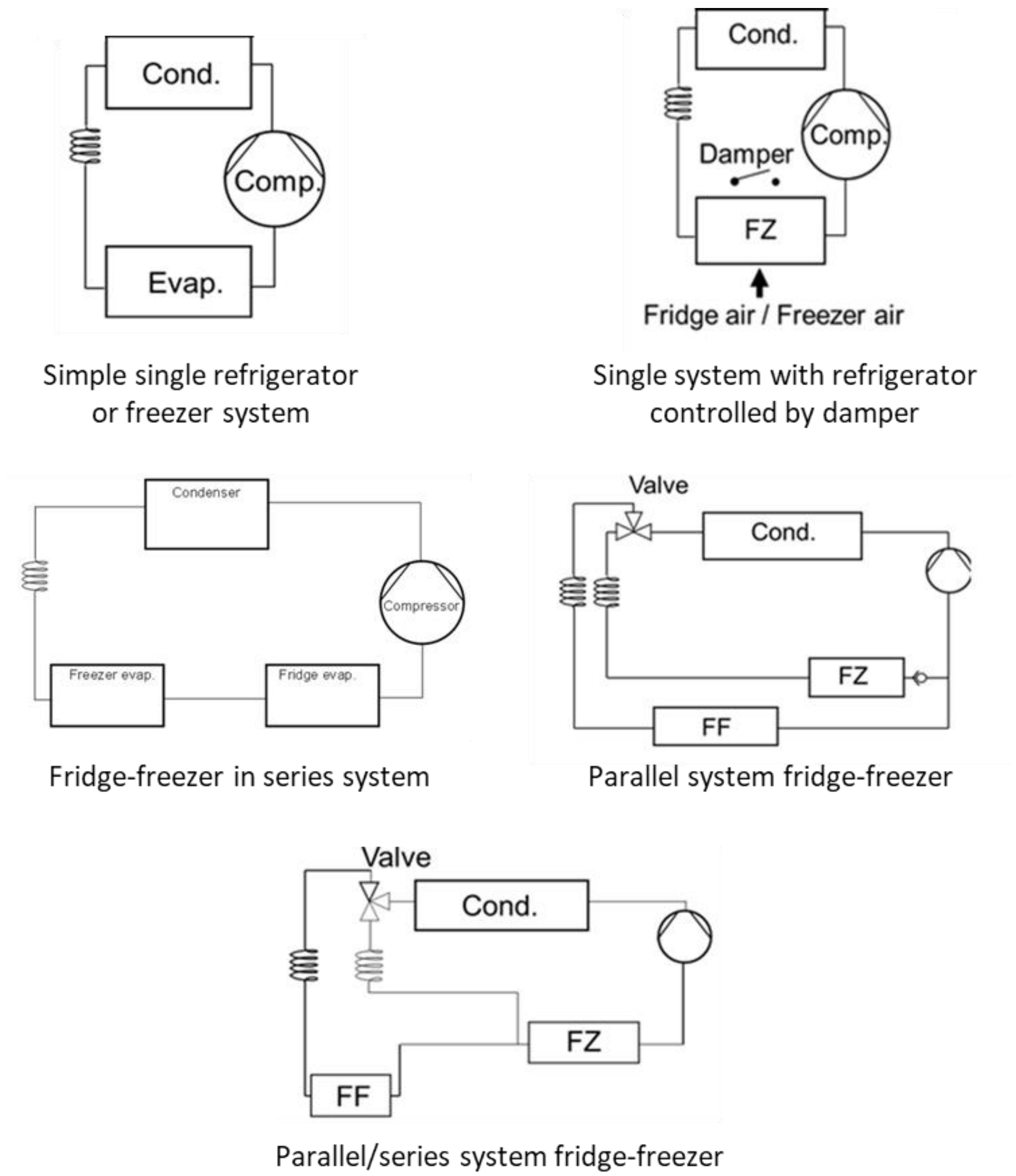

Figure 1. Typical domestic refrigerator designs.

5.5. Numbers of appliances

5.5.1. Domestic cookers

In 2019 it is reported that 4.7 million free standing cookers, 12 million built in ovens, 11.9 million hobs, 5.7 million hoods and 6.4 million microwaves were traded in the EU in 2019[6]. The largest growth was

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[6] https://applia-europe.eu/statistical-report-2018-2019/files/applia-statistical-report-2019.pdf

for free standing cookers, increasing 9.7% from 2018 to 2019. Microwaves showed a rapid decline for 24.2% over the same period.

5.5.2. Domestic refrigerators

Types of domestic refrigerator are predicted to change with time. Projections of UK stock provided by the UK Department of Energy Security and Net Zero (DESNZ) show that upright freezers and chest freezers are likely to remain constant, whilst refrigerators are due to decline and fridge-freezers increase in number up to 2050.

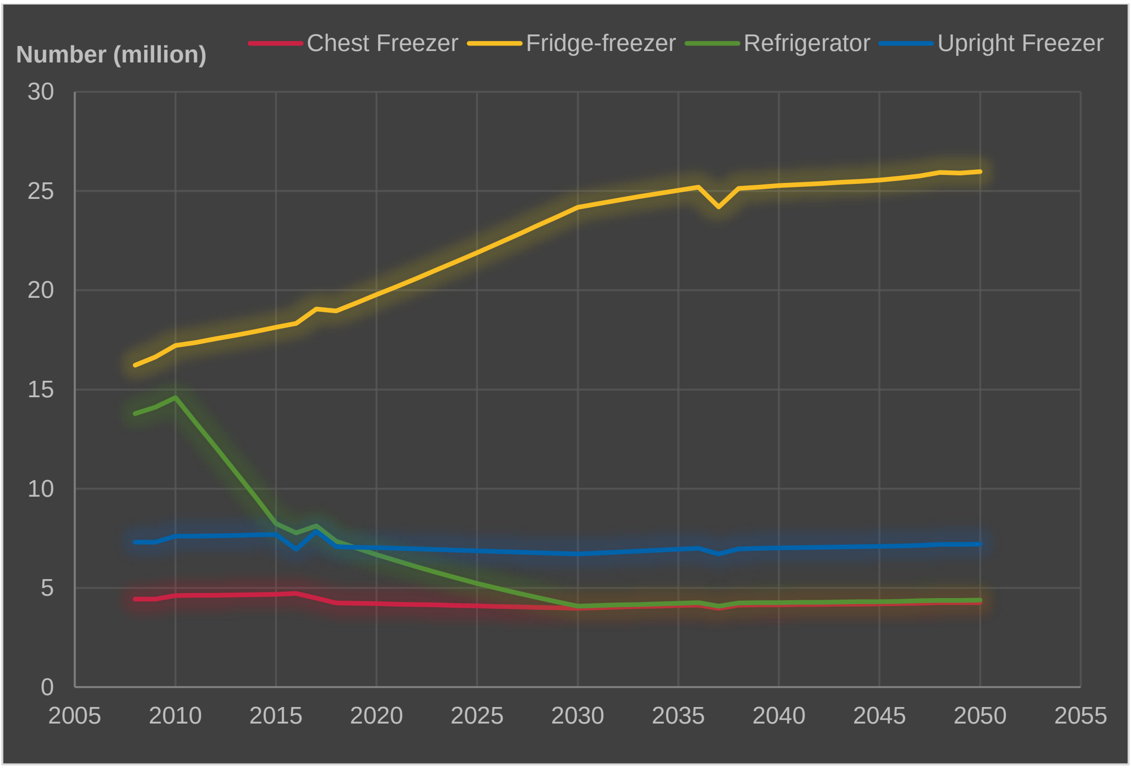


Figure 2. Projections of UK stock of domestic refrigerator types provided by the UK Department of Energy Security and Net Zero (DESNZ).

These projections are based on UK Government estimates of stock energy consumption of the different appliances. Foster et al.[7] suggest that these estimates are a little low when compared to a UK survey of 998 cold appliances were monitored in 766 properties in England[8], but more similar to a French study[9] (Table 1).

[7] Foster, A. and Evans J. Commercial, professional and domestic refrigeration equipment efficiency in the UK: Current and future trends. IIR International Cold Chain Conference, Tokyo, 2024 (in press).

[8] Biglia, A., Gemmel, A.J., Foster, H.J. And Evans, J.A., 2017. Temperature and energy performance of domestic cold appliances in households in England. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2017.10.022.

[9] Dupret, M., Zimmerman, J-P, 2019. Electricity consumption of cold appliances, washing machines, dish washers, tumble driers and air conditioners. On-site monitoring campaign in 100 households. Analysis of the evolution of the consumption over the last 20 years. Proceedings of the ECEEE summer study, 2019.

Table 1. Stock energy consumption and proportion of different types of domestic refrigerator.

	Chest freezer	Fridge-freezer	Refrigerator	Upright Freezer	Average
UK					
Energy per appliance (kWh/a)	416	376	185	316	329
Proportion of each appliance (%)	12%	47%	21%	20%	
Biglia et al.					
Energy per appliance (kWh/a)	420	390	274	342	360
Proportion of each appliance (%)	9%	52%	20%	19%	
Dupret et al.					
Energy per appliance (kWh/a)	354*	386	211	354*	

** Value given was for freezer, not separated into upright or chest.*

6. PERFORMANCE

6.1. Temperature

6.1.1. Refrigerators

Maintaining the required temperature in the fresh and frozen food compartments enables food to be stored for longer periods and is necessary from a safety and nutrition point of view. Frozen food must be stored below -12°C to extend its life period by stopping microbial growth and slowing down the chemical and enzymatic reactions that cause quality loss (Presutto, 2007[10]). The temperature in the fresh food compartment should be kept between 0°C and 4°C. Although many bacteria will not grow (or will grow very slowly) there are still some pathogenic bacteria that can survive and grow at these temperatures. A potential hazard in refrigerated foods is Listeria Monocytogenes, the growth rate of this pathogen increases almost four times when maintained in a refrigerator at 9°C for a period of a week rather than at the recommended temperature of 4°C (Geeraerd, 2010[11]).

Numerous studies have shown that domestic refrigerators run at higher temperatures than recommended by health and food safety legislation; an analysis of various surveys suggests that 54% of refrigerators throughout the world run at near temperatures above 5°C. The air temperatures measured in domestic refrigerators households across the world revealed average minimum and maximum temperatures of -1.5°C and 16.1°C respectively (James et al., 2017[12]).

[10] Presutto, M. 2007. LOT 13: Domestic refrigerators and freezers, Part I - Present situation, Task 1: Definitions, Rev. 4.0. In: ECOCOLD (ed.) Preparatory studies for eco-design requirements of EuPs.

[11] Geeraerd, A. 2010. Food quality and safety modeling for assessing the impact of the cold chain. 1st IIR International Conference on Sustainability and the Cold Chain. Cambridge, United Kingdom.

[12] James, C., Onarinde, B. A., and James, S. J. (2017). The use and performance of household refrigerators: A review. Comprehensive Reviews in Food Science and Food Safety, 16(1), 160-179. https://doi.org/10.1111/1541-4337.12242

The most recent and comprehensive study caried out on 998 appliances in the UK found that the overall mean refrigerator temperature across the study was 5.3°C and the mean freezer temperature was -20.3°C (Figure 3). The mean electricity consumption across all appliances were 354 Kilo Watt hour (kWh) per year which is considerably lower than previously reported (probably due to newer appliances being more efficient) (Biglia et al, 2018[13]).

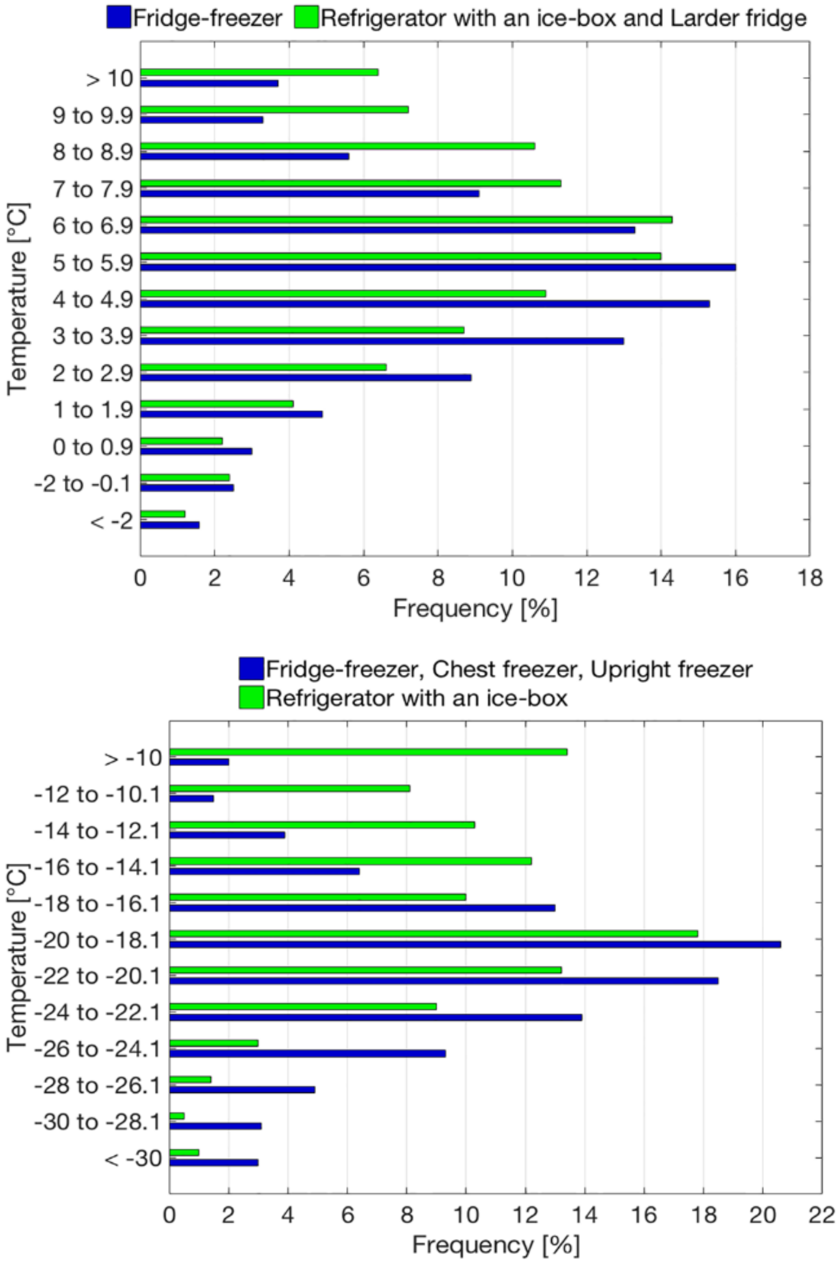


Figure 3. Temperatures measured in 998 appliances in the home: top – refrigerator, bottom – freezer[13].

[13] Biglia, A., Gemmell, A.J., Foster, H.J. and Evans, J.A., 2018. Temperature and energy performance of domestic cold appliances in households in England. International Journal of Refrigeration, 87, pp.172-184.

An argument that has been made is that domestic refrigerators are nowadays quite efficient and that there are limited options to reduce energy further. Furberg (2021[14]) has made an argument that temperature control in domestic refrigerators is now much more important as the food that can potentially be wasted has significantly greater carbon emissions than that from the energy used to operate the refrigerators (especially as the electrical grid decarbonises due to greater use of renewables). For example, Furberg states that the carbon emissions from 1 kg of beef that goes to waste in a refrigerator in Sweden corresponds to the carbon emissions equivalent to 10 years of operating energy. This makes the case well for technologies such as superchilling and options to enhance storage life thought humidity control, control of environmental gasses or decontamination techniques (such as ultra-violet (UV)).

6.2. Energy use

Energy is used in domestic kitchens for heating, hot water, lights, ventilation, cooking, food preparation and refrigeration. Household energy consumption is a large proportion of total energy consumption (TEC) in the EU, representing 27% of final energy consumption and 19% of gross inland energy consumption[15]. Eurostat data can be used to show a breakdown of where energy (final energy consumption) is used in the household (Figure 4). Sixty-four percent of the energy consumption is used in space heating. The only energy use which can be considered as food related in the kitchen is cooking which uses 6% of the total household energy consumption. Information from the ENOUGH project (unpublished) has found that emissions refrigeration energy consumption for homes in the UK is 88% of the value for cooking. Therefore, refrigeration is estimated to account for 5% of the TEC. It falls within the 'Lighting and electrical appliances' category which accounts for 14% of TEC.

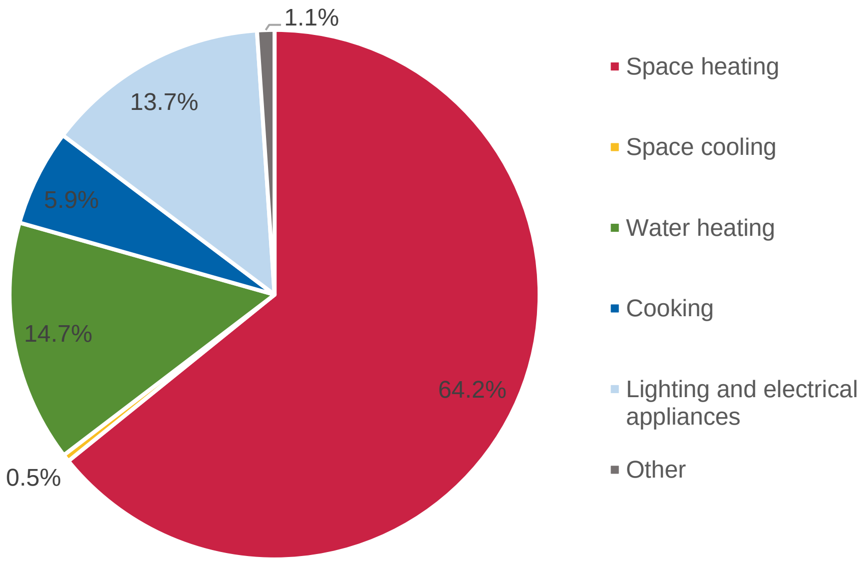


Figure 4. Disaggregated final energy consumption in households (PJ) for EU27 countries.

[14] Furberg, R. How much energy does it take to cool – on food environment and technology. IIR annual lecture 2021.

[15] Energy consumption in households - Statistics Explained (europa.eu).

A significant proportion of this energy is used in the kitchen[16]. In a study carried out on Scottish affordable and social housing it was found that 20–72% (41% mean) of total household electricity consumption was linked to the kitchen, excluding artificial lighting. The authors found that energy efficiency ratings of the cookers, fridges, freezers and washing machines in social housing had the least energy-efficient kitchen appliances compared to those in purchased affordable homes.

6.3. Energy labelling and best available technology (BAT)

EU energy rating labels were introduced in 1994 to improve energy efficiency of electrical appliances. Kitchen (or food related) appliances that come under these regulations are cooking and refrigeration appliances.

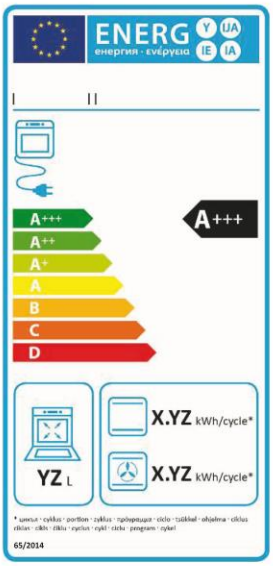
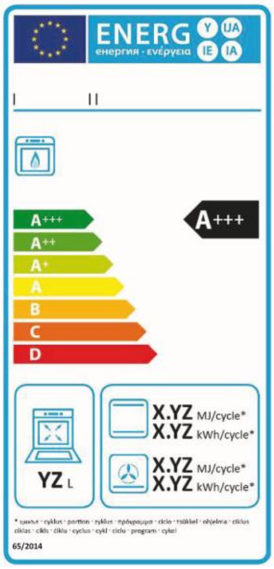
6.3.1. Cooking

New cooking appliances come with an energy label showing their energy efficiency class. These range from A+++ to D for ovens and A+++ to F for range hoods (Figure 5). For cookers there are two different energy labels, one for gas and the other for electric. As the electrical grid decarbonises, electric ovens produce less GHG than gas ovens. Once the electrical grid carbon factor reaches 0.18, there is a parity between gas and electric ovens using the same kWh of energy.

The energy class for ovens is calculated based on the volume of the cooker cavity. Therefore, it is important to consider energy consumption, which might be lower for the same energy class for an oven with a smaller volume cavity. Choosing an oven with a cavity volume, no larger than required, will reduce energy consumption.

According to a search of the European Product Registry for Energy Labelling (EPREL) most oven models listed have an A energy class. According to TopTen.EU the best ovens are A++ energy label. To be listed on TopTen.EU an energy class of A+ is required. If we assume that instead of choosing an A class (with a mean Energy efficiency index (EEI) of 94.5) an A+ class (mean EEI of 72) was chosen, the oven will use 24% less energy. f we assumed the best in class was chosen (EEI of 62), the oven would use 34% less energy.

[16] Foster, J.A. and Poston, A., 2023. Domestic energy consumption: temporal unregulated electrical energy consumption in kitchens in Scottish affordable and social housing. Energy Efficiency, 16(6), p.62.

Domestic oven energy labels:	
 Electric	 Gas

Range hood energy labels:

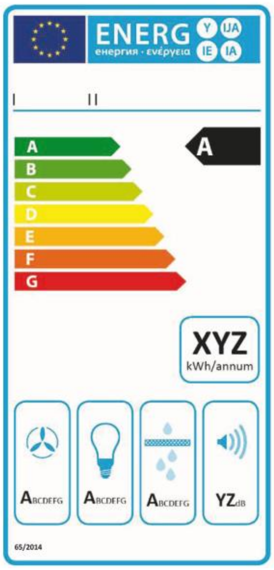
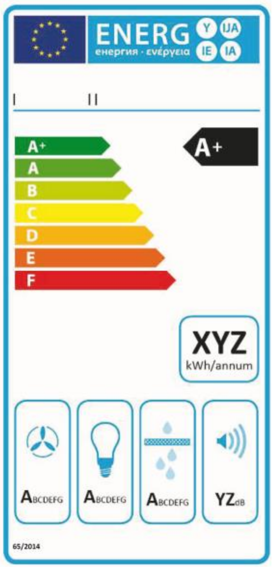
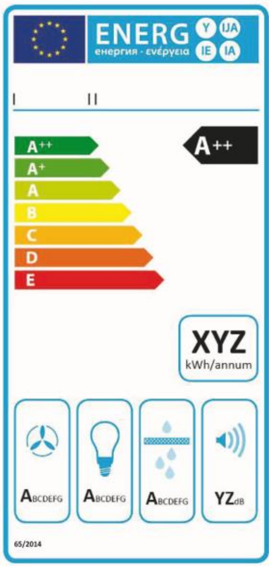
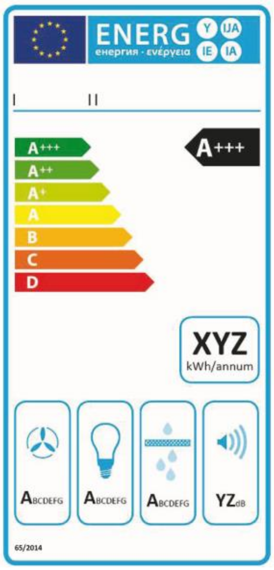
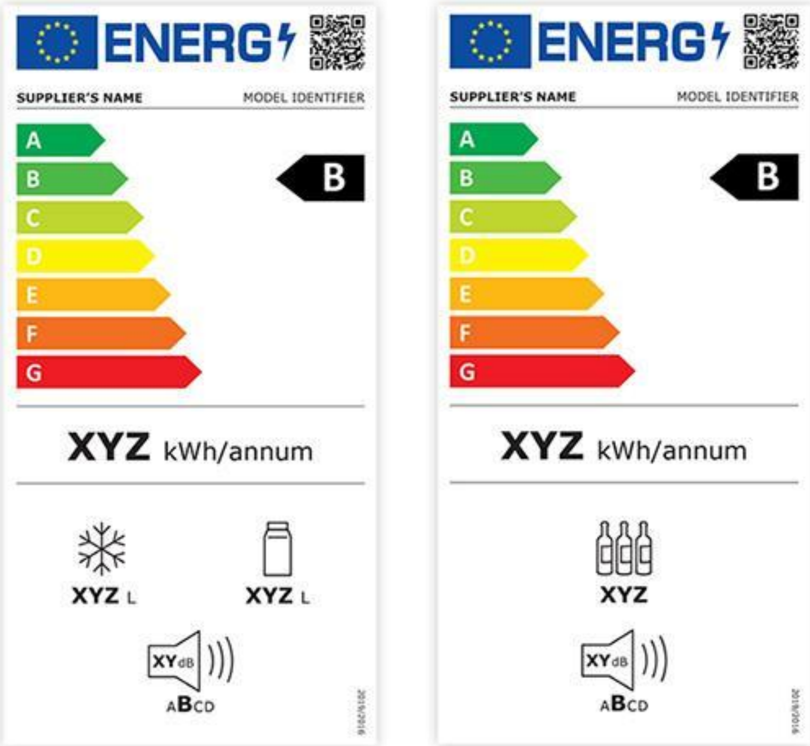
			

Figure 5. European cooker and range hood energy labels.

6.3.2. Refrigeration

Domestic refrigerators are categorised under the following product types, Chest Freezer, Fridge-freezer, Refrigerator and Upright freezer.

Domestic refrigerators are defined by Regulations EC 643/2009 and (EU) 1060/2010, as electric mains-operated household refrigeration appliances with a storage volume up to 1,500 litres. The EU energy labels for household fridges and freezers use, as of 1 March 2021, a scale from A (most efficient) to G (least efficient) (Figure 6).



The labels were updated on 1 March 2021 where they were also rescaled. At the same time the latest version of the tests standards (EN62552-1-2-3:2020 which replaced IEC62552-1-2-3:2015) was applied. The most important modification related to the way in which energy consumption is calculated. A calculation that combines performance at 16°C and 32°C (as opposed to only testing at 25°C previously) was applied. The updated labelling is regulated under Commission Regulations (EU) 2019/2016, 2019/2019, 2021/340 and 2021/341.

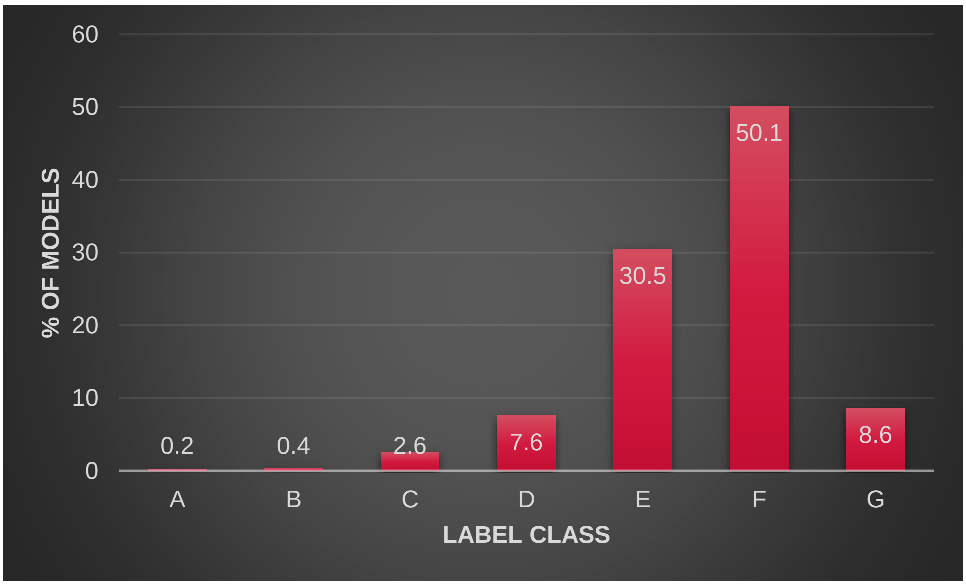


Figure 7. Energy classification of domestic refrigerators from EPREL.

According to a search of the EPREL in 2023 most models listed had an F energy class (Figure 7).

According to TopTen.EU the best refrigerators are A energy class and best freezers are C energy class. To be listed on TopTen.EU an energy class of D or better is required. If we assume that instead of choosing an F class (with a mean EEI of 112.5) a D class (mean EEI of 72) was chosen, the refrigerator/freezer would use 36% less energy. If we assumed the best-in-class freezer was chosen (EEI of 64), the freezer would use 43% less energy.

6.3.3. Energy use in kitchens

Work by Biglia et al (2020[17]) found that energy used in the home and in a standard test varied considerably. Sixty-one percent of 124 appliances were found to consume more energy in the home than the laboratory. The rank order of energy used by appliances was also assessed and found to vary considerably between the laboratory and the home. Reasons for this disparity were not clear, but usage must have an impact as identical appliance models often had very different energy consumption. Due to the fact that appliances tended to consume more energy in the home than indicated in test standards indicates that the impact on energy labelling may be overestimated.

6.4. Refrigerants

Domestic refrigerators in the 1980s used R12 refrigerant with a global warming potential (GWP) of 8500. This refrigerant was banned in 1994 due to its ozone depletion potential. The refrigerant was replaced by R134a. From 2015, refrigerants with a GWP >150 were banned due to European F-gas regulations18. As R134a has a GWP of 1810, it was replaced by the hydrocarbon R600a with a GWP of <1. For this reason, fugitive emissions from refrigerants are only an issue in old appliances (those manufactured before 2015). The emissions from leakage of refrigerants used for UK GHG inventory[19] assumes 1% loss rate during manufacture and installation, 0.1% during operation and 58% during disposal. Legislation should therefore be focused in removing these old refrigerators, due to poor efficiency (high energy consumption) rather than due to their refrigerants and then disposing of the gas properly.

For the smaller integral refrigeration systems that are commonly applied in kitchens the hydrocarbon refrigerant system charges are generally less than 150 g to comply with EN 60335-2-89:2010+A2:2017 (Household and similar electrical appliances. Safety - Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant unit or compressor). Most refrigerant charges for domestic refrigerators are well below the 150 g limit.

6.5. Policy

Foster and Evans[7] reviewed EC's most recent Preparatory Study on household refrigerating appliances[20]. This study predicted the average energy consumption of units sold over the period 2005-

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[17] Biglia, A., Gemmell, A.J., Foster, H.J. and Evans, J.A., 2020. Energy performance of domestic cold appliances in laboratory and home environments. Energy, 204, p.117932.

[18] Regulation on the Use of F-Gases (EU 517/2014, 2014.

[19] Brown, P., Cardenas, L., Choudrie, S., Del Vento, S., Karagianni, E., MacCarthy, J., Mullen, P., Passant, N., Richmond, B., Smith, H. and Thistlethwaite, G., 2021. UK Greenhouse Gas Inventory, 1990 to 2019, Annual report for submission under the framework convention on climate change. Ricardo Energy and Environment, pp655.

[20] VHK and Armines, 2016. Preparatory/review study: Commission Regulation (EC) No. 643/2009 with regard to ecodesign requirements for household refrigeration appliances and Commission Delegated Regulation (EU) No. 1060/2010 with regard to energy labelling of household refrigeration appliances FINAL REPORT. European Commission.

2030 in the EU, for different scenarios, business as usual (BAU), ambitious and lowest life cycle cost (LLCC). Foster and Evans found that the current trajectories of energy efficiency do not appear to be on target. They showed that the 'business as usual' scenario trajectory suggests the average energy class should be B-class, whereas only a few percent of fridge-freezers (most common appliances) models available for sale were currently B-class or better (Figure 8).

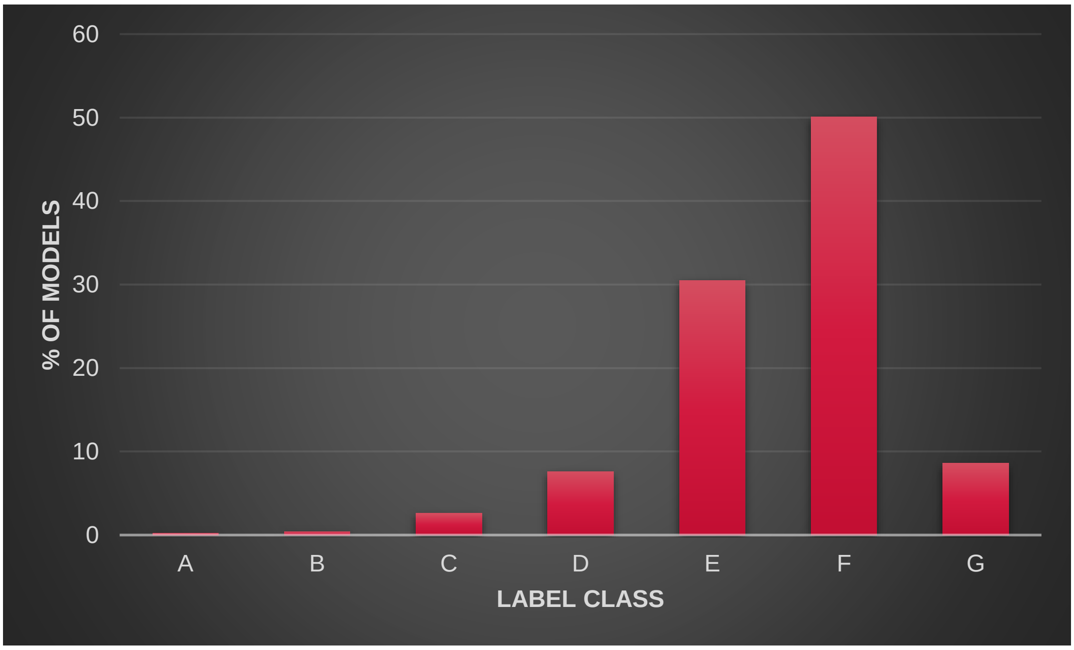


Figure 8 Proportion of domestic refrigerator models at each label class from EPREL in March 2023.

According to Khalid and Foulds[21] policy could ensure capacity-building of low carbon technologies through a market support framework using legislation, carbon taxing and/or subsidies. They suggested that the increased role out of induction hobs could help prevent further lock-in to gas technologies.

Electric cookers are more efficient than gas cookers. Khalid and Foulds[21] stated that natural gas cookers/hobs are 40 to 55% efficient, as opposed to 74% for solid plate and 72% for radiant electric cookers/hobs. The efficient is even higher (84%) for induction cookers/hobs.

According to Eurostat average EU electricity and gas price (for household consumers) in first half 2023 was 0.289 and 0.1187 Euro/kWh respectively. Therefore, even with the improved efficiency of electric, it is about 50% more expensive to run an electric oven/hob. To encourage decarbonisation, this price inequality should be addressed.

[21] Khalid, R. and Foulds, C. 2020. The social dimensions of moving away from gas cookers and hobs: Challenges and opportunities in transition to low-carbon cooking. https://d2e1qxpsswcpgz.cloudfront.net/uploads/2020/05/KhalidFoulds_Gas-cookers-and-hobs_published.pdf.

7. TRENDS

7.1. The environment

The world is experiencing higher temperatures due to global warming. Globally mean near-surface temperature were 1.11 to 1.14°C warmer between 2012 and 2021 than during the pre-industrial level. This makes the last decade the warmest on record. In Europe temperatures have increased even faster over the last decade, with an increase of 1.94 to 2.01°C (depends on data set used). 2020 was the warmest year in Europe since instrumental records began. In particular hight levels of warming were observed across Eastern Europe Scandinavia and at eastern part of Iberian Peninsula.

United Nations Framework Convention on Climate Change (UNRCCC) member countries have committed to the Paris Agreement. This aims to limit global temperature increase to below 2°C (above pre-industrial levels) by 2050 and ideally to limit the increase to less than 1.5°C[22]..

Projections on future temperatures from climate change models indicate that in Europe, land areas will continue to increase in temperature throughout the century at a rate higher than the global average. Depending on the assumptions applied to the models, temperatures could at best increase by 1.2 to 3.4°C and at worst by 4.1 to 8.5°C (by 2071-2100, compared to 1981–2010). Areas of particular concern are north-eastern Europe, northern Scandinavia and inland areas of Mediterranean countries, whereas western Europe, especially in the UK, Ireland, western France, Benelux countries and Denmark expect the lowest levels of warming.

It is clear that extreme temperature events are becoming more common, and this is having an impact on refrigeration systems. Many reports over the last summer stated that food retail refrigeration systems were breaking down due to the hot ambient temperatures. This has meant that many of the top retailers have had to empty cabinets and have been unable to sell refrigerated products. Even if the refrigerated cabinets can continue to keep working, warmer ambient temperatures are having a major impact on costs to run a food retail outlet. A recent report from Imperial College has indicated that a 2°C increase in average UK summer temperature increased refrigeration energy demand by 6%[23]. The same report also found that refrigerated cabinets broke down more in hotter weather increasing maintenance bills. All of this is bad news for food retailers, consumers and the environment as the additional costs will have to be absorbed and food may be wasted if cabinets can no longer cope with the warmer conditions.

Options are available to prevent refrigeration breakdowns. Good maintenance and monitoring can make sure cabinets and refrigeration plant have the best operational performance before they are stressed by warm conditions. Reducing the load on the refrigeration plant though the application of energy efficient technologies can also be beneficial. These options will enable current plant to operate for longer but ultimately design of both the refrigerated cabinets themselves and refrigeration systems need to be adapted to cope with the new higher ambient conditions. As food retail refrigeration systems are expected to have an operating lifetime of 15-20 years, there is a need to make sure new

[22] https://www.eea.europa.eu/ims/global-and-european-temperatures

[23] https://www.imperial.ac.uk/news/198934/warmer-summers-risk-chilling-energy-bill/

systems are able to cope with what is likely to become common rather than rare high ambient temperature events.

Although increasing ambient temperatures impact the performance of refrigeration systems, the impact of climate change goes much further. Associated issues such as droughts and reduced availability of water have an impact on the whole food chain. Food may no longer be able to be grown in certain locations and the whole cold chain system may need to be redesigned to cope with these changes. Climate change may also have wider ranging impacts such as migration of populations from areas where crops can no longer be grown and may have significant impacts on the food security of nations.

7.2. Future trends

7.2.1. Fuels

Natural gas is the major energy source for EU household, accounting for 34% of total energy use, compared to electricity's 25%[24]. Most of this energy (64%) goes into heating the home, with cooking at only 6%. Many kitchen appliances are almost entirely electrical, e.g. food processors and refrigerators, therefore these will decarbonise along with the electrical grid. However, cooking is a mixture of electrical (51%) followed by natural gas (about 33%) for the average EU household[24]. Cooking is generally based on the use of electricity (more than 50 % of the needs in 13 Member States) and gas (more than 50 % in five Member States) with only Malta and Cyprus using petroleum products for that purpose (80 % and 59.3 % respectively)[5]. Natural gas has a carbon conversion factor of 0.184 Kg/kWh, so as nations decarbonise their electrical grid and thus reduce their electrical emissions factors below this value, moving to electricity will reduce emissions from cooking further.

7.2.2. Changes in consumer habits

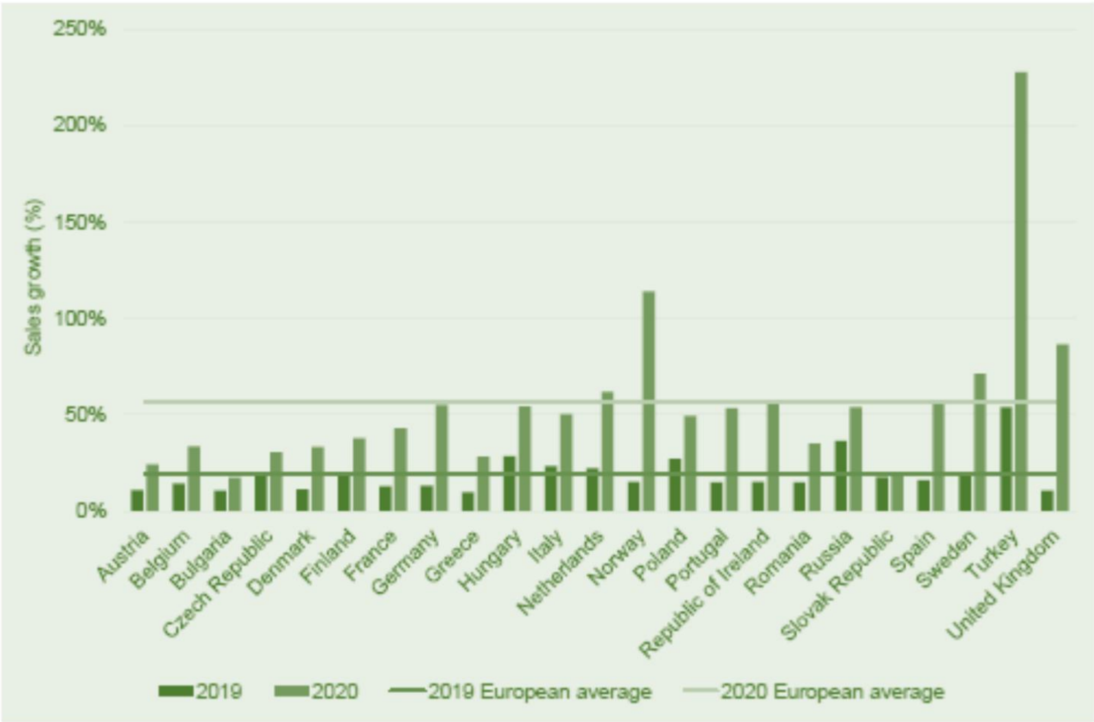
Consumer shopping habits changed rapidly in the COVID-19 pandemic. The use of internet shopping saw rapid increases during the pandemic in some countries. For example, in the UK pre-pandemic ecommerce accounted for 8.7% of all grocery sales. This rose to 15.4% in the pandemic and has since fallen back to 13.3% of all grocery sales[25]. Increases in ecommerce during the pandemic in other European countries were not as significant and this was partially related to the ability of retailers in these countries to service the home delivery demand. Figure 9 shows the sales growth in home delivery in European countries between 2019 and 2020. In all cases sales growth increased or remained stable with an overall increase in growth of 36.6% (overall online sales growth from 19.5% in 2019 to 56.1% in 2020). Certain countries (in particular, The Netherlands, Norway, Sweden, Turkey and the UK) all saw particularly high growth in ecommerce sales in 2020.

Although demand for home delivery has decreased it appears that a significant number of consumers who used home delivery during the pandemic will continue to use home delivery or a click and collect

[24] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households.

[25] https://www.retailgazette.co.uk/blog/2022/03/two-years-on-how-covid-has-changed-the-uks-grocery-sector-forever/

service. More than 50% of consumers intend to continue ecommerce shopping for at least some part of their grocery needs[1].



Source: European Commission Directorate-General for Economic and Financial Affairs

Figure 9. Online food and grocery sales 2019 versus 2020.

Changes in shopping habits have also affected shopping location. Consumers have switched to more local sources, partly due to the pandemic, but also due to personal and sometimes financial motives. This was partially due to the pandemic where consumers wished to stay closer to home (or may even had restrictions on their movements) and potentially had more time to visit multiple smaller retailers[26].

7.2.3. Changes in eating habits

Rising energy costs have had an impact on consumer cooking habits. According to a report from BBC Good Food 9, since the pandemic (where consumers cooked more) many consumers are reporting using the hob less and microwave more to save energy. Consumers are also reporting that they cook meals that require less cooking and cook less energy intensive meals. In extreme cases some consumers are reporting that they no longer use their oven. Consumer trends are to plan meals better and batch cook to better utilise energy. There is also an increase in the purchasing of frozen food. This is likely to have been partially driven by changes in shopping habits in the pandemic (fewer shopping trips and the wish to store foods in case of lock downs). This also drove an increase in purchase of non-perishable foods. Increased energy costs and the financial crisis are also reported to be having an impact on food waste

[26]https://www.theguardian.com/business/2021/mar/23/uk-local-grocery-shopping-could-last-beyond-pandemic-poll-small-stores-food-drink

in the home with 3 in 5 consumers in the UK stating that they are reducing the amount of food they waste and consequently are buying less food[27].

There is a general trend for consumers to consume perceived 'healthier' plant based and more sustainable options. Before the financial crisis (which has changed food choices to those more based on cost) a survey conducted by research company Toluna showed there was a reduction in the consumption of meat-based products with 50% of people saying they have started or were continuing to reduce their meat intake. Since 2019 meat eaters have reduced from 83% to 78%[28]. There is also a growing trend for veganism and vegetarianism (7% saying they planned to consume a vegan diet and 12% a vegetarian diet). There is a growing need for alternative plant-based products which are generally perceived by consumers as being healthy[29].

There is a growing trend for health-based foods. Consumers are also becoming more aware of how their food choices affect the environment and so are more aware of sustainability and interested in provenance and sourcing of foods they buy. In particular packaging has a high profile with consumers who are much more concerned about single use packaging than in the past. One developing trend is for personalisation of food where consumers use technology to select foods that suit their health, welfare and lifestyle choices[30].

All these trends have an impact on retailers who will provide choices to consumers according to demand. Currently the major trend is to provide customers with cheaper alternatives and deals to reduce the cost of eating. Although this has been exacerbated by the financial crisis it is a trend that has been ongoing for several years. In the past consumers still bought treats and would trade up to more expensive options for special occasions. This has reduced due to lack of disposable income. Although current supermarket trends are very much driven by food costs, there is still a strong trend for consumers to be very aware of sustainability issues and want brands and supermarkets to be honest in their claims and avoid greenwashing.

7.2.4. Saving energy and the financial crisis

The financial crisis has impacted customers. In 2019, households in the EU spent 13.0% of their total expenditure on food and non-alcoholic beverages. This was the third-largest category of household expenditure after housing, water, electricity, gas and other fuels (23.5%) and transport (13.1%). The amount of expenditure varies quite considerably between European countries with some countries spending over 25% of their income on food and others as little as 8% (Figure 10)[31]. Household incomes in real terms are decreasing due to increasing prices and limited rises in salaries and benefits. In the UK, household income is projected to decrease by 7% in real terms over 2 years, according to the Office for Budget Responsibility.

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[27]https://www.foodmanufacture.co.uk/Article/2022/09/23/How-are-consumers-changing-their-eating-habits

[28] https://tolunacorporate.com/dietary-trends-and-plant-based-perceptions-in-the-uk/

[29] https://www.foodmanufacture.co.uk/Article/2022/05/30/how-are-consumers-diets-changing

[30] https://sialamerica.com/white-papers/the-4-biggest-consumer-food-trends-shaping-2022/

[31] Eurostat. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20201228-1

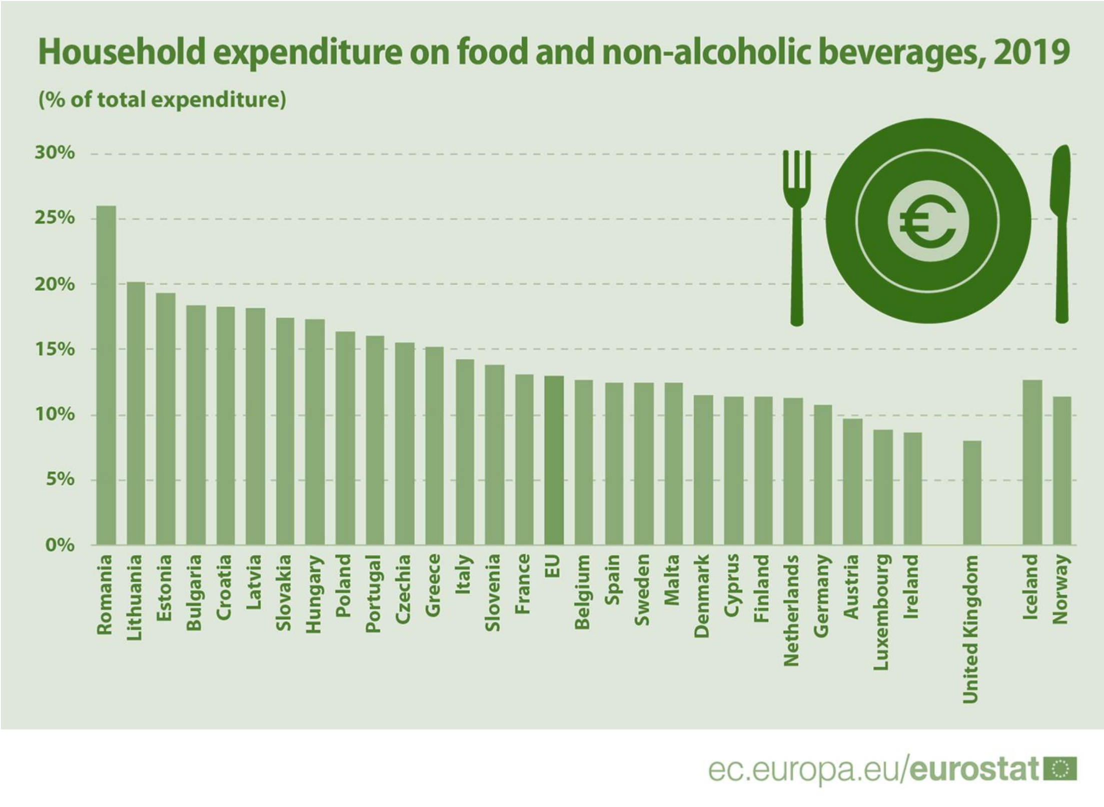


Figure 10. Household expenditures per country in Europe in 2019.

7.3. Circular economy

The EU has developed a 'Circular economy action plan' which was adopted in March 2020. It is one of the main parts of the European Green Deal. The plan aims to make sustainable products the norm in the EU while halving municipal waste in Europe by 2030.

The plan impacts the entire life cycle of products and aims to encourage reduction in waste and circularity in the use of resources. Much of the initiative related to food is targeting food waste, water use and general sustainability of food distribution and consumption. Packaging is also targeted with the aim to increase use of recycled plastics and to use plastics more sustainably.

As part of this initiative the Commission is planning legislation on the right to repair products. The Sustainable Products Initiative will revise the Ecodesign Directive, and it is currently in the public consultation phase. The initiative aims to make products more durable, reusable, repairable, recyclable, and energy efficient as well as to provide end users with a practical means to self-repair their products or choose a third-party service provider instead of going through the manufacturer.

Previously EU initiatives have focused more on end of life whereas the shifts attention to the entire lifecycle of a product. Like the Ecodesign Directive, the Sustainable Products Initiative will provide a general framework, and sector-specific legislation for different product categories. In addition, there is an intention to introduce an EU Digital Product Passport with information on components and their potential for recycling.

8. TECHNOLOGIES/STRATEGIES

Energy saving technologies/strategies were initially identified and listed. In total 54 technologies and strategies were reviewed (see Detailed technology/strategy reviews). Technologies/strategies were only included if they had the potential to reduce carbon emissions. A comprehensive review of each technology was carried out and any references listed. The reviews compared and contrasted available information (peer reviewed papers, conference papers, grey literature, manufacturers data, personal experience) to provide a critical assessment of the validity of the information. The proportion of greenhouse gas emissions that a technology could save and any constraints around the use/application of the technology were reported. In addition, the cost for application of the technology and the technology readiness level (TRL) level were listed if available. If a technology was not currently available, the approximate time until it could be deployed was estimated (Table 2).

> **SCOPE 1 EMISSIONS**
>
> *Scope 1 covers emissions from sources that an organisation owns or controls directly – for example from burning fuel.*
>
> **SCOPE 2 EMISSIONS**
>
> *Scope 2 are emissions that a company causes indirectly when the energy it purchases, and uses is produced.*

The 54 technologies and strategies were classified according to whether carbon savings were scope 1 or 2 and the TRL of the technology (Table 3). Only options with a TRL of 8-9 were considered for full assessment as it was not possible to estimate the impact that lower TRL technologies might have in the future.

Table 2. Review summary information included at the end of each review.

Scope 1 emissions savings (% or another quantifiable metric)	Overall savings that the review indicated.
Quality of scope 1 emissions information	How robust is the available information?
Scope 2 emissions savings (% or another quantifiable metric)	Overall savings that the review indicated.
Quality of scope 2 emissions information	How robust is the available information?
TRL level	Marked as: TRL1-4 TRL5-7 TRL8-9 TRL 1 - basic principles observed TRL 2 – technology concept formulated TRL 3 – experimental proof of concept TRL 4 – technology validated in lab TRL 5 – technology validated in relevant environment TRL 6 – technology demonstrated in relevant environment TRL 7 – system prototype demonstration in operational environment TRL 8 – system complete and qualified TRL 9 – actual system proven in operational environment
Maintainability issues	Any relevant issues are listed.
Legislative concerns	Any relevant issues are listed.
Payback time (years)	Time to recover cost of technology. This is equal to the saving in electrical energy per year divided by the cost of the technology. It does not include other ongoing costs, e.g. maintenance, cost of finance etc.

Table 3. List of technologies/strategies assessed, when they can be applied and the type of emission saving.

Technology	Sector	TRL level	Carbon savings	
			Scope 1	Scope 2
Refrigerated appliances				
Acoustic refrigeration	Refrigeration	4		✓
Advanced controls	Refrigeration	7		✓
Charge optimisation	Refrigeration	9		✓
Dampers	Refrigeration	4		✓
Defrost control (e.g. on demand)	Refrigeration	7-8		✓
Door open warnings	Refrigeration	9		✓
Dual-loop system	Refrigeration	4		✓
Dynamic demand/response	Refrigeration	7		✓
Efficient compressor technology	Refrigeration	9		✓
Electrocaloric refrigeration	Refrigeration	1-2		✓
Evaporator and condenser optimisation	Refrigeration	7-8		✓
Fan-assisted condenser	Refrigeration	8-9		✓
Heat pipes and spot cooling	Refrigeration	5		✓
Improved door gaskets	Refrigeration	9		✓
Improved insulation e.g. vacuum insulation panels	Refrigeration	7		✓
Internal ice makers (removal)	Refrigeration	9		✓
Inverter driven compressors	Refrigeration	9		✓
Liquid line solenoid valve	Refrigeration	8		✓
Magnetic refrigeration system	Refrigeration	3-4		✓
Maintenance and servicing	Refrigeration	7		✓
Nanofluids	Refrigeration	3		✓
Phase change materials	Refrigeration	4		✓
Stirling coolers	Refrigeration	4		✓
Superchilling	Refrigeration	5	✓ (waste reduction)	
System circuit and optimisation	Refrigeration	4		✓
Thermoelectric refrigeration	Refrigeration	4		✓
Thermionic refrigeration	Refrigeration	3		✓
Two-stage system	Refrigeration	5		✓
Vacuum insulated panels (VIPs)	Refrigeration	7		✓
Vortex tube	Refrigeration	2		✓
Wide glide refrigerants	Refrigeration	4		✓
Ovens:				
Air fryers	Cooking	9		✓
Cooker hoods	Cooking	9		✓

Technology	Sector	TRL level	Carbon savings	
			Scope 1	Scope 2
Cooking - gas, electric, induction, microwave, halogen	Cooking	9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Cooking at lower temperatures	Cooking	9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Cooking method, fry, grill, bake, boil/stew, roast, broil, steam	Cooking	9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Door seals and insulation	Cooking	9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Efficient oven design	Cooking	7	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Fan assisted vs natural convection	Cooking	9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Hot water for beverages - kettles, hot taps, coffee machines	Cooking	9		✓
Manual rather than pyrolytic cleaning	Cooking	9		✓
Microwaves	Cooking	9		✓
Oven light control	Cooking	8-9		✓
Pre-heating oven	Cooking	9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Pressure cooking	Cooking	9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Slow cookers	Cooking	9		✓
Temperature control (monitoring of the core temperature)	Cooking	8-9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Viewing windows - level of glazing (single, double, triple)	Cooking	9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Other/ancillaries:				
Dishwashers	Ancillaries	9		✓
IoT and AI	Ancillaries	4-9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Solar electricity	Ancillaries	9	✓	✓
Solar thermal hot water	Ancillaries	9	✓ (dependent on fuel source)	✓ (dependent on fuel source)
Waste utilisation	Ancillaries	3-9	✓ (waste reduction, if decomposition is in home)	

8.1. What can we learn from the reviews?

The technologies/strategies were initially assigned to the following groups to identify which would save the most carbon across a domestic kitchen:

Potential to save carbon:

Low (L): <5% potential saving

Medium (M): >5%, <10% saving

High (H): >10% saving

Payback time:

<1 year

<3 years

<5 years

>5 years

Neutral/limited information

Negative payback (only a carbon saving)

Therefore, technologies and strategies can be divided into sectors of relevance (Figure 11). Those in:

- Category 1 have the highest carbon savings potential and shortest payback and so are things that should be considered immediately,
- Category 2 have high carbon savings potential but will take longer to payback,
- Category 3 have less carbon saving potential but have short paybacks,
- Category 4 have lower carbon saving potential and are longer to provide paybacks.

Other technologies outside of these categories could also be considered but are likely to be of lower relevance.

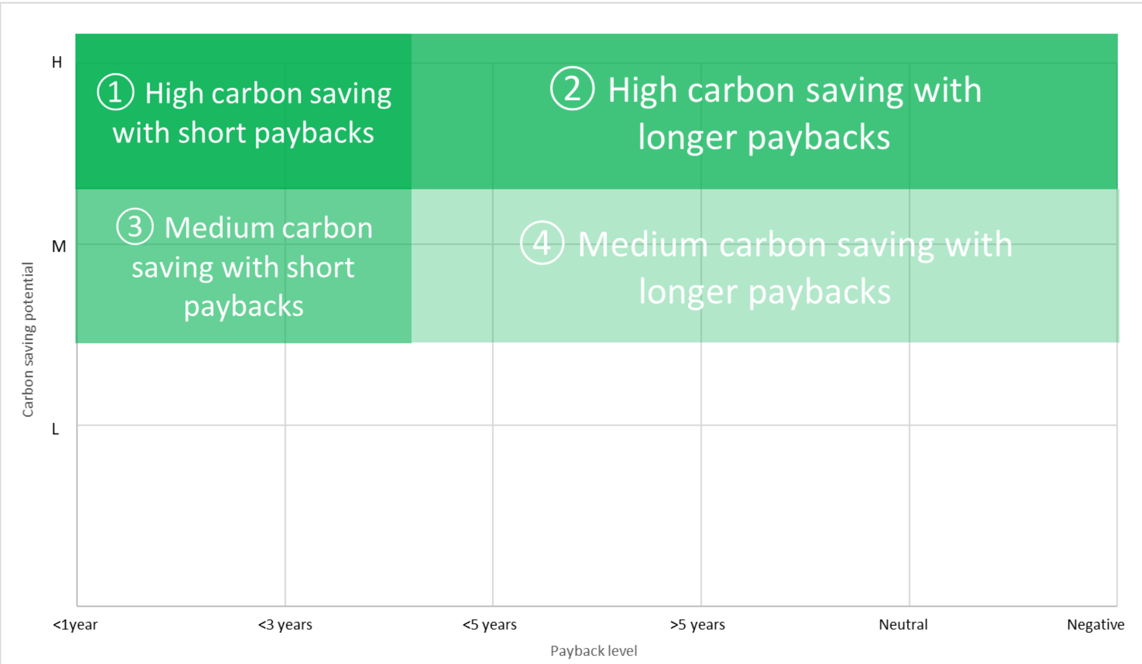


Figure 11. Potential carbon savings and payback sectors.

Technologies with a TRL of 8-9 were assessed using the above methodology. Results are presented in Figure 12. It was clear that quite a few of the reviewed technologies were not available today (only 43% of the technologies reviewed were ranked as TRL 8-9). Those that had a lower TRL were difficult to assess as there was very limited information on the performance of the technologies. It was therefore not possible to assess when the lower TRL technologies would be applied or their future benefits.

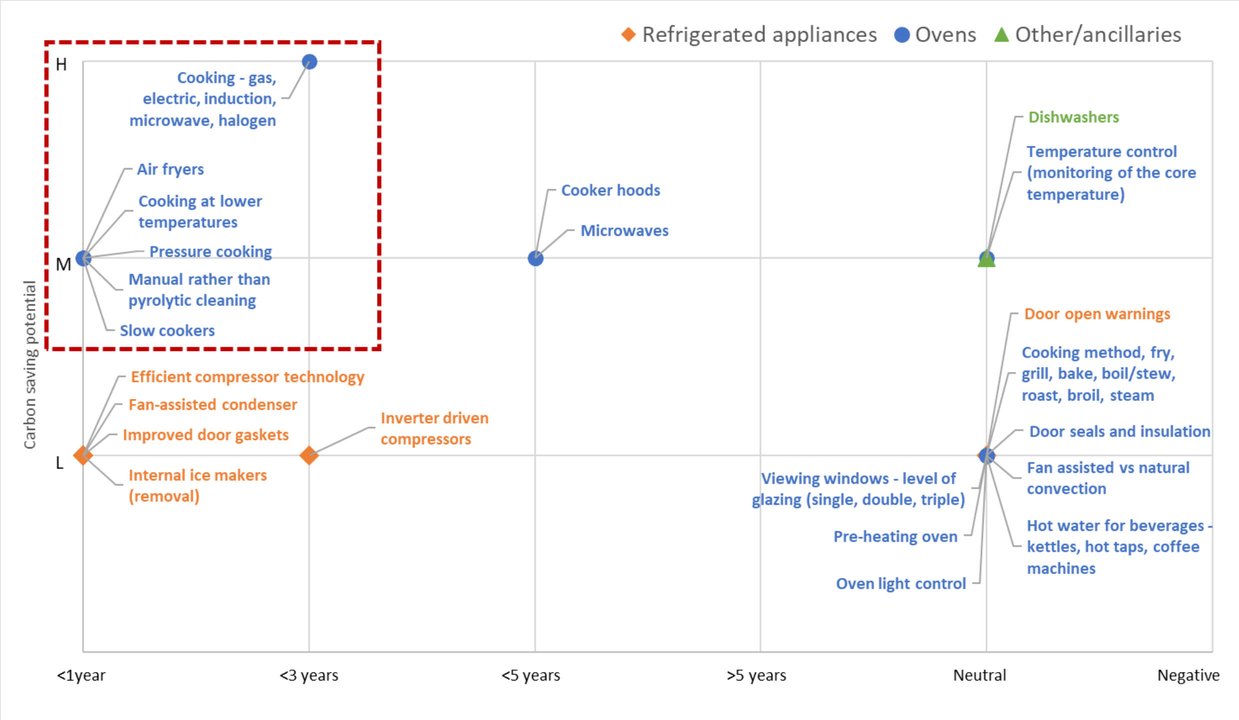


Figure 12. Domestic kitchen options (TRL 8-9) to reduce carbon emissions.

8.2. What strategies should we apply to get to zero carbon in domestic kitchens?

Technologies that could save carbon emissions were selected from Figure 12. These included moving from carbon fuels to grid electric cooking and more efficient cooking methods as these were shown to be the most promising options for kitchens. We also added an assessment of the impact of changing the heating system in the kitchen and applying more efficient electrical appliances.

The impact of applying these technologies was assessed across 6 European countries (UK, France, Lithuania, Norway, Italy, Poland).

WHY WE MODELLED A TYPICAL KITCHEN

To be able to assess the technologies and strategies for a kitchen, we need to consider the time of the year and location. This can only be assessed though an integrated modelling approach to identify overall carbon emissions and energy savings. This combines the operation of the refrigeration and other items such as cooking appliances and dish washing.

8.2.1. Modelling of the kitchen

EnergyPlus with Openstudio as the ‘front end’ was used to the provide heating requirements for the kitchen throughout the year, thus allowing carbon emissions to be calculated. Complete information on the modelling approach is shown in Section 11. The modelling was based on a typical kitchen based in the UK. The inputs to the model are shown in Section 11.1.2.

8.2.2. Baseline kitchen

The baseline kitchen contained a:

1. Cooker
2. Microwave
3. Kettle
4. Refrigerator
5. Dishwasher

The baseline kitchen details are presented in Table 4 and the schedule for the operation of appliances is shown in Figure 13. Full details of the modelling inputs are provided in section 11. All emissions were from fuels as it was assumed there would be no impact of any fugitive emission from the refrigerator using isobutane (R600a) refrigerant.

Table 4. Baseline kitchen details in each country.

Country	France	Italy	Lithuania	Norway	Poland	UK
Weather file location	Paris	Rome	Kaunas	Oslo	Warsaw	London
Floor area (m^2)	13.4					
Height (m)	2.5					
Heating fuel	NG	NG	Biomass	ASHP	Coal	NG
Heating set point	18°C (between 6h and 23h) 16°C (between 23h and 6h)					
Fuel for cooking	Electric	NG	NG	Electric	NG	NG
Oven power (W)	2130	3270	3270	2130	3270	3270
Other appliances:	Electric					
Microwave power (W)	1250	1250	1250	1250	1250	1250
Kettle power (W)	2000	2000	2000	2000	2000	2000
Refrigerator power (W)	44.5	44.5	44.5	44.5	44.5	44.5
Dishwasher power (W)	1800	1800	1800	1800	1800	1800

NG – natural gas

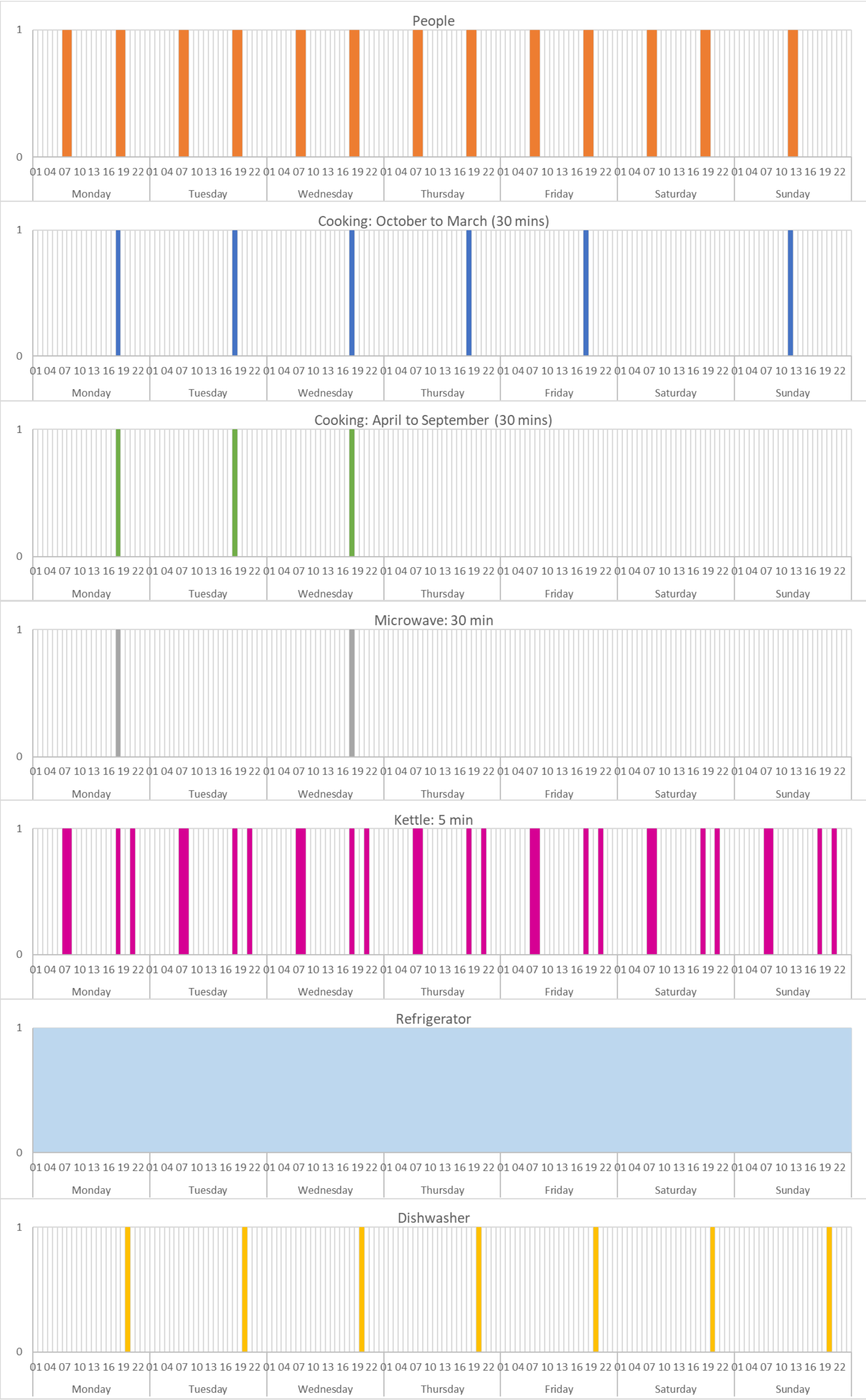


Figure 13. Appliance usage schedule.

8.2.3. Scenarios modelled

Impact of climate change. The impact of climate change alone between 2020 and 2050 was calculated. This assumed no other changes to the baseline kitchen were applied. An RCP 4.5 climate change scenario was used to simulate changes to the weather (temperature and humidity). This is described by the Intergovernmental Panel on Climate Change (IPCC) as a moderate scenario in which emissions peak around 2040 and then decline.

Impact of grid carbon intensity (CI). The impact of changes to the grid CI were calculated for the baseline kitchen in 2020,2030, 2040 and 2050. It was assumed that there were no other changes to the baseline kitchen. The relevant electrical CI was applied for each country for the different years (obtained from government projections in each country). It was not possible to identify predicted electrical CI into the future for Norway or Italy and so it was only possible to assess impact for 2020 for these countries. For Poland, it was only possible to obtain electrical CI up until 2040 (Figure 14).

Impact of applying technologies. The following technology scenarios were modelled when added to the baseline kitchen in all the countries where relevant (some counties already had some technologies used in the baseline):

1. Space heating with air source heat pumps (ASHP)
2. Electric resistive cooking when not already used: Resistive cooking was 73% more efficient than gas cooking (gas was 47% efficient)[32].
3. Electric Induction cooking: Induction cooking was 84% more efficient than gas cooking[32].
4. More efficient cooking appliances: the cooking appliances (cooker, microwave and kettle) used 10% less energy.
5. More efficient refrigeration: the refrigerator used 10% less energy.
6. More efficient dishwasher: the dishwasher used 10% less energy.
7. ASHP, induction cooking, more efficient cooking appliances, refrigeration and dishwasher all combined.

[32] Khalid, R. and Foulds, C., 2020. The social dimensions of moving away from gas cookers and hobs: Challenges and opportunities in transition to low-carbon cooking. London: UK Energy Research Centre.

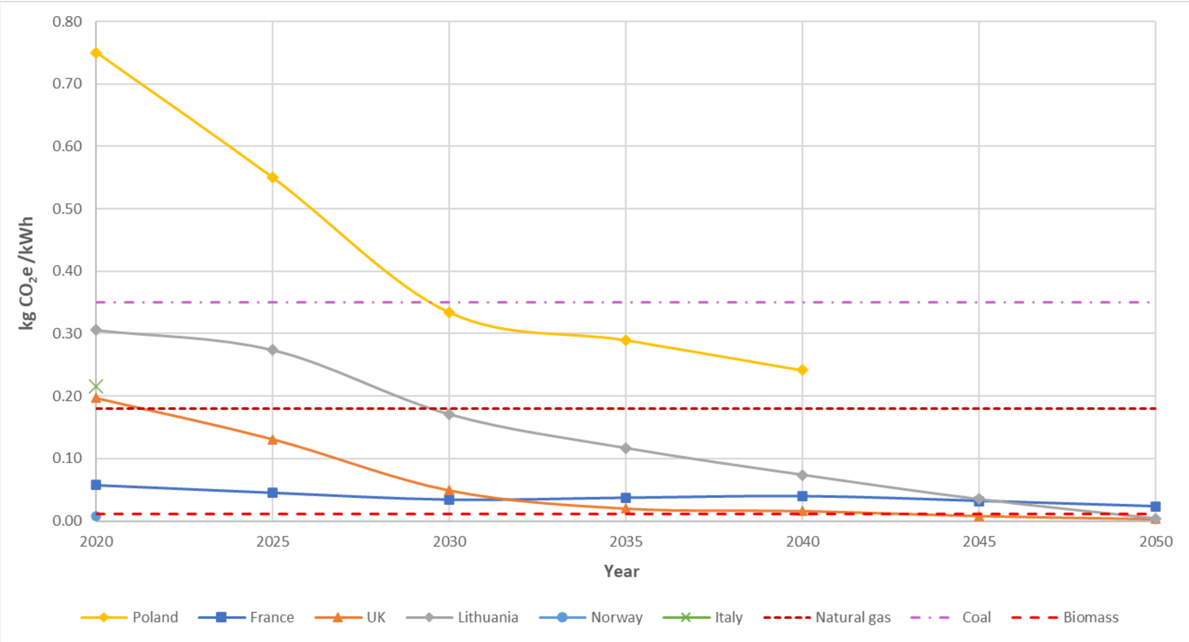


Figure 14. Carbon intensity factors used to calculate carbon emissions from the kitchen.

8.2.4. Cumulative carbon emissions

Predicted carbon emission savings were integrated over time, to show accumulated carbon emission reductions. Although there are ambitions to reduce net carbon emissions to zero by 2050, this is a rather arbitrary target and the rate at which this is achieved is also important. The earlier that carbon emissions are reduced, the less overall emissions occur, which is a significant factor in reducing global warming. By applying the combined scenarios, we calculated the total carbon savings that can be achieved from 2025 to 2050 and the impact of accelerating the move to climate friendly technologies.

8.3. What we found from the modelling

8.3.1. Can the 'do nothing' scenario achieve zero carbon?

The impact of climate change and electrical CI were considered individually to assess impact.

Impact of climatic temperature change: Figure 15 shows the impact of climatic temperature change alone on annual energy consumption for the 6 locations in 2020 and 2050 (2040 for Warsaw). The graph presents information divided into heating, lighting, equipment (oven) and other equipment (refrigerator, kettle, microwave and dishwasher). It should be noted that different fuels sources are used in the 6 countries and so the annual kWh totals are not truly comparable as we are comparing gas, biomass and coal. The energy consumption was measured at the entry to the building, therefore efficiency of fossil fuel boilers was considered and the electricity consumption was the final energy consumption at the building not the energy consumption at the power stations. The figures are presented to show the impact of increased ambient temperature between 2020 and 2050 (2040 for Warsaw) within each country.

The reduction in energy consumed in 2020 and 2050 were relatively small (overall 2.7 to 5.1%). The was due to the increasing climatic temperature reducing the need for space heating (which was reduced by between 7.9% and 13.7%).

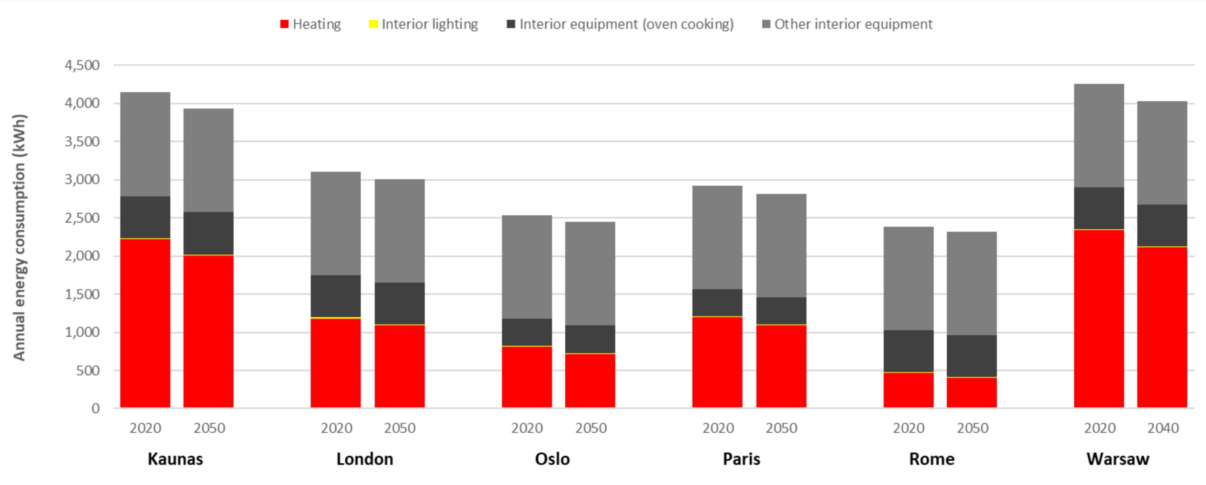


Figure 15. Impact of climatic temperature change on energy consumed between 2020 and 2050/2040 for the 6 locations studied.

Impact of changes to electrical grid CI: changes to electrical grid CI over time had most impact on emissions for the kitchens in Warsaw, London and Kaunas (Figure 16). The impact in Paris was less significant as the electrical grid CI only reduces marginally between 2020 and 2050.

Although carbon emissions were reduced in the locations assessed, it would not be possible to achieve zero carbon emissions in any of the locations due to the grid CI not reaching zero carbon or due to the utilisation of fossil fuels (as emission intensity of these are constant).

> **DO NOTHING SCENARIO**
>
> *If the case study kitchen made no changes between 2020 and 2050, it is only possible to reach close to net zero if electricity was used as the main heating, cooking and appliance fuel source.*

The accumulated carbon emitted between 2020 and 2050 for the 'do nothing' scenario is presented in Table 5. Clearly Paris had the lowest accumulated carbon emissions and Warsaw the highest.

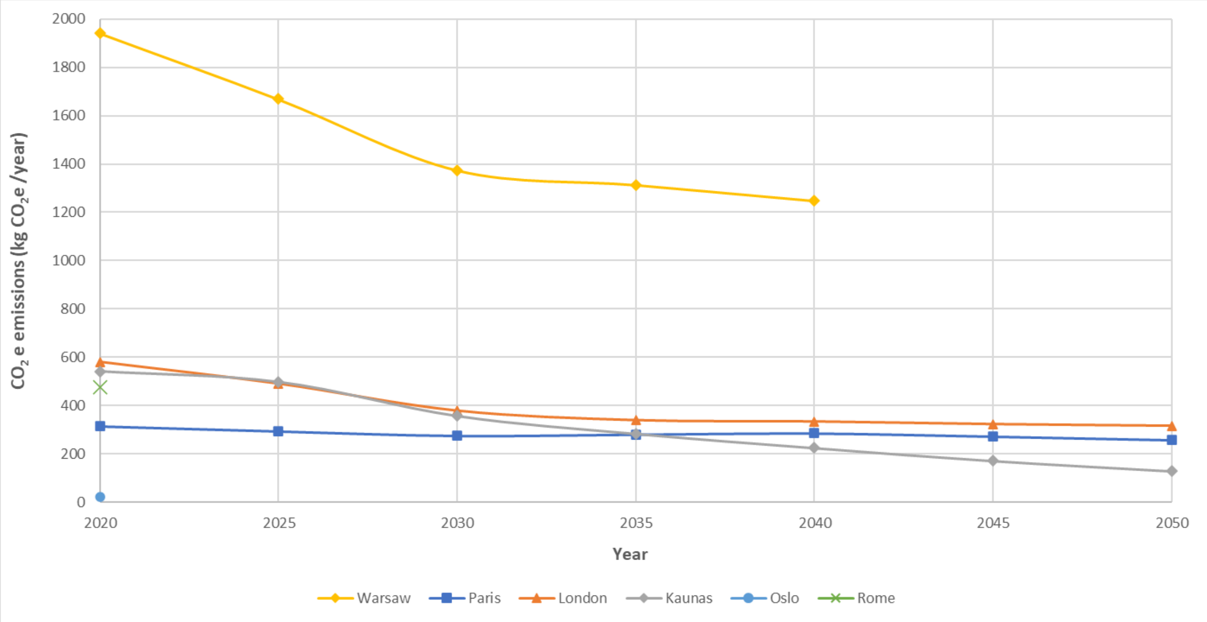


Figure 16. Impact of grid carbon emission factor change on total carbon emitted by the kitchen in the 6 locations studied.

Table 5. Accumulated carbon emitted between 2020 and 2050 (2040 for Warsaw) for Kaunas, London, Paris and Warsaw for the 'do nothing scenario'.

	Accumulated $kgCO_{2e}$ emitted between 2020 and 2050/2040
Kaunas	9,361.13
London	11,553.38
Paris	8,442.97
Warsaw (2040)	29,826.25

8.3.2. How much energy and carbon can be saved by the application of alternative and more efficient technologies

Each technology was applied individually and in combination to the baseline kitchen and the impact was assessed in 2020. In terms of energy consumption, it is not valid to compare the varied baseline fuel sources against each other purely in terms of energy, as for example, 1 kWh of gas is not comparable with 1 kW of electricity, which may have used many kWhs of gas in its production. The only country where a true comparison between the baseline and alternative technologies can be applied is Norway as all fuel used in the kitchen was electricity, including the baseline. For the other countries which applied gas, coal or biomass, the impacts of the technologies can only be compared in terms of carbon emissions. The impact of the technologies on electricity use and carbon reductions are shown in Figure 17 and Figure 18 respectively. The impact to 2050 for the combined technologies is shown in Figure 19.

The carbon emissions from the kitchens compared against the baseline in 2020 are shown in Table 6. Applying the technologies all reduced carbon emissions in London, Oslo and Rome. This was because the product of efficiency and grid CI in these countries mean that when electrifying the heating and cooking that there were benefits.

Electrification in Paris was in almost all cases beneficial. The only technology that alone did not reduce carbon emissions was more efficient refrigeration where the carbon emissions marginally increased. This was due to the efficient refrigerator generating less heat which had to be replaced by more gas heating. The gas had a higher CI than electricity (0.18 kgCO_2e/kWh compared 0.057 0.18 kgCO_2e/kWh for electricity in France).

In Kaunas where biomass was used for heating there was no benefit of applying an ASHP in 2020 as the CI for biomass was so much lower than the CI of the electricity grid. Once the grid in Lithuania decarbonises this will change. In countries with current high electrical grid CIs (Lithuania and Poland) the benefits of moving from gas cooking to electrical cooking options did not always reduce carbon emissions as the grid CI was higher than that for gas. However, as the grid decarbonised in these counties, this will change.

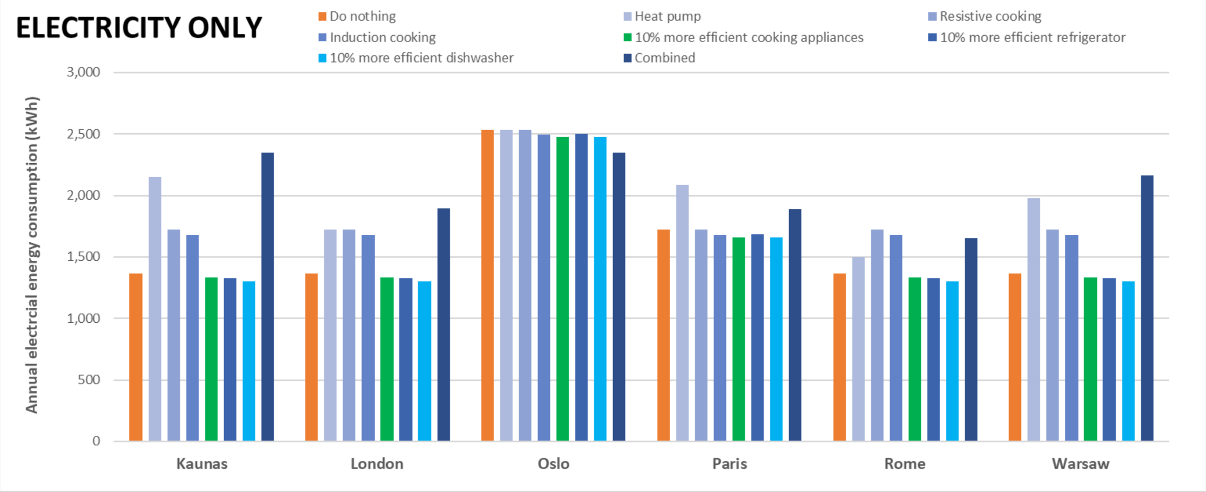


Figure 17. Impact on electrical energy consumption of technologies individually and applied together for the 6 locations.

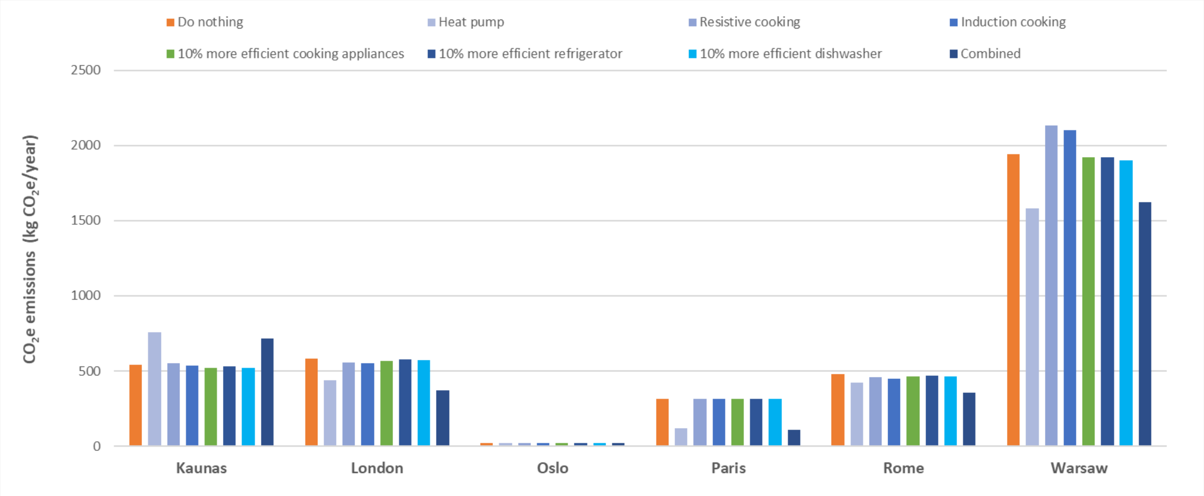


Figure 18. Impact on carbon emissions of technologies individually and applied together for the 6 locations.

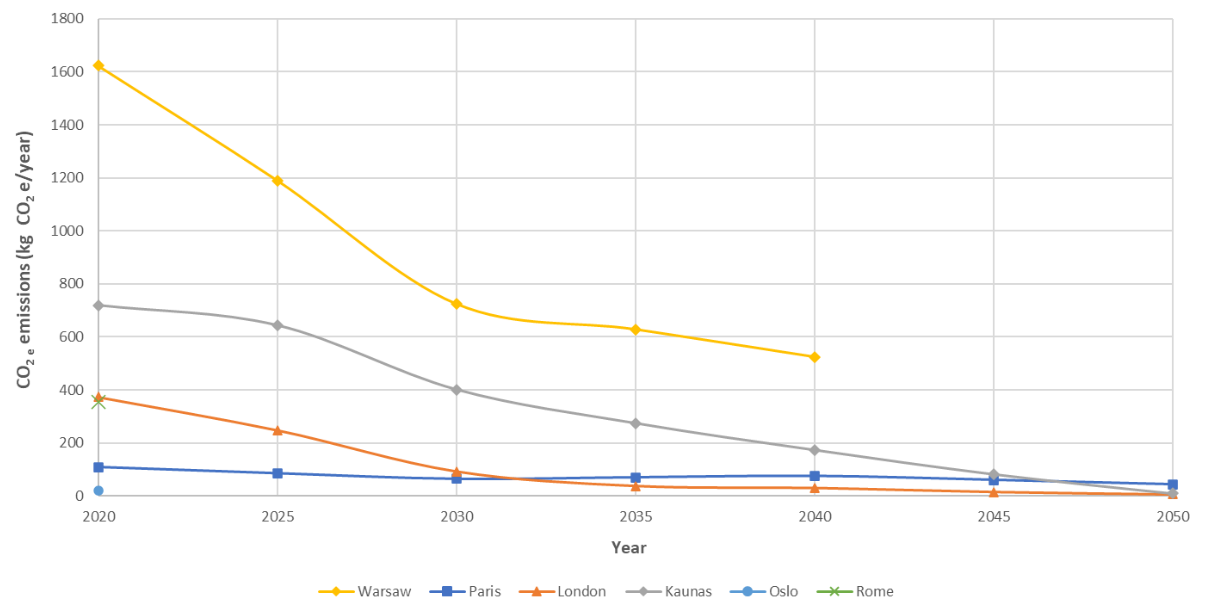


Figure 19. Impact of grid carbon emission factor change on total carbon emitted in the combined scenario in the 6 locations studied.

Table 6. Carbon emissions for applied technologies in 2020.

Negative percentages indicate an increase in emissions		Kitchen in:					
		Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline	kg CO_2e/year	541	581	20.3	315	477	1,942
ASHP	kg CO_2e/year	757	438	20.3	120	421	1,580
	% change	-39.9%	24.7%	N/A	62.0%	11.7%	18.6%
Resistive cooking	kg CO_2e/year	552	559	20.3	315	457	2,134
	% change	-2.1%	3.8%	N/A	N/A	4.2%	-9.9%
Induction cooking	kg CO_2e/year	538	551	19.9	314	447	2,104
	% change	0.6%	5.2%	1.6%	0.4%	6.2%	-8.4%
More efficient cooking appliances	kg CO_2e/year	522	569	19.8	314	462	1,920
	% change	3.5%	2.0%	2.3%	0.1%	3.2%	1.1%
More efficient refrigeration	kg CO_2e/year	529	578	20.0	316	471	1,923
	% change	2.2%	0.6%	1.2%	-0.4%	1.3%	0.9%
More efficient dishwasher	kg CO_2e/year	521	571	19.8	314	463	1,900
	% change	3.7%	1.7%	2.3%	0.4%	2.8%	2.1%
Combined	kg CO_2e/year	718	373	18.8	108	355	1,623
	% change	-32.7%	35.9%	7.2%	65.6%	25.5%	16.4%

8.3.3. How much carbon can be saved

The total carbon emitted between 2020 and 2050 for the kitchen in Warsaw, Kaunas, London and Paris for the 'do nothing' and combined technologies different application times is shown in Figure 20. In most cases more carbon is saved if the technologies are applied early. However, this is only the case in countries where the grid decarbonises rapidly.

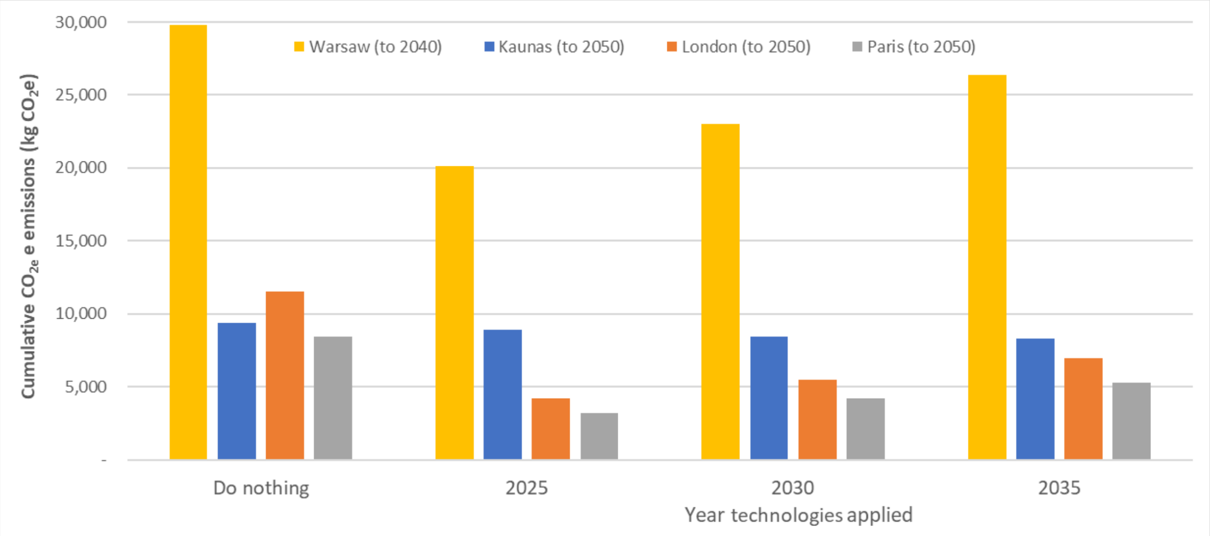


Figure 20. Carbon emitted by the kitchen in different locations from 2020 to 2040/50.

8.4. Recommendations

The modelling of the varied technological options in the 6 locations provided information on the best technologies to apply in domestic kitchens.

The electricity-based technologies applied reduced carbon emissions if the electrical grid CI in a country was less than the baseline fuel CI and/or the technology was very efficient. Applying the technologies was beneficial in most locations but this was found to not always the case. For example, in Kaunas, which was considered in the model to use biomass for heating, the CI for biomass was lower than the CI of the electrical grid and will remain so for many years. This does not necessarily mean that biomass is the best option as there are other impacts to consider associated with biomass (such as sustainability of the source material). Each fuel source should be considered holistically, and its use balanced against the various impacts its use may have.

OUR RECOMMENDATIONS

- *Moving to an ASHP for heating is the lowest carbon option in countries where currently gas or resistive heating is used.*
- *Always purchase the most efficient equipment that is available on the market.*
- *In locations where grid carbon emissions are low (London, Oslo, Paris, Rome) it is almost always beneficial to apply electricity based technological interventions as rapidly as possible to ensure cumulative carbon emissions are maximised.*
- *Benefits of interventions vary according to location and when they are applied. Carbon emissions are very dependent on the electrical grid emissions factor in a country and the emissions from the fuel type applied. Therefore, always consider individual situations.*

Carbon savings in 2020 differed across the 6 locations examined. The greatest combined savings were in Paris (65.6%) due to moving from gas heating and the low electrical CI in France. In Warsaw the carbon emissions increased due to the high electrical CI of the grid. However, as the grid decarbonises in Poland this will change, and carbon reductions will be achieved by applying these technologies. In Norway which is already predominantly electrified there was limited benefit of any of the technological interventions with only a combined carbon saving of 7.2% in 2020.

A great deal of decarbonisation should occur naturally through reductions in the electrical CIs. In Lithuania and the UK, these are predicted to reach almost zero by 2050. France already has a low electrical CI, and this was not predicted to change dramatically through to 2050. Although we were unable to find how electrical CI would change in the future in Norway it is already very low. There is no evidence that Norway will change the way they generate electricity and so it seems highly likely that the electrical CI in Norway will remain low moving forward. No official information on electrical CI was available for Italy. The trend in Italy over the past 20 years has been for electrical CI to decrease and if this trend continues then domestic homes will also be much lower carbon emitters in 2050[33]. The country that stands out as not achieving the low electrical CI as fast as other European countries

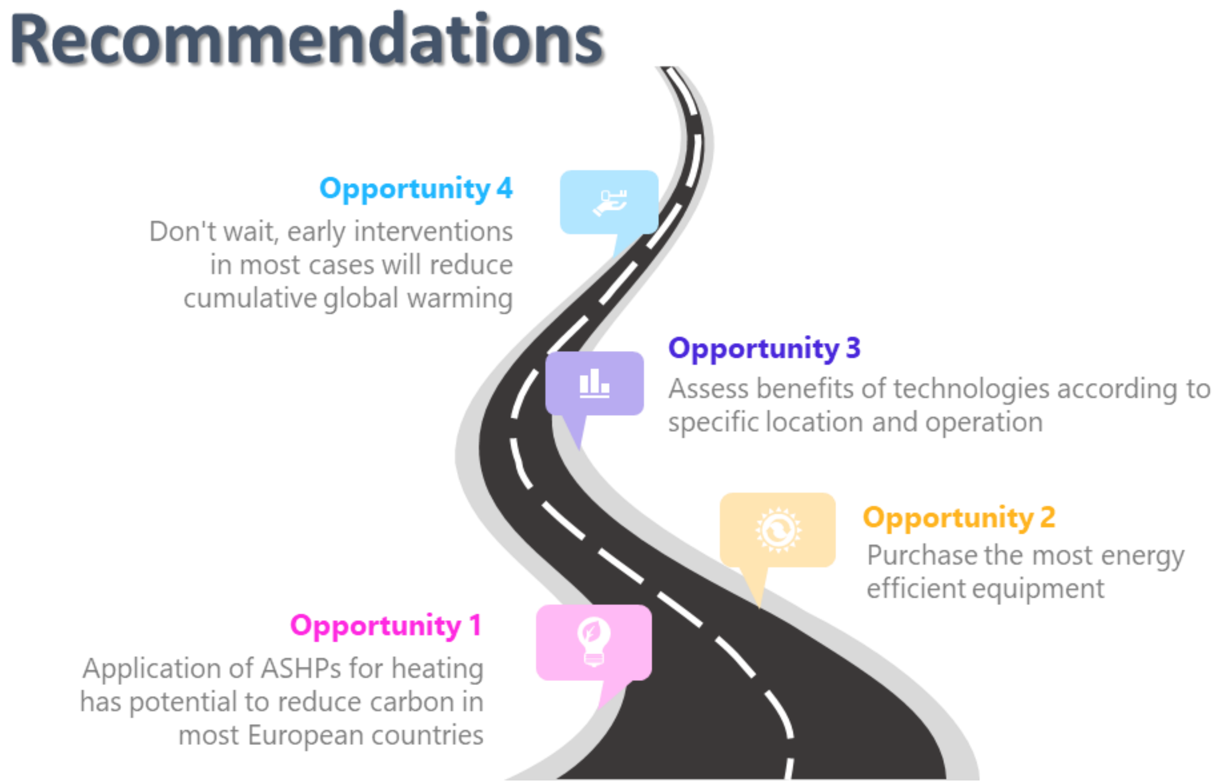
[33] https://www.statista.com/statistics/1290244/carbon-intensity-power-sector-italy/

is Poland. Although the grid is decarbonising in Poland it is still predicted to be at a relatively high level in 2040 (no data for 2050 could be identified for Poland).

Without the electrical CI decreasing there was no potential for countries (apart from Norway where the CI of the electricity grid is already very low, having zero carbon kitchens. Projecting into the future, kitchens in the UK, Lithuania and France (together with Norway which is already almost zero carbon) could be close to zero carbon in 2050. The exception is Poland where the electrical CI is decreasing but is still significantly higher than the other countries examined.

The road map investigated the options which were assessed as being most economic. Most of the opportunities to apply technologies were only applicable to new equipment and so uptake is related to replacement rates of appliances and heating equipment. This may delay uptake of new technologies unless incentives are in place for householders to encourage uptake of low carbon options.

Overall, one clear outcome from the modelling was that not all interventions had the same impact in the different countries evaluated. This was due to several factors which included the electrical CI in each country and the baseline fuels. It is essential to assess each kitchen individually to ascertain the most beneficial interventions. It was clear from the modelling that in most cases it is important to act quickly to achieve the greatest cumulative carbon emissions and that applying low carbon interventions should be prioritised at the earliest opportunity. However, in terms of reducing carbon, electrification should only be applied once the product of the carbon intensity and efficiency of the equipment is lower for electrical equipment than fossil fuel equipment.



9. DETAILED TECHNOLOGY/STRATEGY REVIEWS

9.1. Refrigeration

9.1.1. Acoustic refrigeration

Although thermoacoustic refrigerators have the potential to cover the whole spectrum of refrigeration down to cryogenic temperatures, it is most likely to be used for low-capacity equipment initially (Tassou et al 2010).

The main benefits are that they use environmentally safe, inert gasses such as air, Argon and Helium. Systems can be open or closed; closed systems have shown the greatest potential to date. Two variants of the closed system are available:

1. Closed, standing wave system:

   The driver is typically a loudspeaker. Sound waves are used to create a resonant standing wave within the "stack". As the gas oscillates back and forth within the stack it creates a temperature difference along the length of the stack due to expansion and compression by the sound wave.

2. Closed, travelling wave system:

   This type of travelling wave device was used on the Ben and Jerry's ice cream cabinet. The driver for this system is a motor and piston. Unlike the standing wave system, the temperature difference for this system occurs in a regenerator rather than a stack. The system is designed so that the air will oscillate between the hot and cold heat exchangers through the regenerator matrix as the pressure is increased and decreased.

Work at Penn State University has developed a demonstrator acoustic refrigerator for storage of ice cream which is currently undergoing further development with the view to future commercialization (Poese et al, 2004).

Prototype units have been developed, the most famous being the Ben and Jerry's ice cream freezer (2004). Work is still needed to increase COPs to the level of vapour compression systems (Defra ACO403). Flow through systems (also referred to as open systems) would eliminate heat exchangers and reduce system complexity and cost but more research is required into this configuration (Tassou et al 2010). Efficiency achieved so far is 0.1 to 0.2 of Carnot's efficiency; conventional systems achieve 0.33 to 0.5 (Wetzel and Herman 1997).

Inefficiency in systems already built and tested is generally cited as being a result of inadequate tolerances in assembled apparatus, whereas heat exchangers are cited as the cause for high cost and complexity.

Development of flow-through (open) systems could also eliminate heat exchangers and reduce system complexity and cost (Tassou et al 2010) but these require acoustic dampers which result in significant restrictions to gas flow.

Ismail et al (2021) recently reviewed several newer refrigeration technologies including thermoacoustic and concluded that to achieve high efficiency, a high temperature heat source is required. Current systems were reported to achieve a COP of up 3.2 and have a TRL of 4. Current systems cannot yet be produced economically with current fabrication technologies.

Developments are needed in the design of stacks, resonators and compact heat exchangers for oscillating flow. However, although more recent work has been caried out to improve component performance (for example Yahya et al, 2017) the technology does not seem much nearer to being commercialised. Spoor et at (2021) corroborated this by concluding that although thermoacoustic systems have some advantages, the argument to use them was not compelling enough compared to established technology. They concluded that the main potential was for zero-boiloff liquid hydrogen storage followed by waste-heat powered air conditioning. Other applications had relatively lower potentials for commercial refrigeration.

Unless legislation prevents the use of more efficient vapour compression systems (for environmental or safety reasons) the efficiency of acoustic refrigerators will need to be improved to exceed that of vapour compression systems to enable uptake of this technology (Tassou et al 2010).

Scope 1 emissions savings (% or another quantifiable metric)	100%
Quality of scope 1 emissions information	Good
Scope 2 emissions savings (% or another quantifiable metric)	Negative (less efficient than conventional systems)
Quality of scope 2 emissions information	High
TRL level	4
Maintainability issues	Not known
Legislative concerns	None
Payback time (years)	not commercialised.

9.1.2. Advanced controls

Applying smart control and logic to domestic refrigeration has the potential to optimise energy use. Today, most household refrigerators use conventional (on/off type) controllers for controlling the compressor. Better control is claimed to be able to save 2.5% of the energy for active and 4.5% of energy for passive user-profiles whilst still maintaining the desired cabinet temperatures (Kapici et al, 2022). The refrigeration system applied integrated machine learning-based forecast of door opening events with fuzzy logic controllers. The authors first applied a Bayesian neural network, logistic regression, and decision tree techniques to predict user behaviour. After one week of training the system could predict the door opening events with higher than 80% accuracy. They secondly applied fuzzy logic controllers to use the door opening predictions to regulate parameters of the main refrigerator controller (maximum compressor speed, air temperature setpoint of fresh food compartment, and time offset to control the time of defrosting events).

A similar type of study carried out by Belman-Flores et al (2019) found energy savings of 3% by applying a fuzzy logic system to control the speed of the compressor. The controller assessed the frequency and duration of the door openings. This ultimately reduced the compressor speed to a minimum value and reduced the number of times the compressor was turned off when the door was open.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	Good
Scope 2 emissions savings (% or another quantifiable metric)	2.5-4.5%
Quality of scope 2 emissions information	Medium
TRL level	7
Maintainability issues	None
Legislative concerns	None
Payback time (years)	No information available but anticipated to be low

9.1.3. Charge optimisation

Dmitriyev and Pisarenko (1984) showed that the rate of decrease of COP with over-filling is higher than that with under-filling the system. Thus, exceeding the optimum charge of refrigerant by 10% caused a decrease of COP of 6-12%, whilst decreasing the charge of refrigerant by the same amount decreased COP by only 4-6%. A similar result was found by Hao et al (2021) who found that by optimising the charge in a domestic fridge-freezer that they could save 10% of the energy.

Bjork and Palm (2006) stated that with too low a charge in a refrigerator under test conditions, the evaporator superheat increased and with too high a charge, the suction line became cold. Both cases lead to increased energy consumption. Increasing charge from 31 to 40 g increased the energy consumption by 31% with an ambient temperature of 25°C.

Overall savings are dependent on the initial optimisation of the refrigerant charge. There is limited information to suggest that refrigerant charge is poorly optimised. Potentially in the past this could have been the case as domestic refrigerator energy consumption measurement was made at 25°C. The new test standard now applied for energy labelling applies 16 and 32°C to overcome this issue.,

Pisano et al (2015) found for light commercial appliances that from an energy efficient perspective that an overcharged system was more stable (as long as the suction temperature was above the ambient dew point limit). Ambient temperatures of between 20°C and 35°C were modelled and the relative COP for varied charges presented. The results indicated that the maximum COP reduced by up to 10% for each 5°C increase in the ambient temperature with a corresponding refrigerant charge variation of about 5 g.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Up to 31% has been reported, but such issues are unlikely to be an issue in most refrigerators today
Quality of scope 2 emissions information	Low

TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	No quantifiable information available, but cost of reducing or increasing the refrigerant will be minimal (but probably is applied by all manufacturers)

9.1.4. Dampers

Operating a refrigerator with variable temperature compartments (e.g. fridge-freezer) from one refrigeration systems has challenges as the compressor suction pressure has to operate at the condition required by the lowest temperature compartment. Li et at (2020) examined the use of a novel air distribution system and air supply dampers. The main impact of the work was to prove temperature control could be achieved using the novel air distribution system, but the authors stated that energy would also be decreased. However. this was not quantified.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Not quantified
Quality of scope 2 emissions information	Low
TRL level	4
Maintainability issues	Potential for dampers to ice up or stick
Legislative concerns	None
Payback time (years)	Not quantified

9.1.5. Novel defrost systems

Traditionally defrosting of domestic refrigerated appliances is normally initiated by a timer or simple fixed logic e.g. after a certain number of on-cycles of the compressor. However, the need for defrosting can be sensed or better predicted and only initiated when required. This avoids excessive defrosting and energy consumption associated with recovery from defrosts. For example, electric-field sensors can be used for frost detection (Sanchez, 2008). Alternatively, prediction of defrost need can be achieved using more sophisticated algorithms including factors such as number of door openings, compressor operation time and room temperature. Control systems can also be trained using fuzzy logic (Barthel 2012).

Adaptive defrost control has been developed on a beverage refrigerator which adjusts the operation of the appliance to ambient conditions or usage (Vitor et al, 2020). Using an algorithm that assesses power, door opening, and temperature it was possible to optimise defrosting and reduce overall power consumption by 0.8% in steady state and 2.6% when the appliance doors were opened.

Methods to prevent heat gain to the appliance during defrosting have been proposed by Zhao et al (2019). They suggested applying a special cover to block the infiltration passage to the evaporator fan in a frost-free freezer during defrosts. They found that the defrost duration was reduced by 3.4%, the temperature rise within the appliance storage area reduced 1.6°C during the defrost cycle and the overall energy consumption for defrost and recovery cycles was reduced by 1.9%. They also suggested that further optimisation could be made by adjusting the delay of the fan starting after defrosting.

Yoon et al (2018) investigated the use of pulsating defrost heaters to improve defrosting efficiency. Of the systems considered the best performance was obtained by the high-power sheathed heater with individual pulsating mode. The temperature variation was 5.0°C, and the defrosting efficiency improved by 15%. The impact of controlling the power to defrost heaters was also further assessed by Jeong et al (2021). They found that it was possible to optimise the efficiency of the defrost heater (convective or radiant) and increase efficiency by 6.7%. By doing this the maximum temperature on the evaporator decreased and the temperature distribution on the evaporator was more uniform. Depending on the level of frost accumulatio the optimum power required varied and could be optimised.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	1.9-6.7%
Quality of scope 2 emissions information	Medium
TRL level	7-8
Maintainability issues	Unlikely
Legislative concerns	None
Payback time (years)	Not quantified

9.1.6. Door open warnings

Door open warnings can be audible and/or visual alarms which alert the user to a door which has been left open. On some models of fridge-freezer, there may be a door open warning for one compartment but not the other.

When present, the warnings not only help to avoid temperature abuse, but also excessive moisture ingress, which particularly in the freezer results in frosting of the evaporator. If the door opening period is extensive, frosting can be severe and difficult or lengthy defrosting will be required, with associated increases in energy consumption.

It is particularly difficult to indicate energy savings for this technology as the savings are entirely dependent on the time that the appliance door is left open with and without a warning. However, it is clear that once a door is left open for a period of time, that the appliance will begin to operate continually. A typical appliance would operate approximately 50% of the time and so if the door was left open for any period of time the energy consumption would approximately double.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Not able to quantify
Quality of scope 2 emissions information	Low
TRL level	9
Maintainability issues	None identified
Legislative concerns	None
Payback time (years)	Not able to quantify

9.1.7. Dual-loop system

Most fridge-freezers operate using one refrigeration circuit with one compressor (Figure 1). However, using separate refrigeration circuits and compressors for the refrigerator and freezer has been considered as a more efficient option (dual loop system). The major issue with this system is the cost and space requirements of an additional compressor. Also, the fact that the two compressors will probably have a lower overall efficiency (isentropic, volumetric) than one larger compressor that would be used in a single cycle may reduce overall efficiency. Nevertheless, some theoretical and practical experiments have shown energy savings for a dual loop system. Savings of 20% were predicted (Smith et al, 1991; Bare et al, 1991) and actual savings of 16% achieved by (Pedersen et al 1986; Pedersen et al, 1987). However, these results are from over 25 years ago when compressor technology was still developing. Several other pieces of work were also identified that suggest that dual loop systems are beneficial in terms of energy, but these applied old refrigerants such as R12 or rotary compressors which are not applicable to today's appliances (Won et al, 1994). It remains to be shown whether these results would still be applicable with modern day compressors, especially variable speed compressor, which might compensate for the lower capacity.

More recent work carried out by Tang et al (2018) has found that to make a dual loop system energy efficient on/off control is not best suited to this design. It was stated that a semi-compulsive control strategy (the freezer uses an on-off strategy, and the refrigerator operates depending on whether the freezer is on or not) could save 2.2% of the energy compared to a compulsive control strategy (refrigerator operates while the freezer is on). The system examined had an added sub cooler between both systems where the freezer liquid line was subcooled by the refrigerator circuit (Figure 21). This links the operation of the 2 systems and adds efficiency.

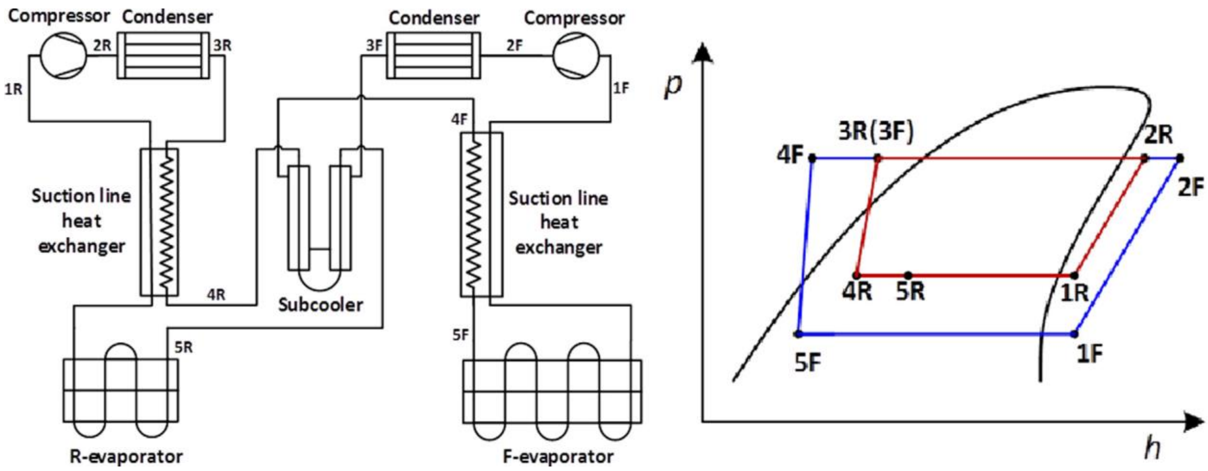


Figure 21. Schematic of coupled dual-loop refrigerator system (left) and p–h diagram (right) (from Tang et al, 2018).

Fang et al (2019) followed a similar approach by installing a sub cooler between the 2 refrigeration circuits. They also applied a R290/R600a mixture which was preferentially separated so that R600a rich refrigerant was supplied to the refrigerator and R290 rich refrigerant supplied to the freezer (Figure 22). The cost for the modified system was 21% higher but the energy use was 26-35% lower (depending on condensing temperature).

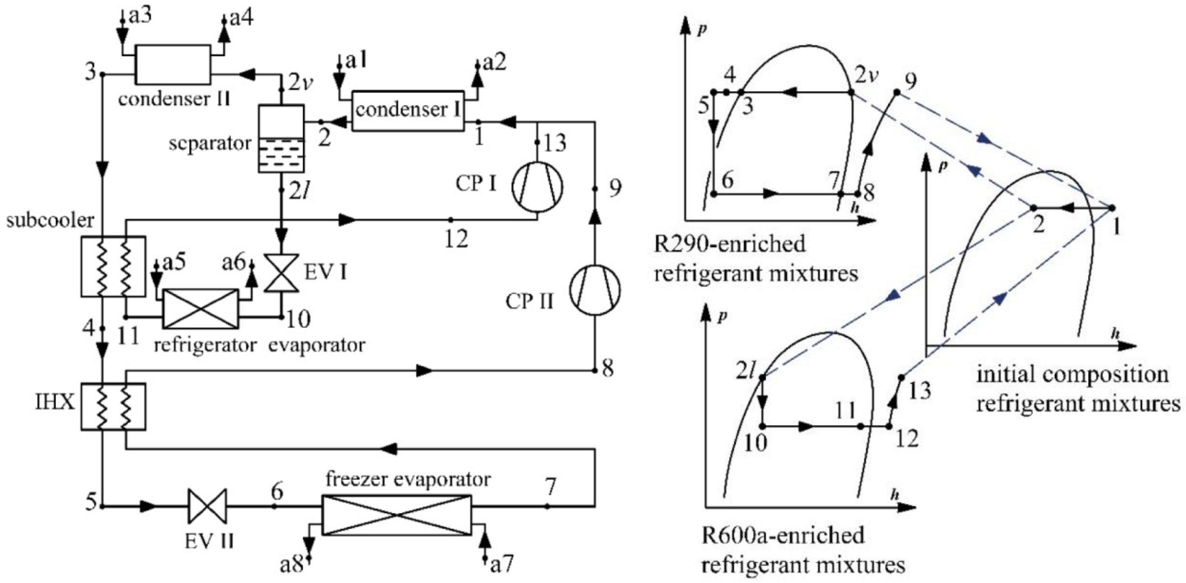


Figure 22. Schematic diagram of modified refrigeration cycle (MRC); (left) Cycle pressure-enthalpy diagram of MRC (right).

Based on experimental results, the energy consumption of an optimised dual-loop cycle was decreased by 14.2%, compared with that of a bypass two-circuit cycle in the same refrigerator/freezer platform (Yoon et al, 2012a). Yoon et al 2012b found that an optimised dual-loop cycle using R600a and hydrocarbon (HC) mixtures used 14.2% and 18.6%, respectively less energy, compared with that of a bypass two-circuit cycle using R600a in the same fridge-freezer platform.

Scope 1 emissions savings (% or another quantifiable metric)	Negative (likely to be higher)
Quality of scope 1 emissions information	Medium
Scope 2 emissions savings (% or another quantifiable metric)	Up to 35% (very variable dependent on design and baseline comparison)
Quality of scope 2 emissions information	Medium
TRL level	4
Maintainability issues	None
Legislative concerns	None
Payback time (years)	0.6 years (Fang et al)

9.1.8. Dynamic demand/response

Reducing the demand on the electrical grid can avoid carbon intensive generation which makes up a large part of the generation when demand is high and renewable generation is low. Increasing demand when renewable generation is high, can allow all of available renewable generation to be used, whereas in some circumstances renewables are turned down to stop overload of the grid, wasting renewable resources. This is likely to become more of an issue as the proportion of renewables on the grid increase. At times of high renewable generation, energy-using systems which have storage capacity can be run longer to build up reserve capacity, this allows them to be turned off at times of high demand.

Dynamic demand is where the demand for electricity is reduced when the frequency of the electrical supply drops. When frequency drops, it means that energy generation is struggling to keep up with demand, so dynamic demand helps by effectively shedding load.

This should not be confused with demand response (or arbitrage) describes changes in electrical usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time. A common example is cold stores that shift load while providing a buffer which can be used to balance off-cycling during peak times. Cold stores, freezers and refrigerators can offer flexibility as they can be ‘over cooled’ and then switched off for 30– 60 minutes, possibly more if not opened or the food creates a thermal battery.

Both dynamic demand and demand response have the same goal to adjust demand on the grid to help the grid run more efficiently, they just use a different method to do this, hence why they are considered together in this section.

If the food itself cannot be used to provide the thermal damping, additional thermal storage can be used. Arteconi, Hewitt and Polonara (2012) suggested that cooling thermal energy storage such as water, ice or an eutectic salt solution could be used.

Typically, in the UK, demand rises at the start of the working day reaching a plateau between 9:00 and 16:00, and rising again between 16:00 and 17:30 owing to lighting loads and increased domestic demand. Lowry (2018) showed that demand is not a perfect predictor of CI, with a correlation coefficient of only 0.66 for a data period for 1 week in January 2017. He developed models to predict the period of high CI. The best models were able to predict the peak CI period (+/- half hour) 1 day in advance with a success rate of 25%, compared to prediction by random chance of 6%. He found that using the best model to determine the timing of demand reduction can achieve an improvement in carbon emissions reduction of 20%.

In smaller appliances the use of thermal energy storage is often stated as an important factor in the application of dynamic demand. Phase change materials (PCMs) enable longer off periods and greater flexibility in shifting off periods. PCM application is estimated to add ~$50 per unit (Rodrigues et al, 2022).

One issue with dynamic demand/response is that once appliances are brought back onto the grid, they may create very high momentary demands. Control, and protection devices can help overcome these issues. Controllers can also be used to predict demand (based on weather for example) and pre-cool appliances to enhance/lengthen dynamic demand periods. They can also ensure that food remains at safe temperatures and identify best candidates to provide demand responses (Postnikov et al, 2019).

Using historical half hourly electrical emission factors, it is possible to calculate the potential benefits of carbon emissions by moving demand. The following assumption for shifting demand was used; the refrigeration system was switched off for half an hour per day and the demand was moved to a half hour either before or after the switch off. This is best done when the difference between subsequent half hourly emissions factors is largest. By taking the maximum difference in carbon emissions for electricity every consecutive half hour in a day in the UK in 2022 and averaging gives 11.7 gCO_{2e}/kWh. This is 6.0% of the CI in 2022. To get the average saving, we need to divide by the number of half hour periods in a day which gives an average saving of 0.12%. This assumes the optimum period could be predicted each day, which is not possible but gives a best case.

The issue for individual domestic refrigerators is that they are unlikely to have sufficient capacity to provide any meaningful grid impact unless households are clustered together by their energy provider or by an aggregator. Therefore, dynamic demand is more readily taken up by larger chains or the contributions of smaller outlets needs to be aggregated, either by an aggregator or the energy supply company. Smaller users (approximate minimum of 100 kW per site) will tend to use an aggregator to manage their demand. Larger uses (upwards of 1 MW per site) can deal directly with the UK National Grid. Businesses signing up to provide Frequency Response services typically achieve around a two-year payback on equipment (McManan-Smith 2015).

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	0.12% of electrical energy assuming 0.5-hour energy shift to next or previous half hour, assuming perfect prediction of demand period in advance.
Quality of scope 2 emissions information	M
TRL level	7
Maintainability issues	None

Legislative concerns	Unknown
Payback time (years)	Frequency response 2 years.

9.1.9. Efficient compressor technology (variable-speed linear compressors and variable capacity compressors)

The majority of refrigerated appliances use constant speed reciprocating compressors. In real life usage, these compressors are generally at part load conditions, which means they cycle on and off, resulting in cycling losses estimated to be up to 9% by Bjork and Pam, 2006.

Variable-speed linear compressors (VSLC) and variable capacity compressors (VCC) can avoid such cycling by running at reduced speed or capacity. They can contribute to energy reduction if the evaporator temperature can be raised. Both options would require attention to design and control of the evaporator fan(s) which would also run continuously and offset some of the energy savings.

Inverter drives allow compressor speed to vary depending on the thermal load and various control triggers such as in response to an open door. Compared with on-off cycling of a fixed speed compressor, considerable savings in energy can be achieved. For example, under standard test conditions Chang et al 2004 found that a fridge-freezer with a single inverter-driven compressor used 22% less energy at an ambient of 15°C and 34% less energy at an ambient of 30°C, compared with a fridge-freezer with a single fixed speed compressor. However, the effect of different door opening regimes can have a significant impact on the energy use (Liu et al, 2004). Chang et al (2008) showed an increase in energy efficiency of up to 35% of a variable frequency over a fixed frequency compressor.

Both of these technologies are already penetrating the market, with varying reported impact on energy. Lee et al (2008) reported large scale use of linear compressors developed by LG in Korea, with typical energy savings of 25% compared with reciprocating compressors. Similar claims of 20% compressor energy savings were reported by Fisher and Paykal using oil-free linear compressors developed by compressor manufacturer Embraco (Anon, 2010). The same manufacturer also claimed compressor energy savings up to 45% when using variable capacity compressors to replace a conventional fixed speed reciprocating model. In work on a domestic refrigerator by Binneberg, Kraus and Quack (2002) they converted an off-the-shelf hermetically sealed compressor to operate with a frequency converter (FC). Comparing tests with and without the FC resulted in energy consumption being decreased by approximately 20% when using the FC (compared to the on/off mode).

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	20-45% (depends on baseline comparison)
Quality of scope 2 emissions information	Medium
TRL level	9 (for variable speed compressors)
Maintainability issues	None identified

Legislative concerns	None identified
Payback time (years)	Savings of ~€92/year were achieved though energy reduction by Pedersen et al. It is assumed this would easily outweigh the additional costs of the compressor and so paybacks of <1 year are anticipated.

9.1.10. Electrocaloric refrigeration

Electrocaloric cooling is the electrical analogue of magnetocaloric cooling. Electrocaloric materials change their temperature when exposed to electric fields. The resulting changes in entropy and temperature of the material are known as the electrocaloric effect (Nesse et al 2008). The technology does not use a conventional refrigerant and so have claimed environmental and safety benefits. Energy savings are expected by some researchers but as the technology is still at the developmental stage no evidence was found to support this. In 2006 researchers from Cambridge University reported in 'Science' that thin films of perovskite PZT showed a giant electrocaloric effect with the materials cooling down by up 7°C in a field of just 25 volts (Mischenko et al, 2006). The electrocaloric phenomena has been known since 1930 (Scott, 2011) but the technology remains at the experimental science stage with a small number of experimental prototypes and patents in existence. There are two main threads to current research, cryogenics and room temperature, this study is only concerned with the latter. Polymeric materials such as copolymers of PVDF and triflouroethylene are the most promising materials but it is expected that crystals such as ammonium sulphate could give even better results if their ionic conductivity were greatly reduced. (Scott, 2011)

At typical refrigeration temperatures, a 6.5K temperature difference can be achieved; larger temperature differences (20 to 30K) have only been measured at much warmer temperatures 350 – 400 K (Scott, 2011). Giant Electro Caloric Effects and Large Electro Caloric Effects (ECE) have been measured in thin film materials but not at temperatures useful for typical domestic refrigeration and not on a scale suitable to meet the cooling demands of domestic refrigeration. In addition, Perovskites and ferroelectric polymers which have high ECE are lead based which have environmental impacts. Other alternatives are available such as Barium Strontium Titanate are being investigated to overcome this issue.

The technology is a long way from practical use in the cold chain. Current challenges include fabricating multilayer films of the correct materials and then building a fridge and heat exchangers around them. In addition, Scott (2011) identified the following:

- Optimisation of engineering design such as efficient and reliable thermal switching from source to sink under each cycle.
- Optimisation of copolymers of PVDF and research of alternative materials such as ammonium sulphate crystals.
- Extension of the temperature range.

Ismail et al (2021) reviewed recent work in the area and concluded that the technology has potential with COPs of 7-10 possible, but that the TRL level was still very low (TRL of 1-2). The opportunities for the technology seem limited currently, as systems have so far not achieved high temperature spans required for domestic refrigeration systems (maximum temperature differences of ~14K have so far been achieved).

Scope 1 emissions savings (% or another quantifiable metric)	100%
Quality of scope 1 emissions information	high
Scope 2 emissions savings (% or another quantifiable metric)	None as cannot achieve temperature spans
Quality of scope 2 emissions information	High
TRL level	1-2
Maintainability issues	Not known
Legislative concerns	Potential issue with lead
Payback time (years)	Not able to quantify, too low TRL

9.1.11. Evaporator and condenser optimisation

Improving the efficiency of the heat exchangers in a refrigerated appliance can have a significant impact on overall energy consumption. A more efficient evaporator can reduce the temperature difference between the evaporator and the refrigerator air, allowing higher evaporating temperatures and consequently higher system COPs (Bansal et al, 2011). Similarly, improved condenser efficiency reduces the temperature difference between the condenser and the external ambient air also leading to higher system COPs.

Improvements can be achieved by increasing the surface area of existing designs of heat exchanger, or by introducing new types of more effective exchangers. It has been reported that the edges of evaporator can be poorly utilised (Björk, Palm and Nordenber, 2010).

As described by Barthel and Gotz (2012), increasing the heat exchange area of both the evaporator (by 10-20%) and the condenser (by 5-10%) can provide efficiency gains, which were stated to pay back economically in 6-18 years depending on the model and other design choices. An alternative approach is to use enhanced fins and/or tubes to achieve improved heat exchanging capacity, although one study estimated the possible overall energy reduction potential due to these improvements was only about 1-2% (DOE, 2010).

Tosun and Tosun. (2020) assessed experimentally the impact of varied evaporator designs and capillary diameters/lengths (8 evaporator designs, 2 capillary diameters and 2 capillary lengths) in a fridge-freezer two-circuit cooling system with bypass or parallel evaporators. As part of the work, they assessed the importance of each parameter on the performance of the system (using a general linear method) and found that the evaporator design had by far the greatest impact on performance. Surface area of the evaporator was found to be the most important factor in energy consumption and was achieved with a finned 12 pass evaporator. Compared to the worst-case evaporator (a 19-pass wire on tube design) the best evaporator was able to save ~46% of the energy used by the appliance.

Advanced designs of heat exchangers, such as egg crate type evaporators (Bansal et al, 2001) and improved hot-wall condensers (Bansal and Chin, 2002), also have the potential to improve energy efficiency. Micro channel heat exchangers are a promising development, but further research is needed.

External and fan-assisted condensers have significantly better performance than designs incorporated into the appliance walls (see section on fan-assisted condensers).

Scope 1 emissions savings (% or another quantifiable metric)	Not quantified
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	1-46%
Quality of scope 2 emissions information	Medium
TRL level	7-8 depending on design
Maintainability issues	None identified
Legislative concerns	None
Payback time (years)	6-8 years

9.1.12. Fan-assisted condenser

Most condensers fitted to domestic refrigerators are cooled by natural convection, either via a skin condenser or a wire and tube condenser. However, in most professional refrigeration it is common to apply a fan assisted condenser. Some smaller, cheaper systems apply technology similar to that applied in domestic refrigerators and so the technology is reviewed in relation to these appliances.

Forced convection type condensers are rarely used but can provide greater heat transfer effectiveness. Often, they are not used due to cost constraints, noise issues or insufficient space availability. Although adding a fan to a condenser adds an energy penalty the reduction in condensing temperature could potentially counteract this.

Whitman et al stated that the refrigerant in a natural convection condenser on a domestic refrigerator would typically condense at approximately 110°F (43.3°C). Data from RD&T show a condensing temperature of 37 and 41°C at an ambient temperature of 23 and 29°C respectively for a natural convection condenser. Using a fan assisted condenser the refrigerant may condense at 95°F (35°C). The difference in condensing temperatures would, using a Carnot COP calculation, generate savings of approximately 12%, ignoring fan power. Typically, a fan for a condenser would use 2.5 W (Beko part no: 4364270285). Therefore, if an appliance uses more than approximately 20 W a fan assisted condenser would save energy.

Controlling the condenser fan speed has been shown to have positive benefits. Angermeier, and Karcher (2020) suggested that the ideal condenser fan speed could be calculated for steady state conditions if a constant evaporating pressure was assumed and the compressor efficiency, subcooling, and superheating known. By applying an optimisation algorithm COP savings of up to ~10% appear achievable compared to a constant fan speed (Dowling, 2020).

Scope 1 emissions savings (% or another quantifiable metric)	Instead of increased efficiency, evaporator size could be reduced, reducing scope 1 emissions.
Quality of scope 1 emissions information	n/a

Scope 2 emissions savings (% or another quantifiable metric)	Up to 12%
Quality of scope 2 emissions information	Medium
TRL level	8-9
Maintainability issues	None identified
Legislative concerns	None identified
Payback time (years)	None identified, but considered low as controller based

9.1.13. Heat pipes and spot cooling

Heat pipes have potential for spot cooling or for moving heat away from critical points in a refrigeration system or refrigerated equipment.

Very little work is published on heat pipes in domestic refrigerators. Most work has limited application for domestic homes or applies to absorption or Peltier appliances. Cao et al (2020) modelled the potential to operate loop heat pipes to link the freezer and refrigerator in a domestic appliance to recover cold energy from the freezer. Simulations showed potential to reduce energy but some potential issues with practical implementation of the design.

Work on heat pipe shelves in commercial cabinets was published by Jouhara et al (2017). They found that heat pipes in the shelves reduce temperature differences from back to front of the shelves and reduced energy consumption by 12%. However, the work changed the cabinet design by replacing the metal rear back panel with a wooden panel and this may have affected the conduction of the baseline shelf performance. In the heat pipe test the authors placed a condenser section into the rear cabinet duct which increased conduction. Some of the effect seem may therefore have been due to conduction and not the heat pipe exclusively. In addition, the working fluid in the heat pipe was ammonia which might not be acceptable to all end users in domestic markets.

One more recent use of heat pipes has been explored by Tian et al (2019). They used heat pipes to overcome the heat transfer limitations of PCMs. Although no information is provided on energy savings or fully quantified benefits there may be some potential to explore the use of heat pipes and thermal storage.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Limited information applied directly to domestic refrigerators
Quality of scope 2 emissions information	Low
TRL level	5
Maintainability issues	Not known
Legislative concerns	Depends on refrigerant

Payback time (years)	No evidence

9.1.14. Improved door gaskets

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. These seals deteriorate over time. 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.

As reported by Bansal et al 2011, published research into gasket improvements has been limited. As improvements are made in other areas (e.g. wall insulation) it is probable that the efficiency of door gaskets will assume a greater relative importance to the overall performance of refrigerators. According to Fine and Lupinacci (1994) heat flow through the gasket region of the cabinet contributes significantly to the total load and finite element analysis (FEA) has shown that heat flow can be reduced by 50% by minor changes to the design of the flanges on the door and cabinet. Barthel and Gotz, 2012 reported that heat conduction through the gasket accounts for 2.7% of the total heat load. If it is assumed that this can be reduced by 50%, there is potential for a 1.35% reduction in energy using improved gaskets. Liu, Yan and Yu (2021) have more recently assessed gasket design and suggested alternative materials and designs that could save energy. They suggest compared to a 2019 baseline that energy efficiency could be reduced 3-5% by improvements to gasket design.

Air infiltration due to deterioration in door seals varied between freezers and chillers. In work carried out Afonso and Castro (2010) they found that for equivalent air leakage rates the air infiltration was twice the value in a freezer than a chiller due to lower temperatures in the freezer. Deterioration in seals was found to have a significant impact on energy consumption. When new the seals 3.6% of the energy used to run the compressor was spent on the air infiltration and 96.4% on heat gains through the walls. When seals deteriorated the percentage of the compressor energy attributed to air infiltration rose to 18.5%. A 40% increase in the energy consumption of the compressor was measured when a double door refrigerator-freezer was tested with poor seals compared to new seals. However, this seems excessive and possibly applied to very old and damages seals.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	3-5%
Quality of scope 2 emissions information	Low
TRL level	9
Maintainability issues	Current seals deteriorate
Legislative concerns	None
Payback time (years)	No quantified evidence of costs and so payback cannot be calculated

9.1.15. Improved insulation e.g. vacuum insulation panels

For a refrigerated appliance which spends the majority of its time with doors closed, one of the principal ways of reducing heat gains is to improve the insulation. Increasing the thickness of conventional insulation e.g. polyurethane (PU) can achieve this, but this reduces the useful net volume inside the appliance. Advanced insulation, such as vacuum insulation panels (VIPs), can be used instead to offer better resistance to heat transfer with the same or even lower thickness. Reducing the heat gain has a corresponding reduction in the energy consumption of the compressor.

Bansal et al (2011) reviewed several studies with VIPs in domestic refrigerators. In one study, energy savings of up to 20.4% were achieved in comparison with 1990s technology insulation, depending upon such factors as the area covered, the resistivity of the panels, edge losses, etc. while other studies achieved 25% performance improvements.

VIPs are currently expensive, and this has limited their use to higher end and specialised refrigerated appliances, but increased use and technological advances should lead to cost reductions. For some uses of VIPs there are concerns over robustness and longevity, e.g. in buildings and transport applications they may be vulnerable to damage and loss of vacuum. In the walls of refrigerated appliances, they would be relatively protected. To ensure complete insulation and structural integrity, VIPs are best integrated into the blown foam, and this provides further protection. Verma and Singh (2019a) reported that VIPs should achieve approximately a 20% energy saving in domestic refrigerators compared to standard PU. They assessed the benefits of 3 types of VIP (fumed silica VIP, glass fibre VIP, alternate core VIP) against PU. The fumed silica VIP provided the lowest energy consumption (19.6% less than PU foam) but added weight to the appliance (addition of 2.48 kg). The payback time for the fused silica was 3.2 years. Verma and Singh (2019b) also reviewed performance of VIPs in cold chain equipment. They concluded that a refrigerator with 56% of its external surface area covered in VIPs would achieve 21% energy saving (compared to PU)

Work by Hammond and Evans (2014) found that embedding the VIP into the PU foamed walls of traditional refrigerator and freezer cabinets was a good option. Thermal modelling of the insulation of a range of typical refrigerator and freezer cabinets used throughout the cold chain was carried out both with and without VIPs embedded in the insulating walls. The potential energy savings and payback times were calculated. For refrigerators the average payback was 9.7 years, for freezers it was 4.5 years. In the modelling a domestic refrigerator-freezer, a professional service refrigerator, a professional service freezer (both upright models) and a retail display chest freezer were modelled. The professional cabinet was modelled in an ambit of 25°C. Paybacks for the refrigerator were at best 4.7 years and for the freezer 1.4 years. Energy savings were for the best payback options were 5.7 kWh/yr (refrigerator) and 19.1 kWh/yr (freezer). However, this was for minimal use of VIPs that gave the best paybacks in 2014. With reduced VIP costs and increased energy costs the balance may no longer be the same. If VIPs were applied more extensively the maximum energy savings were 110.4 kWh/yr for the refrigerator and 410.7 kWh/yr for the freezer. Energy savings were between 32 to 60% depending on the way the VIPs were applied.

Other options for advanced insulation include aerogels and panels filled with inert gases such as argon and krypton, but these are even more expensive and have seen limited application to date.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	12-60% (~20% is realistic and agreed)
Quality of scope 2 emissions information	Medium
TRL level	7
Maintainability issues	Potential issues with integrity of the VIPs
Legislative concerns	None
Payback time (years)	1.4-4.9 for a freezer, 4.7-18.3 for a refrigerator (at 2014 costs)

9.1.16. Internal ice makers removal

Internally situated ice makers are a common feature found on larger, so-called American-style refrigerator-freezers. These ice makers employ an internal motor and a heating element to avoid the motor freezing up. A National Institute of Standards and Technology (NIST) study (Yashar and Park 2011) found that automatic ice makers increased energy consumption by between 12 and 20%. This agreed well with previous research (Meier and Martinez, 1996) which found that energy used by new fridge-freezers increased by around 10% if an ice-maker was fitted, with 5% being attributed to the heater and motor. Re-testing after two years of field use in domestic kitchens found that the increase had risen to 14%.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	10-20%
Quality of scope 2 emissions information	Low
TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	As this is removing a feature the payback is instant

9.1.17. Inverter driven compressors

Variable speed compressors (VSCs), otherwise known as variable capacity compressors (VSCs) have been shown to be more efficient than fixed speed compressors (Abdelaziz and Cotton, 2021). They are usually marketed to the domestic customer as inverter compressors. Inverter compressors are already being used on fridge/freezers by some manufacturers. It seems likely that as energy consumption becomes more important and the costs of these compressors reduces, their application will become more widespread.

Inverter drives allow compressor speed to vary depending on the thermal load and various control triggers such as in response to an open door. Compared with on-off cycling of a fixed speed compressor, considerable savings in energy can be achieved. For example, under standard test conditions Chang et al 2004 found that a fridge-freezer with a single inverter-driven compressor used 22% less energy at an ambient of 15°C and 34% less energy at an ambient of 30°C, compared with a fridge-freezer with a single fixed speed compressor. However, the effect of different door opening regimes can have a significant impact on the energy use (Liu et al, 2004).

Chang et al (2008) showed an increase in energy efficiency of up to 35% of a variable frequency over a fixed frequency compressor.

Application of this technology requires more complex or additional components (inverter, variable speed compressor, digital control) which add to the initial cost of the appliance.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	22-35%
Quality of scope 2 emissions information	Medium
TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	No information but expected to be <3 years based on savings

9.1.18. Light emitting diode (LED) lighting

Already applied and so not reviewed.

9.1.19. Liquid line solenoid

All domestic refrigerators operate using a capillary expansion device. This is due to the lower cost of a capillary tube compared to a thermostatic or electronic expansion valve, their suitability for charge optimised systems and the availability of small sized valves.

Capillary tubes require optimisation during the design stage to achieve ideal evaporating temperatures. The capillary tube is optimised for a particular set of conditions and will not operate most efficiently outside of these conditions.

One of the main issues with capillary tubes is that during off cycles, gas can migrate across the tube into the evaporator where it condenses. This adds a heat load to the evaporator and unless the refrigerant is boiled during the start of a compressor cycle the condensed refrigerant can be taken as liquid back to the compressor, potentially damaging the compressor. One option to prevent this occurring is to add a liquid line solenoid that prevents migration of gas across the capillary. If a solenoid is applied, it is also necessary to use a high back starting compressor and so some level of redesign is necessary. Some food service cabinets already have liquid line solenoid valves fitted. The percentage across the whole market is unknown but some cabinets most certainly do not apply this technology.

Rubas and Bullard (1995) found that refrigerant migration across the capillary resulted in 16-32 kJ of energy being added to the evaporator. Most of the migration occurred as liquid in the few minutes after the compressor stop. The condenser design was found to have a large impact on the off-cycle losses and amount of liquid and vapour migration across the capillary tube. They also found that migration was affected by ambient temperature with less migration at lower ambient.

Björk, et al (2010) state that most of the refrigerant is contained in the evaporator and compressor in the off cycle. The start-up and shut down energy impacts can be between 5-37%. Björk and Palm (2006) found losses due to on/off cycling in a domestic refrigerator were estimated to reduce the efficiency by 9% and the capacity by 11% based on a refrigerator using 0.71 kWh/day. Most of these losses were the result of improperly charged heat exchangers at the compressor start-up. Kocaturk et al (2007) found in a freezer cabinet that the off-cycle losses resulted in 5-15% increased energy consumption.

Figure 23 shows the effect of including a liquid line solenoid in the refrigeration circuit of a chilled professional service cabinet under different operating conditions (FRISBEE, 2011). Over all the tests there was no effect on overall mean temperatures of test packs placed in the cabinet, but energy consumption was significantly higher in trials without the liquid line solenoid. Energy savings of approximately 30% were found with the solenoid in the circuit.

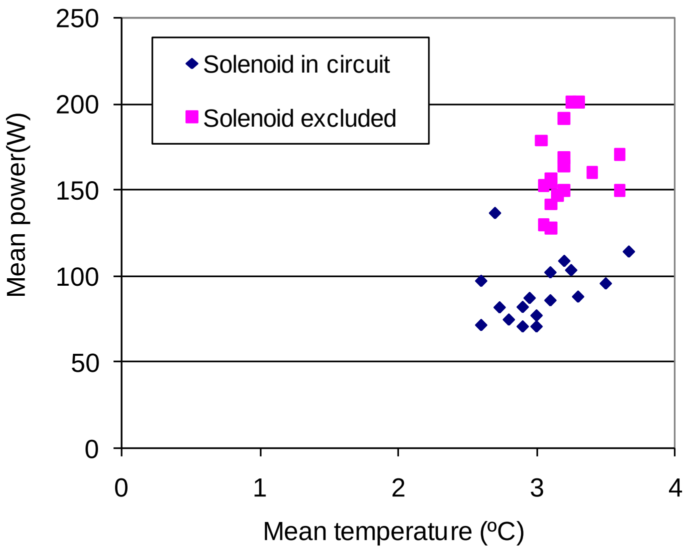


Figure 23. Effect of including a liquid line solenoid in a refrigeration circuit.

A liquid line solenoid or an electronic expansion Valve (EEV) is the best method to overcome the off-cycle losses. Knabben et al (2020) investigated replacing a capillary with an EEV in a domestic refrigerator. They found though practical work and modelling that the system with the EEV used more energy than the capillary system in most cases (due to the extra thermal load generated by the valve). If the internal heat was made more effective and the heat dissipated by the EEV was mitigated it was possible to save between 4-9% of the energy for the system with the EEV applied compared to the system with the capillary tube. However, the authors noted that the results were quite system dependent and so optimisation for each product would be necessary.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	5-37% based on domestic refrigerator
Quality of scope 2 emissions information	High
TRL level	8
Maintainability issues	None identifies
Legislative concerns	None identifies
Payback time (years)	No information available but solenoid valves (without any scale discount) are between approximately €50-60. In the above example 9% at 0.71 kWh/day at 30 p/kWh ~8 years

9.1.20. Magnetic refrigeration system

Technologies such as magnetic cooling have potential advantages such as no flammable refrigerants and potentially high efficiencies above those of vapour compression technologies. Magnetic refrigeration takes advantage of the magnetocaloric effect; the ability of some metals to heat up when they are magnetised and cool when demagnetised. Much of the original work and most prototypes developed were based on the use of gadolinium magnets that are rather expensive. More recent work has looked for new materials that are cheap, have suitable transition temperatures and exhibit a large magnetocaloric effect. Magnetic refrigeration has the prospect of efficient, environmentally friendly and compact cooling for a wide field of applications.

Astronautics Corporation in America and Chubu Electric Power Co Inc in Japan have both produced rotary magnetic refrigerator systems. The highest COP reported for a near room temperature, permanent magnet system was 2.4. This was based on a 560 W cooling capacity at zero temperature span. For a 5K temperature span and 20°C sink temperature, the COP reduced to 0.6 and the cooling duty to 159 W (Lewis et al, 2007).

Gschneidner and Pecharsky (2008) predicted that production of near room temperature, magnetic refrigeration systems will grow to 1000 units by 2015, by which time they would consider the technology to be commercialised. However, was clearly an over ambitious prediction.

Successful commercialisation will require (Lewis et al, 2007):

- ‘Magnetic refrigerants’ with a larger magneto caloric effect to be produced in large quantities.
- Permanent magnets need to be stronger, smaller and cheaper.
- Improvements could be made to the cycles.
- Improvements to the engineering design of the systems.

Camfridge began a project with Whirlpool in 2009 and expected demonstration units to be available in 2012. However, this has not materialised due to a number of issues related to the magnets themselves and also the methods to apply the cooling to a refrigerator (Whirlpool, 2009; Wilson et al, 2006). Cooltech have developed a prototype magnetic refrigerator and applied it to an Arneg enclosed serve-over cabinet. The technology was demonstrated during the Euroshop fair in 2014.

Ismail et al (2021) reviewed developments in magnetic refrigeration. They concluded that materials for construction are not yet available and so this limits large scale commercialisation. Most (95%) of the e-rare earth magnets used for the technology are produced in China. Potentially the technology can achieve high COPs (up to 9.44) but this is very dependent on the materials applied. The main current focus is cryogenic coolers and mobile refrigeration and not domestic or food service refrigeration.

Scope 1 emissions savings (% or another quantifiable metric)	100%
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	50% claimed by manufacturers but appears unlikely as claims do not always include pumping power and losses. Claims not independently validated.
Quality of scope 2 emissions information	Low
TRL level	3-4
Maintainability issues	Unknown
Legislative concerns	None
Payback time (years)	n/a

9.1.21. Maintenance, servicing and ageing

Fall of in performance of smaller refrigeration systems may originate from several sources. The impact of door seals is covered elsewhere. Insulation may break down or lose thermal integrity, heat exchangers may become dirty and less effective, or refrigerant may leak resulting in reduced operational performance. Although relatively difficult to fully quantify the impacts of maintenance it is clear that this can have an impact on both direct and indirect emissions.

Hueppe et al (2020) assessed age related efficiency of domestic refrigerators and found that there was an increase in thermal conductivity of the PU insulation of 15%.in the first year. This was related to a change in cell gas composition. This is primarily due to the cell gas diffusing out of the insulation and being replaced by ambient air and water vapour. Paul et al (2022) expanded this work and indicated that energy could be increased by up to 36% over a product life of 18 years. After 2 years energy was increased by up to 11% (over 11 appliances examined) (Figure 24). Modelling indicated that the average energy increase over 16 years was 27%.

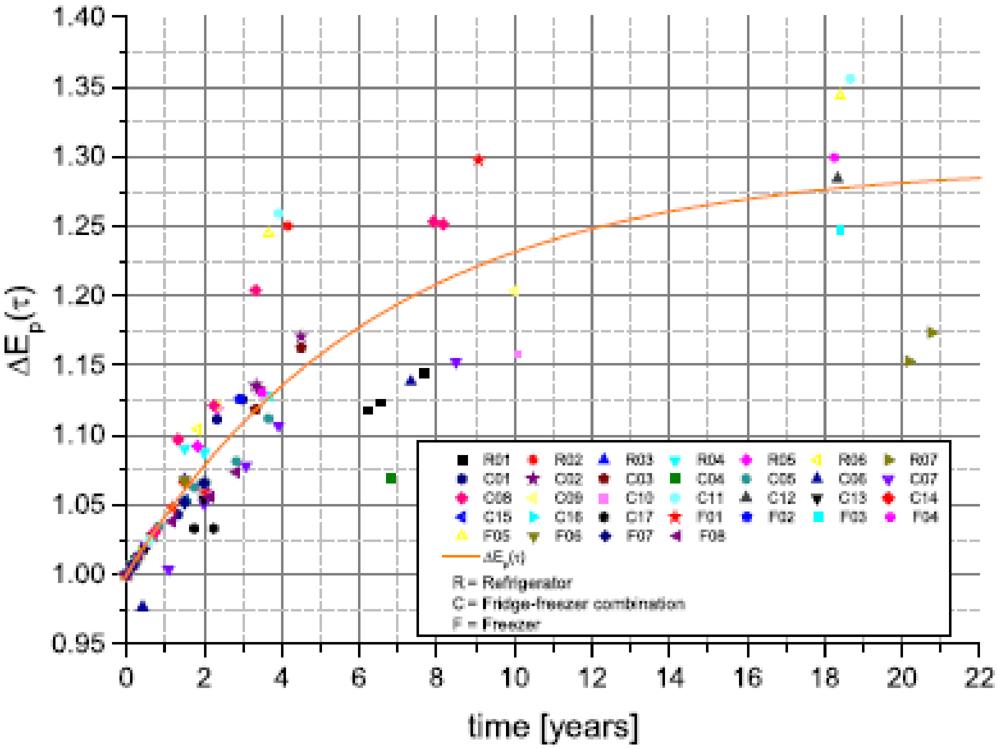


Figure 24. Corrected energy consumption and consolidated aging function ΔEp(τ) (line).

The impact of any refrigerant leakage is not the refrigerant itself (which for new refrigerators in Europe is exclusively R600a) but the impact of the loss of any refrigerant on the performance of the refrigeration system. Leakage of refrigerant from hermetic refrigeration systems has always been reported as being low and this was confirmed by Tomlein et al (2019) who found almost no leakage in a survey in Slovakia.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	None
Scope 2 emissions savings (% or another quantifiable metric)	Up to 27% on average (insulation). However, currently no technology to prevent this fall off in performance
Quality of scope 2 emissions information	High
TRL level	7
Maintainability issues	Non known
Legislative concerns	None known
Payback time (years)	Non known

9.1.22. Nanofluids

Nanofluids are engineered colloidal suspensions of nanoparticles (1-100 nm) in a base fluid. The size of the nanoparticles imparts some unique characteristics to these fluids, including greatly enhanced energy, momentum and mass transfer, as well as reduced tendency for sedimentation and erosion of the containing surfaces. To enhance heat transfer, nanofluids were developed, based on mainly copper and aluminium nanoparticles (Eastman et al, 1996). These nanoparticles have a high thermal conductivity and, hence, should improve the heat transfer near the laminar sub-layer (Jana et al 2007; Lee et al, 2007; Ko et al 2007). Recent experimental work at NIST with varying concentrations of nanoparticle additives indicate a major opportunity to improve the energy efficiency of large industrial, commercial cooling systems. NIST have shown that dispersing low concentrations of copper oxide particles (30 nm in diameter) in a common polyol ester lubricant and combining it with R134a improved heat transfer by between 50 and 275%. Success in optimising mixtures of refrigerants, lubricants and nanoparticle additives could be beneficial. High-performance mixtures could be swapped into existing chillers, resulting in immediate energy savings. Due to improved energy efficiency, next-generation equipment would be smaller, requiring fewer raw materials in their manufacture.

Bondre et al (2019) assessed the performance on nano-refrigerants in a domestic refrigerator. The work covered 4 configurations (3 nanoparticle concentrations in polyol ester (POE) oil and 1 with pure POE oil). Nanoparticle Al_2O_3 concentrations if 0.05, 0.1, 0.2% were assessed. The 0.1% concentration was found to give the best performance and improved the COP of the system by 17.27% and energy consumption by 32.48%.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Limited quantified evidence but potentially up to 32.5%
Quality of scope 2 emissions information	Low
TRL level	3
Maintainability issues	Unknown
Legislative concerns	None
Payback time (years)	Not known

9.1.23. Phase change materials

Bista et al (2018) reviewed the work on use of PCMs in refrigerators (attached to the evaporator, in the cold space or on the condenser) and concluded each option had varied benefits but needed to be correctly optimised in terms of phase change temperature, thickness, thermal load and refrigeration system design. Savings of 12-26% were reported (most typically ~8%).

PCMs installed in contact with the evaporators in household refrigerators and fridge-freezers have been shown to reduce energy consumption. Azzouz et al 2009 installed PCMs on the back face of a wire-on-tube evaporator in a typical gravity circulation refrigerator and reported that evaporation temperatures stabilised and increased, resulting in a 10 to 30% improvement in COP. More recently, a similar approach was evaluated in a dual compressor fan-assisted fridge-freezer as part of the FRISBEE project (Deliverable D.6.7.2). In this work it was reported that evaporator temperatures were very similar, but that the run-time of the compressor serving the freezer compartment was reduced, giving an energy saving of 5.6% for that compressor. There was little impact on the run-time of the fridge compressor, partly as the choice of PCM melting point seemed not to be optimal. Visek et al (2014) raised the evaporating temperature (by 8.4 K) in a sequential dual evaporator fridge-freezer by attaching a PCM to the refrigerator roll bond evaporator. This reduced overall energy consumption by 3.5%. The main benefit of a PCM was the reduced number of compressor starts which reduced system losses (Khan and Afroz, 2013).

The benefit gained will depend on the type of appliance (e.g. gravity or fan-assisted, fridge or freezer) and on the careful matching of the PCM to allow it to melt and solidify in the correct temperature range. It is important to take into account the compressor duty, as shown in a recent study by Marques et al, 2014 of the effect of refrigerator compressor size on efficiency, which found that larger compressors were more efficient but required use of PCMs inside the compartment to store cooling capacity and reduce the number of compressor starts.

Another option for PCM application is around the condenser. Cheng et al (2011) found that adding PCMs as heat stores around the condenser of a typical refrigerator allowed continuous heat dissipation during both on- and off-cycles. This lowered the condensing temperature and raised the evaporating temperature, leading to energy savings of around 12%.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Typically 10-12%
Quality of scope 2 emissions information	Medium
TRL level	4
Maintainability issues	Not known
Legislative concerns	None
Payback time (years)	No information

9.1.24. Stirling coolers

Stirling coolers are closed-cycle regenerative thermal machines which compress and expand a gas. Free piston machines use a moving magnet or linear machine to facilitate heat absorption and heat rejection respectively (but compression and expansion can also be performed by compressive waves, see acoustic refrigeration). Such units can have maximum cooling capacities up to 100 W with larger capacity units, up to 300 W, reported to be under development. Applications are in domestic and portable refrigerators and freezers as well as a beverage can vending machines. COP between 2 and 3 have been reported for cold head temperatures around 0°C, and values around 1 for cold head temperatures approaching -40°C.

Although the rapid start-up and cool down of Stirling coolers is often cited as a major benefit, they are generally limited in their application by the low heat transfer co-efficient between the working fluid (gas) and the inside wall of the cylinder/heat exchanger; this generally makes them bulky and difficult to implement practically. They are also quoted as being highly reliable and light weight which are advantages for portable refrigeration equipment.

Ismail et al (2021) reviewed the application of Stirling coolers. They concluded that there were barriers to application caused by manufacturing cost in comparison to vapour compression technology. TRL was assessed at 4 with the COP of current systems being low <1. If this could be improved then there could be potential for the technology for use in portable refrigerators and freezers, beverage and vending machines. Improvements in efficiency are possible when the Stirling cooler was combined with other systems, but this increases cost and complexity and so it unlikely to be commercially viable.

Scope 1 emissions savings (% or another quantifiable metric)	100%
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	None
Quality of scope 2 emissions information	Medium
TRL level	4
Maintainability issues	None identified
Legislative concerns	None identified
Payback time (years)	No quantified information

9.1.25. Superchilling

Superchilling is one of several terms used to describe the partial freezing of food products, i.e., 5-30% of the freezable water is frozen, although there is no commonly agreed definition (Bantle et al., 2016). The following benefits can be achieved through superchilling according to Kaale and Eikevik (2014): maintain quality; extend shelf life; minimise energy labour and transport costs; reduce environmental impact. When discussing possible benefits of superchilling in a domestic setting, the focus is on reducing food waste through shelf-life extension.

Coskun et al. (2022) studied raw beef and seabass stored under superchilled conditions, including temperature fluctuations, and compared them with chilled storage. The three treatments were (A) -3.0 ± 0.8 °C, (B) -3.0 ± 2 °C and (C) 1 ± 2.5 °C, and they studied quality parameters such as drip loss, microbiology (TVC, TVB-N and Pseudomonas spp.), lipid oxidation and sensory evaluation. They found that superchilled treatments prevented lipid oxidation in beef for a longer period of time (13 days to reach threshold value (A) vs 11 days (B, C)), but also that drip losses were higher for the superchilled treatments in this case. The latter was explained by the temperature fluctuation, and not necessarily an effect of superchilled storage. Sensory evaluation included a panel to judge appearance, texture, odour and overall acceptability of the samples. For the beef samples, the rejection score (value below 4 on a 0-7 scale) was reached after 7 days for chilled treatment while it took 13 days for the superchilled treatments. For the seabass samples, rejection score (value below 3 on a 0-5 scale) took 8 days for chilled treatment while it took 14 days for superchilled treatments. In addition, microbiology analyses also showed that the superchilled treatments gave prolonged shelf life (lower TVC and Pseudomonas spp.). It stands to reason that if shelf life can be doubled by applying superchilling at home, food waste could be reduced and thus GHG emissions saved. However, no sources have been found which quantify this saving.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	5-7
Maintainability issues	n/a
Legislative concerns	n/a
Payback time (years)	n/a

9.1.26. System optimisation

The parallel circuit system is considered by Choi et al (2018) to be the most efficient dual evaporator cycle. Authors such as Yan et al (2020) have looked at optimising the operation of parallel two-circuit cycle frost-free fridge-freezers as refrigerant is not always immediately available when the refrigerator or freezer need cooling. This increased pull down time and reduces temperature control. Yan et al assessed the use of variable sized capillary tubes, evaporator fan speed and refrigerant charge for a circuit with a variable speed compressor. Although only optimised for one condition the authors saved 9.27% of the energy used compared to the base case.

Yoon et al (2011) also examined methods to improve the performance of a parallel fridge-freezer system. They examined refrigerant charge, refrigerator capillary tube design and heat transfer area of the refrigerator evaporator and found that they could save 8.8% of the energy compared to an equivalent bypass two-circuit system (Figure 25). A further 1.8% energy could be saved by optimising the operating sequence and refrigerant recovery operation time.

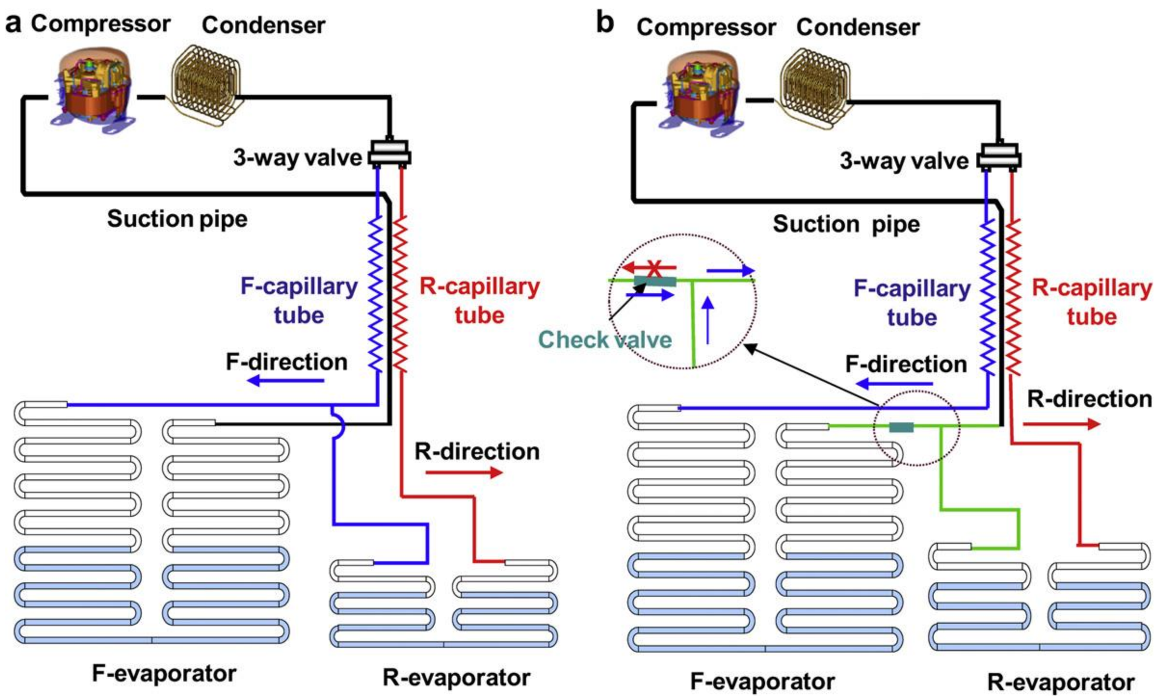


Figure 25. Schematic diagrams of (a) the bypass two-circuit cycle and (b) the parallel cycle.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	8.8-9.27%
Quality of scope 2 emissions information	Low
TRL level	4
Maintainability issues	None
Legislative concerns	None
Payback time (years)	No information

9.1.27. Thermoelectric refrigeration

Thermoelectric (TE) or Peltier devices are lightweight, small, and inexpensive and do not utilise high GWP refrigerants. TE devices are less efficient than vapor compression technology except where the temperature lift is <5°C (Ismail et al, 2021). Currently the COPs reported are 0.3-0.8. Although there is potential to improve efficiency these systems cannot be produced economically.

There is no published information on the use of Peltier coolers in domestic refrigerators (expect for very small beer can coolers) and so the potential energy savings are unknown. It would appear likely that the most suitable application would be to spot cool an area of high temperature or specific areas within a refrigerator where lower temperature is required. However, good design and optimisation could potentially overcome such issues without the use of a more complex additional technology such as Peltier cooling. Thermoelectric generators also require a large direct current (DC) and an AC/DC converter which makes the costly.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	None achieved compared to vapour compression
Quality of scope 2 emissions information	Medium
TRL level	4 (except for can coolers)
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Not able to quantify

9.1.28. Thermionic refrigeration

Thermionic cooling is based on the ability of a material to change temperature by applying an electric field under adiabatic conditions.

The name thermionic arises from thermionic emission, which is the thermal excitation of hot electrons from a metal surface (Mahan 2001). A thermionic device has two thin films separated by a vacuum layer. If a voltage is passed across the gap, the most energetic electrons on the negative side 'jump' across to the positive side. As the electrons leave the negative side, they get colder. Potentially such device can be thermodynamically very efficient and could outperform classic direct expansion refrigeration systems.

Thermionic refrigeration is not currently applied to the cold-chain and most cited applications are for solid-state, on-chip cooling or temperature regulation for sensors and other electronic devices.

The major benefits would appear to be reduced direct emissions (no HFC). Energy savings are expected by some researchers but as the technology is still at the developmental stage no evidence was found to support this. Based on a purely theoretical study, Mahan and Woods (1998) proposed that efficiencies twice that of existing thermoelectric devices and comparable to existing vapour compression systems could be achieved but note that materials with a suitable work function (<0.3 eV) are not yet available.

Scope 1 emissions savings (% or another quantifiable metric)	100%
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Not quantifiable

Quality of scope 2 emissions information	n/a
TRL level	3
Maintainability issues	Non known
Legislative concerns	Non known
Payback time (years)	Non known

9.1.29. Two-stage system

Two-stage systems are generally applied to industrial refrigeration plant. Generally, domestic refrigerators have one condenser, one or two evaporators, one compressor and a suction line heat exchanger. Some benefits of a 2-stage system have been reported (Jaster, 1990a and b). The major advantage of such a system is that each compressor needs to work over a lower pressure ratio and therefore can operate more efficiently. Theoretical improvements of 48.6% are claimed possible.

These results are from over 25 years ago when compressor technology was still developing. It remains to be shown whether these results would still be applicable with modern day compressors. In addition, the costs for a 2-stage system would probably be prohibitive in the cost competitive domestic market.

Scope 1 emissions savings (% or another quantifiable metric)	Probably higher
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	48.6%, claimed but limited evidence to support this.
Quality of scope 2 emissions information	Low
TRL level	5
Maintainability issues	None identified (however, a second compressor may add to maintenance)
Legislative concerns	None
Payback time (years)	No information identified

9.1.30. Vacuum insulated panels (VIPs)

VIPs consist of an open cell foam slab enclosed in a barrier film (Brown et al, 2007). A high vacuum is achieved within the enclosure, maintained by the impermeability of the barrier film and by the presence of a gas absorber (or getter) within the enclosure. The foam slab maintains the physical dimensions of the panel, supporting the barrier film, reduces convection by the remaining gas molecules and the radiant heat transfer across the panel. The getter absorbs water vapour, atmospheric gasses and gasses emitted by the slab during the life of the panel to maintain the vacuum.

The thermal conductivity of VIPs is around one fifth of that of the PU foam typically used. VIPs typically have a thermal conductivity of around 3 mW/m.K (measured at the centre of a panel). However, the film material does influence the conductivity of the panel as a whole and 5 mW/m.K would be more typical when considering the complete panel. For a given thickness of wall, the heat gain through the walls could be reduced by as much as 80%. Recent research (Hammond and Evans, 2014) has shown that VIPs embedded into PU foamed walls will yield 86% of the expected benefit (assuming manufacturers' thermal conductivity data); the remaining 14% being equivalent to the variation in thermal conductivity of the PU and VIP (within claimed manufacturing tolerances).

Conventional insulation (PU) has two major benefits compared to VIPs; these are low cost and the mechanical properties; PU foam can be used to add rigidity to a cabinet whereas VIPs must be protected from indentation, puncture or buckling to avoid damage to the foil coating. Furthermore, any panel joints of poor integrity can quickly offset all losses.

The present cost of VIPs is more than that for PU foam. The main benefits of VIPs are the reduced thermal transmission for the same thickness, the reduced space taken by the insulation for the same thermal transmission or a combination of these two, especially where energy indexes are calculated based on internal volume and external dimensions are constrained.

Energy savings can be made but unless space is of a high value, the additional cost of the VIP is unlikely to be justified currently alongside the option of adding more PU foam. Paybacks depend on how the VIP is applied and how many walls of an appliance have VIPs applied. Evans and Hammond (2014) provide costed payback for the application of VIPs to domestic, professional and retail chillers and freezers. For domestic refrigerators the paybacks calculated caried between 4.1 and 11.8 years. However, uptake of the technology will reduce costs and so it is expected that if commercialised that paybacks will reduce.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	86% of heat gain through walls
Quality of scope 2 emissions information	Medium
TRL level	7
Maintainability issues	Need to maintain membrane seal
Legislative concerns	None
Payback time (years)	Depends on application, 4-12 years

9.1.31. Vortex tube

A vortex tube is a separation device which has no moving parts. Gas is injected into a swirl chamber and exits via a longer tube as two air streams, one hot and one cold. As the compressed air enters the swirl chamber (or vortex generator) the air accelerates to a high rate of rotation (as much as 1,000,000 rpm). A small amount of the hottest gas is allowed to escape via the conical nozzle at the longer end of the vortex tube and the remaining air returns down the centre of the vortex tube to exit as cold air through the shorter end (Figure 26). It is believed that a pressure difference occurs through the gas due to the centrifugal force. The resulting compression at the walls, expansion at the centre and heat transfer between the two streams within the vortex tube then result in the cold and hot air stream separation.

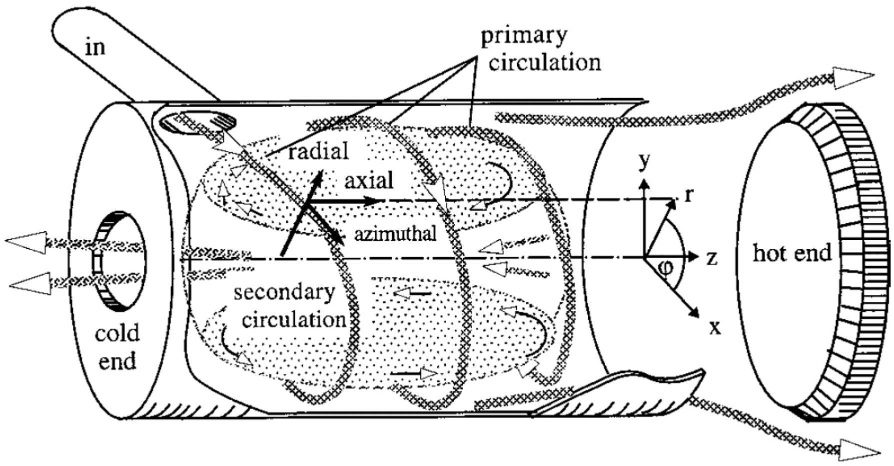


Figure 26. Vortex tube taken from (Ahlborn et al. 2000]).

A vortex tube was used by Choi et al (2018) to generate 3 different evaporating temperatures to provide cooling for 3 separate compartments (Figure 27). Such a system is claimed to have higher efficiency and is more adjustable. Simulations indicated that R290 and R717 has better performance than R600a, R22 and R134a. The authors did not compare the design to a conventional system and so it is not possible to determine whether energy savings could be achieved. However, they stated that a COP for the R290 and R717 systems were 1.495 and 1.281 respectively.

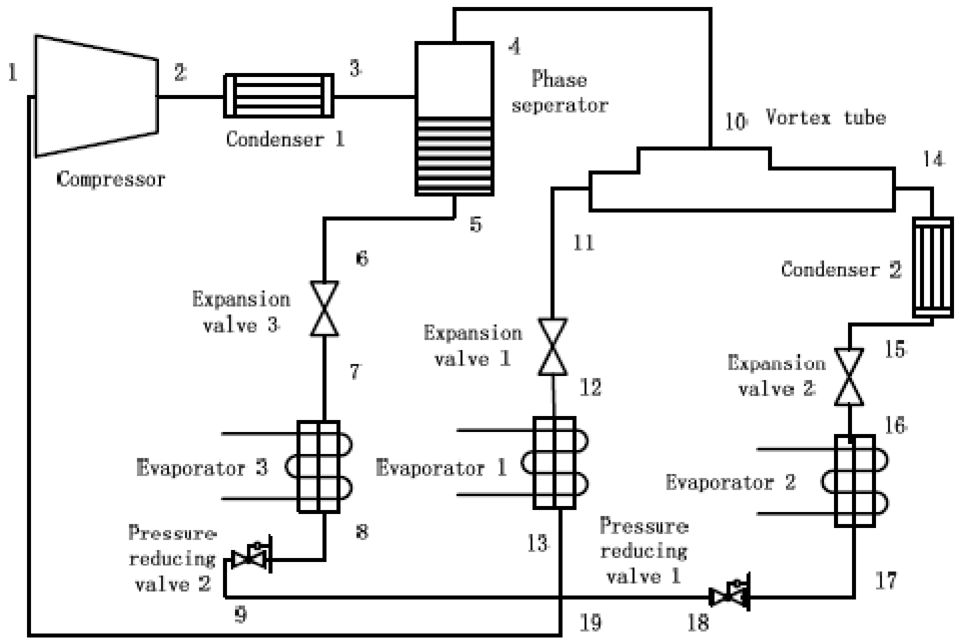


Figure 27. Novel cycle with a vortex tube.

Scope 1 emissions savings (% or another quantifiable metric)	100% assuming the gas is air.
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Limited information to quantify savings
Quality of scope 2 emissions information	Low
TRL level	2
Maintainability issues	Not known
Legislative concerns	None
Payback time (years)	Not known

9.1.32. Wide glide refrigerants

Current refrigerants used in domestic refrigerators are azeotropes (boil at a constant temperature). It has been suggested that zeotropic refrigerants that have a wide temperature glide (i.e. boil over a wide temperature range) could have advantages in domestic refrigerators. This is partly because many domestic appliances require a chilled and frozen section and so the technology of using a wide boiling refrigerant can have direct benefits in providing different temperatures in each compartment.

Early work to develop the application of wide glide refrigerants suggested that to achieve energy savings the temperature glide between the bubble and dew point temperatures need to be matched to the evaporator cooling or condenser heat rejection loads. In a counter current configuration, the heat transfer in the evaporator and condenser can be carried out with a near constant temperature driving force (Figure 28). This results in a reduced pressure ratio between the condenser and evaporator comparted with an azeotropic fluid (Bensafi, and Haselden, 1994). The authors state that zeotropic refrigerants are best suited to situations where there is a natural need to cool or heat though a range of temperatures (e.g. air conditioning or heat pumps) and is less suited to temperature maintenance applications such as cold stores. The authors provide some rules of thumb to design zeotropic mixtures and recommend that the fluids selected have approximately a 45 K difference in normal boiling points and that lower pressure fluids should be favoured (the authors suggested ~6 bar in the evaporator should be aimed at). The paper describes how heat exchangers for zeotropic refrigerants should be designed as it is important to ensure counter current flow between air and refrigerant, co-current flow of the 2 phases of the refrigerant and high local heat transfer coefficients. The work examined a number of zeotropic blends, but all would not be acceptable for today's market as have too high GWPs. Nevertheless, the authors found that ~20% compressor power savings were achievable. More recent design advice for developing zeotropic blends is provided in Rajapaksha (2007). However, the author does not provide information on energy savings that could be achieved.

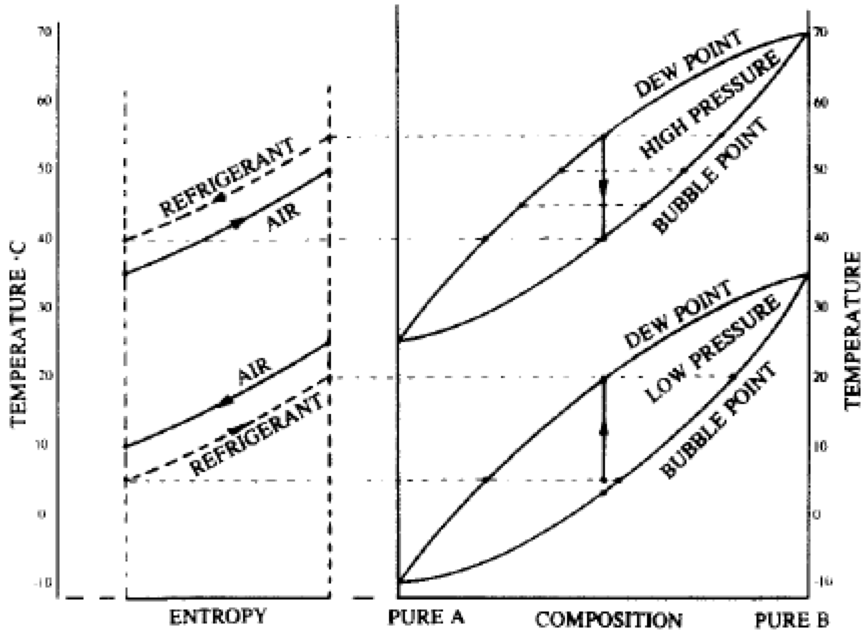


Figure 28. Temperature-entropy and temperature-composition diagrams illustrating the mixed refrigerant system. Upper pair of lines are for condenser and lower pair for evaporator (from Bensafi, and Haselden, 1994).

The use of wide glide refrigerants in this format is often termed a Lorenz-Meutzner cycle after the original inventors of the cycle. Lorenz and Meutzner (1975) claimed 20% energy savings using a R22/R11 mixture for a 2-compartment refrigerator/freezer. Other studies using R22/R123 have shown a 9% reduction in energy consumption and predicted improvements in COP of 16-20% (Liu et al, 1995). A further modified version of the Lorenz-Meutzner cycle was developed by Radermacher and Jung (1993) which incorporated suction liquid heat exchange in the freezer and refrigerators compartments. Experimental tests demonstrated savings of 16.5% using an HFC mixture (Zhou et al, 1994) and 17.3% energy savings using a hydrocarbon mix of propane/n-butane/pentane (R290/R600/n-c5) (Liu et al, 1995). Yoon et al (2012b) showed a reduction of 11.2% in energy when using R290/R600 instead of just R600a.

Scope 1 emissions savings (% or another quantifiable metric)	Dependent on refrigerants applied
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	9-20%
Quality of scope 2 emissions information	Medium
TRL level	4
Maintainability issues	None identified
Legislative concerns	None identified

Payback time (years)	No information but the cost of refrigerant is unlikely to increase considerably

9.2. Ovens and heating equipment

9.2.1. Air fryers

Due to the cost-of-living crisis, air fryer sales have risen dramatically (3,000% increase from end of 2021 to end of 2022) (Sky News, 2024). This is because they are economical to run and take very little time to warm up. Air fryers are much smaller than ovens and so less heat is wasted heating the oven, rather than the food.

Ferreira et al. (2017) describe the process of air frying as circulating hot air uniformly around the food instead of immersing it in hot oil. According to Banino (2022), air fryers use a combination of radiation through a heating element at the top and convection by rapid airflow through fans. Thus, the appliance is rather a special variant of convection oven than a fry, enabling the preparation of dishes other than fried food. Air fryers for domestic application are typically countertop devices.

Scientific publications regarding the energy consumption of air fryers, especially in comparison to other cooking technologies are scarcely available. Manufacturers state the energy savings by using an air fryer compared to a conventional oven (energy class A) to be 70% when preparing frozen fries (Tefal, 2024) or 60% when preparing one chicken breast or salmon filet (Philips, 2024). Gibbs (2023) compared the energy costs to cook a 600 g chicken breast in a conventional fan oven or in an air fryer and states costs of €0.27 in 02/2024 for the conventional oven and €0.20 for the air fryer which is a reduction of 26%. Hooper and Sturla (2023) investigated the energy demand and costs related to cooking a range of foods in nine different domestic appliances. They found that products with a longer cooking time like baked potato (350 g) lead to an energy consumption of 0.85 kWh in an air fryer compared to 1.03 kWh in an electric oven and 1.49 kWh in a fan assisted oven, giving a reduction in energy consumption of 43% comparing the air fryer to the fan assisted oven.

Azmi et al. (2019) determined the optimal temperature and duration for baking moist cakes in an air fryer and convection oven and found an optimal temperature of 150°C for both cases and a baking time of 25 min for the air fryer and 35 min for the convection oven suggesting possible benefits regarding energy efficiency for the air fryer. In terms of cooking time, Hooper (2023) showed considerable differences between different models - for the 10 tested models with a rated power of 1,400 W operated at a calibrated temperature of 180°C the time taken to achieve minimum safe cooking of a frozen burger varied between 17 and 25 minutes.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	26 to 70%
Quality of scope 2 emissions information	The information was retrieved from online articles and
TRL level	8-9

Maintainability issues	None
Legislative concerns	None
Payback time (years)	Strongly depends on the usage time

9.2.2. Cooker hoods

Energy consumption of hoods is a function of a set of factors such as aerodynamic design, fan power curves and filter pressure drop curves as a function of dirt load, but also lighting energy. Cicconi et al. (2017) developed a method and calculation tool that can support designers in the early estimation of product energy performance, including the calculation of EEIs of hoods with respect to these factors. Further energy losses may arise due to effects on the HVAC balances of the kitchen. Using LEDs, the latter should be a minor contributor. According to suppliers (Cool Blue, 2023), with an energy-efficient A++ range hood, the annual energy costs are about €10. By contrast, a range hood with an E energy label is less energy-efficient and costs €42 per year on average. The EU (Anon., 2015) provides consumers with guidelines for correct selection and use of hoods, including: (1) Use a low setting and use the boost, if necessary, (2) a well-ventilated kitchen makes the range hood more efficient, (3) replace odour filters and clean regularly to keep the filter efficiency high, as a saturated filter cannot perform and leads to longer usage times.

Braunlich et al. (2023) claimed that the energy consumption of cooker hood systems mainly results from the sum of the ventilation heat losses due to the exhaust air volume flow (without heat recovery) during the operating time of the cooker hood and the infiltration losses due to leaky exhaust air flaps outside the operating time as well as thermal bridging effects of the exhaust air flaps.

Zhao et al. (2013) investigated different types of hood shapes and side panels to improve the capture efficiency. Higher capture efficiency may correlate to lower energy use, as time of operation could be reduced. Basic site tests and computational fluid dynamics (CFD) analysis were conducted. The simulated results showed that increasing hood volume did not improve capture performance. However, side panels did improve the capture efficiency, especially at higher positions. In addition, when the exhaust opening was located at the rear of the hood, the hood capture efficiency was enhanced.

Demand Control Kitchen Ventilation (DCKV) systems have been suggested for commercial food service facilities and could potentially also apply for domestic use (US Department of Energy, 2015). DCKV systems adjust the quantity of kitchen hood exhaust and incoming outdoor air, leading to energy and cost savings. It was found that the energy and cost savings that can be achieved by installing DCKV varies between food service facilities due to site- and equipment-specific factors such as geographic location, operating hours, DCKV system features, and system cost. The implementation of a functional and efficient ventilation solution for an entire food service operation can be a complex matter, involving both air speed and flow balancing within and between building spaces. Taking these aspects into consideration, it may be even more difficult to implement for domestic application, where every kitchen is different in size, layout and facilities, while commercial kitchens of a particular brand may be quite similar. The below applies for commercial kitchens.

DCKV saves energy by adjusting the quantity of kitchen hood exhaust and incoming outdoor air to reflect the amount of cooking taking place under the hood. Energy savings directly relate to

1. Reduced run time of fan motors of the exhaust unit and balancing air supply unit(s) (makeup airflow/HVAC)
2. Reducing need for heating/cooling of the makeup air by the HVAC system to balance the heat losses through the exhaust.

DCKV relies on detection of cooking activity under the hood using sensors (temperature/optic/IR, energy input, time), and applies control algorithms to translate the sensor signals into adjustment of the fans of the exhaust and HVAC/makeup air supply units.

The controls include a VFD (variable frequency drive) to adjust the motor speeds of the exhaust hood and makeup air unit fans, ventilation dampers in the hood and the HVAC supply, and smart shutdown of cooking appliances.

The extent of the energy savings of DCKV is related to (Fisher et al., 2013):

- Exhaust ventilation rate: the benefits are expected higher for larger unit systems (with rates above 5000 CFM)
- Geographical location: the benefits are expected higher in regions with large demands for cooling/heating and small for systems that only have makeup air supply with conditioning.
- Operating hours: more savings are expected for systems with longer operating hours.
- Fan characteristics: the savings are expected larger for energy consuming fans (with a high static pressure and low efficiency).
- Other energy use factors: heating, cooling and dehumidification setpoints, position of the heating appliances in the kitchen, thermostat position and operation

Retrofit options can be considered based on specific criteria such as ventilation rate, size and design of the hoods, operating hours, HVAC requirements.

Further research has considered aspects of hood installation and appliance placement that can significantly impact the hood performance (Fisher et al., 2015).

Scope 1 emissions savings (% or another quantifiable metric)	For DCKV: Average total fan power reduction: 57% (30-80%) Average exhaust fan power reduction: 26% (15-40%) Average annual fan energy savings: 40500 kWh/yr (7900-150800 kWh/yr)
Quality of scope 1 emissions information	Based on research of 1 research group (PG&E Food Service Technology Center,CA, US) reported in an ISI Journal (Fisher et al., 2013) considering 11 different types of food service operations at different sites in the US. PG&E FSTC aims to provide unbiased, comprehensive information about energy use and efficiency (with ref to https://www.pge.com/en_US/small-medium-business/business-resource-center/training-and-education/food-service-technology-center.page). The research has led to updates of the US national codes (The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 154, NFPA 96, UMC, ASHRAE/IES Standard 90.1 and California Title 24) and changing the way CKV systems are designed and operated as explained in (Fisher et al., 2015). The work has also led to a report by the US Department of Energy explaining the practical roll-out of DCKV (US Department of Energy, 2015).
Scope 2 emissions savings (% or another quantifiable metric)	HVAC energy reduction, no average values reported. One particular case claim 29% savings (see below).

Quality of scope 2 emissions information	Reported in (US Department of Energy, 2015)
TRL level	9
Maintainability issues	Continued maintenance of the exhaust and HVAC systems
Legislative concerns	-
Payback time (years)	1-5 years: return on investment analysis has been performed (US Department of Energy, 2015) for specific cases: • A system with 6000 CFM exhaust flow and 4800 CFM makeup air flow in California and 13.1 h of daily operation had a 61% fan energy reduction and a payback time of the investment of 3.5 years at an electricity cost of $0.15/kWh • A system of 22500 CFM exhaust flow and 19500 makeup flow in California with a 24/7 operation had a 62% fan energy reduction and 29% savings on HVAC had a payback time of less than 1 year.

9.2.3. Cooking - gas, electric, induction, microwave, halogen

Li et al. (2022) assessed the environmental and economic impacts of various types of cooking fuels and stoves from a Chinese situation perspective where cooking was still largely done with solid fuels. According to the assessment results, the environmental impacts were highly influenced by the types of fuels and the efficiency of stoves used for cooking. Using biogas, liquefied petroleum gas (LPG), and natural gas for cooking instead of solid fuels could significantly reduce environmental emissions. The average annual cost of electricity was higher than that of natural gas. Regarding the substitution effects from other energy sources, using natural gas for cooking was better than using electricity generated from coal. In this framework, the environmental benefit of electricity substitution was only 10%–20% of natural gas substitution, and the corresponding increasing cost for residents was 1.5 times that of natural gas substitution. This analysis confirms earlier work of Ramanathan and Ganesh (1994), that showed production/transfer efficiency of electric energy ovens to be only 25%, compared to 90% for direct gas fired appliances. The production/transfer efficiency relates to the efficiency of the fuel up to the point it is used. For example, only 10% of the energy of the natural gas is lost before it is used, whereas 87% of the energy from electricity is lost. This does not consider the efficiency of the oven, in this case the gas oven may lose 50% of its heat, whereas the electric oven only 20%.

As electricity generation from cleaner and RES increases, the benefit of electric cooking will become significantly larger, which is the case in the EU. In recent years there has been a trend towards electric ovens, partly also because of an increase in the number of built-in appliances where installation of electric ovens can be more convenient. A practical study revealed gas ovens to consume up to 50% more energy per use than electric ones, and gas hobs 25% (Anon, 2023a). According to Ramanathan and Ganesh (1994), the end-use efficiency of LPG and natural gas for cooking was typically only 50% while the end-use efficiency of electricity was approximately 80%.

Atuonwu and Tassou (2021) analysed different electrified technologies that could significantly reduce food processing greenhouse gas emissions, compared to conventional thermal treatment due to the combined effects of electricity grid decarbonisation, end-use energy-efficiency, and time savings. For home cooking the following technologies are relevant:

- Microwave (MW) heating acts by direct effects of the electromagnetic waves on the dipole rotation of molecules and ionic conduction inside foods. It usually is implemented in a closed cavity within which the electromagnetic waves, generated usually by magnetrons, are delivered to the food material.

    - MW reduces energy consumption and processing time due to volumetric heating of the food only, without a need of a heating medium (such as hot air or steam) Jouquand et al. (2015) studied the optimization of microwave cooking of beef burgundy in terms of nutritional and organoleptic properties. Energy consumption of the optimised MC conditions was lower than the conventional process (4.67 kWh vs 6.52 kWh, 28% lower) and the cooking time was decreased by 56% compared to traditional cooking in a convection oven.

    - An energy assessment was carried out by Lakshmi et al. (2007) for rice cooking in a microwave oven at various power levels. Although the absorption of microwave energy in water was 86-89%, the conversion efficiency of electrical to microwave energy was approximately 50%. The performance of microwave ovens was also compared with our earlier studies on both electric rice-cookers (ERC) and pressure cookers. Among the cooking appliances assessed, ERC was the most energy-efficient while microwave cooking offered the least cooking time (15-22 min). Microwave cooking was on par with pressure cooking, the most commonly followed method of cooking rice, in terms of energy consumption, besides, it offered shorter cooking time. Nowadays electric energy use efficiency of microwaves has increased to 65-75% for 2450MHz magnetrons, so the above comparison may be outdated.

    - In this context, more practical oriented research (Anon. 2023b) showed that the microwave oven was overall more energy efficient and cheaper than the hob for foods which are usually boiled in lots of water such as vegetables. When these are cooked in a microwave only small amounts of water are needed and cooking is much quicker (with energy use savings from 65 to 70%), whereas on a hob lots of water is used and it takes a long time to come to the boil and then cook. For heating or warming up food such as baked beans or porridge then the hob proved to be less energy consuming (from 8 to 72%). For most meals a microwave oven is also cheaper than an electric oven (from 25% to 78%). Generally speaking, the greater the time differences between the different cooking methods, the greater the savings. However, it was noted that the advantage of the microwave oven is reduced if multiple foods/meals are cooked in a conventional oven together. For example, roasting a chicken with all the vegetables at the same time as opposed to separately in a microwave. The differences between conventional and microwave cooking of specific foods are also confirmed by Hager and Morawicki (2013) who performed a review from different resources and listed cooking efficiencies between 16% and 98%.

o In terms of food quality, combination heating with hot air and/or radiation heating has been advised.

- Induction heating uses an alternating voltage source that supplies electrical energy to a coil, creating alternating magnetic fields around it. The fields couple without electrical contact, to metallic processing vessels or pipe sections housing the food, producing heating effects in them by magnetic hysteresis and eddy currents. Basaran et al. (2018) considered tomato paste sterilization/pasteurization. After assumptions and theoretical calculations for both conventional and inductive heating, it was found that the inductive heating system had 95% energy use efficiency while the conventional heating system with electric boiler had 75% energy use efficiency. Anon. (2023a) claimed a 30% reduction in energy use for induction hobs compared to standard electric hobs. Rose and Morawicki (2023) tested the energy consumption and efficiency of cookpots operating with induction, infra-red (IR), resistance plate, resistance coil, and electric pot. Of the five appliances tested, the induction cooktop and the electric pot were the most energy efficient and took the least time to boil water. Induction lost efficiency by approximately ten percentage points when used with large pots, thus reinforcing the importance of matching the pot size with the heating element. Based on earlier works, Hager and Morawacki (2013) compared standard test results of end use efficiency of induction stoves compared to different alternative techniques and reported more than 80% for induction cooking compared to 50-65% for other electric methods, and only 25-35% for gas stoves.

- Halogen hubs were shown by Hager and Morawicki (2013) to have a similar end use cooking efficiency (75-90%) as the induction stove.

Hager and Morawicki (2013) further list various improvements that can be made to different electric and gas heating appliances and the expected effects on energy use efficiency.

To calculate the payback of microwave versus convection ovens the following data was used;

	Convection-oven	Microwave
Average price (€)	446	654
Average energy use per cycle (kWh)	0.87	0.22
Cost per cycle (€)	0.34	0.08
Cycles per year	200	200
Cost per year	67.9	17.0
Payback period (years)		4.1

To calculate the payback of induction versus conventional/resistive hobs the following data was used;

	7 kW 4-plates electric resistance hobs	7 kW 4-plates induction hobs
Average price (€)	632	939
Average energy use per cycle (kWh)	0.75	0.38
Average cost per cycle (€)	0.29	0.15
Cycles per year	400	400
Cost per year	117.0	58.5
Payback period (years)		5.2

Scope 1 emissions savings (% or another quantifiable metric)	100% from gas to electric.
Quality of scope 1 emissions information	Few numbers on public webpages. Very few numbers in peer reviewed publications.

Scope 2 emissions savings (% or another quantifiable metric)	For electrified technologies: between 25% and 80% energy savings for microwave heating compared to conventional ovens and hobs for some foods. No or little savings in other cases. Up to 30% energy savings for induction/halogen hobs compared to conventional hobs.
Quality of scope 2 emissions information	Common to all electric methods
TRL level	9
Maintainability issues	None in particular.
Legislative concerns	None.
Payback time (years)	4.1 years for microwave versus convection oven 5.2 years for induction versus conventional/resistive hobs

9.2.4. Cooking at lower temperatures

"Low-temperature cooking" is a culinary technique in which heat is typically supplied to the food in the temperature range of 60-95°C (and does not refer to the temperatures reached inside the food). This approach offers energy-savings benefits due to the need to maintain lower temperatures, leading to reduced heat loss to the surroundings. Cooking at lower temperatures also helps minimise mass and energy losses caused by evaporation, especially when cooking liquids below their boiling points (Opadokun, 2019). For instance, in the context of stewing, a common method involves simmering liquids instead of boiling them. Simmering entails cooking a liquid at temperatures slightly below its boiling point, e. g. for water typically around 82-95°C (Hager and Morawicky, 2013), while boiling necessitates heating the liquid to its boiling point, e. g. for water at approximately 100°C.

The empirical findings of Popali et al. (1979) underscore the energy efficiency inherent in low-temperature cooking, with their investigation revealing a noteworthy disparity in energy inputs between cooking potatoes at a temperature between 85°C and 87°C as opposed to temperatures between 80°C and 82°C. Specifically, the study reports a marked reduction in energy consumption, from 0.09 kWh/kg to 0.06 kWh/kg, with a commensurate increase in cooking duration from 45 minutes to 105 minutes when decreasing the cooking temperature. According to Hager and Morawicky (2013) Scarisbrick et al. (1991), has demonstrated energy savings ranging from 4-13% when baking at lower temperatures.

According to Opadokun (2019), Brundrett and Poultney (1979) conducted an investigation of the energy efficiency of heating liquids (including simmering rather than boiling). Through a series of experiments involving heating pure water to varying temperatures between 40°C and 100°C and maintaining these temperatures for 45 minutes, they observed substantial reductions in energy consumption at lower cooking temperatures. Opadokun (2019), drawing from the findings of Brundrett and Poultney (1979), highlighted a significant disparity in energy consumption and mass losses between boiling and simmering pure water, with the former resulting in considerably higher evaporation rates compared to the latter (e. g. the mass loss of water increased from 600 g/h at 90°C to 1800 g/h at 100°C; the power needed increased from 600 W at 90°C to 2000 W at 100°C). According to Hager and Morawicky (2013), the research of Brundrett and Poultney (1979) showed that simmering (at 90 °C) rather than boiling (at 100 °C) can reduce the energy consumption between 69-95 %, with the greatest reductions being achieved when using pot lids. However, for short cooking times, e. g. when using a ceramic hob and a stainless-steel pot, Oberascher et al. (2011) demonstrated that heating pure water (250 ml, 500 ml and 1000 ml) from 15°C to 90°C incurred similar energy consumption and mass losses, irrespective of the presence of a pot lid, until reaching the boiling point.

Low-temperature cooking can be achieved using conventional kitchen appliances, with some modifications. For instance, using fans in traditional ovens can improve heat circulation and reduce energy consumption by about 30% (Probert and Newborough, 1985). Additionally, specialised cooking devices like sous vide cookers and slow cookers offer further opportunities for energy-efficient cooking. Studies, such as the one by Amann et al. (2007), have shown that slow cookers (more information can be found in the review on slow cookers) can substantially reduce energy use, with potential savings of over 60 % for certain dishes like meatloaf.

Moreover, innovative approaches, such as solar thermal-driven stoves as investigated by Popali et al. (1979), underscore the potential for leveraging alternative energy sources in culinary practices, aligning with broader sustainability goals and development of rural regions.

Scope 1 emissions savings (% or another quantifiable metric)	Up to 95 % (when directly burning fuel for cooking)
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Up to 95 %
Quality of scope 2 emissions information	The information was retrieved from peer reviewed journal papers
TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Depends strongly on domestic prices for energy and usage

9.2.5. Cooking method, fry, grill, bake, boil/stew, roast, broil, steam

Cooking can be defined as the preparation of food by application of heat for a certain amount of time. Alternatively, the generation of heat can be done within the food by electromagnetic waves by using a microwave (Hager, 2013). The process of cooking is responsible for 6 to 61 percent of the total greenhouse gas emission of certain foods (Frankowska, 2020) and energy use could be reduced by 18% by changing cooking methods (Reynolds, 2017). Each cooking method has its own associated greenhouse gas emission dependent on the fuel/energy source (electricity, natural gas, wood, etc.) and the type and efficiency of the appliance that is used (Cimini, 2022; BC Hydro, nd).

Generally, cooking methods that require higher temperatures and longer cooking times tend to have higher emissions (Frankowska, 2020). Greater portion sizes being cooked at once are always more energy efficient when using the same cooking method. For electric appliances it was found that cooking four portions took between 0.11 MJ and 1.3 MJ per portion, while cooking a single portion takes 0.29 MJ to 5.1 MJ per portion (Carlsson-Kanyama Annika, 2001). User behaviour can account for up to 30% difference in energy consumption when using equivalent equipment to cook (ETSAP, 2012)

Boiling, stewing and steaming:

Boiling involves cooking food in water at or near its boiling point. Greenhouse gas emissions from boiling primarily come from the energy used to heat the water. Electric kettles are found to be highly energy efficient as almost all the electrical energy goes into heating the water (Carlsson-Kanyama Annika, 2001). This makes an electric kettle 35% to 60% more efficient than a hotplate for boiling water (Carlsson-Kanyama Annika, 2001) and 50% less electricity is used then when using a stovetop (BC Hydro, nd). Stewing on the other hand involves cooking food slowly in liquid at low temperatures. Stewing in a slow cooker uses less energy than boiling the same foods (Frankowska, 2020). Steaming involves cooking food using steam generated from boiling water. Greenhouse gas emissions from steaming, like boiling come from the energy used to heat the water. Steaming is more energy efficient because of shorter cooking times (W.D.Colledge Co.LTD, nd). Using a microwave for boiling, stewing and steaming instead of a stovetop saves on greenhouse gas emissions as there is less rate of energy loss over a shorter time needed to reach the cooking temperature (Frankowska, 2020).

Baking, roasting, broiling:

An oven is typically used for baking, roasting and broiling. Preparing food by oven roasting requires more energy among different appliance types due to higher temperatures and longer cooking durations, resulting in higher greenhouse gas emissions and are generally the least sustainable option for cooking food (Frankowska, 2020). Broiling involves cooking food directly under high heat. Broiling may require less energy compared to roasting due to the shorter cooking time and direct exposure to heat (Hager, 2013).

Frying:

Frying is conventionally done by submerging food in hot oil. The primary source of emissions in frying comes from the energy required to heat the oil (Sonesson, 2003). Air frying can be an alternative to frying foods in oil. In the process of frying potato chips greenhouse gas emissions can be reduced by using a hot air frying method versus conventional deep frying. Carvalho et al. (2018) showed a reduction by 90.7% CO2-eq per year when hot air frying, mainly due to the elimination of the frying oil.

Grilling:

Grilling involves cooking food over an open flame or hot surface by radiant or contact heat (ETSAP, 2012). Greenhouse gas emissions from grilling depend on the type of fuel used, such as charcoal, propane, natural gas, or electricity. Charcoal grilling typically produces higher emissions compared to other methods (Cimini, 2022). Electric grills powered by RES have the potential for lower emissions compared to those powered by fossil fuels (Frankowska, 2020).

Food differs in taste, texture and aroma depending on the cooking method used. Switching between cooking methods is therefore not always possible.

In order to still compare cooking methods an approximation of specific energy consumption (SEC) per kg of raw food has been made by Foster (2006):

- Roasting: 9 MJ/kg (gas or electricity)
- Frying: 7.5 MJ/kg (gas or electricity)
- Boiling: 3.5 MJ/kg (gas or electricity)
- Microwaving: 0.8 MJ electricity/kg

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Depended on the cooking method, food type, fuel/energy source, appliance, cooking time. According to Foster (2006) the specific energy required for a kilogram of raw food: - Roasting: 9 MJ/kg (gas or electricity) - Frying: 7.5 MJ/kg (gas or electricity) - Boiling: 3.5 MJ/kg (gas or electricity) - Microwaving: 0.8 MJ electricity/kg
Quality of scope 2 emissions information	Good
TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Not relevant, most households have access to a range of cooking appliances at an estimated cost of 50 to 1500 euros.

9.2.6. Door seals and insulation, reduced heat load

In the context of electric ovens, energy losses can occur through radiation, convection and when the oven door is opened (Gumaer 1915). Improved insulation can help to maintain a more uniform temperature field within the oven, which is essential for efficient cooking (Krishnamoorthy et al. 2012). Insulation reduces heat loss to the environment and thus improves energy efficiency. The use of high resistance insulation materials, such as thick insulating cotton, can significantly improve the thermal efficiency and temperature uniformity of the oven. In addition, seals around the oven door and other openings are important to prevent heat loss, which can further improve energy efficiency by reducing the need for additional heating to compensate for lost heat. (Qiyuan 2021)

Bignardi et al. (2013) summarised that significant efforts have been made in the past two decades to improve the energy efficiency of home appliances. Consumers are increasingly interested in the potential savings from energy-efficient appliances. Domestic electric household ovens have a reported thermal efficiency of about 12.7%. Most of the heat input is absorbed by the structure (e.g. walls, door and insulation) or dissipated to the surroundings. Approximately 47% is absorbed by the oven structure, 25% is lost through the walls, and 15% is lost as evaporated moisture through the vent. To reduce this energy dissipation, one possible solution is to design a high-efficiency or low-emissivity oven (LEO). LEOs are electric appliances that were developed in the late 1990s as energy-saving devices. Their main feature is that they reflect a high proportion of thermal radiation onto the food, while only a limited amount of energy is absorbed by the oven's walls and structure. LEOs achieve a much quicker thermal response and reach the required air temperature in one-third of the time of a similar conventional oven. This oven design resulted in a thermal efficiency of 23% which is a 10.3% increase in thermal efficiency compared to conventional domestic ovens (12.7%).

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	10.3%
Quality of scope 2 emissions information	The information was retrieved from, peer reviewed journal and conference papers and textbooks
TRL level	8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Depends strongly on domestic prices for energy and usage

9.2.7. Efficient oven design

Improving energy efficiency of ovens has been suggested by means of design improvements. In most studies, computer simulation approaches such as CFD are used to assess the effects of design changes on energy efficiency (Al-Nasser et al., 2021; Chhanwal et al., 2012; Therdthai et al., 2003). CFD computes fluid flow, heat and mass transfer in ovens to render spatial and time maps of important process variables such as temperature and moisture of the fluid and product, and the different heat transfer rates composing the overall energy balance. In some cases, the CFD analysis is calibrated using experimentally determined inputs (Khatir et al., 2013; Paton et al., 2013).

Ramirez-Laboreo et al. (2016) modelled a small convection-radiation oven and explored the energy flows. Two different one-hour cooking processes were simulated to analyse the energy behaviour of the system: a convective cooking method such as bread baking and a mostly radiative process like meat roasting. To properly compare the results, the set point oven temperature in both simulations was 200 °C with the same initial temperature. was more evenly distributed in the convective process and the load received a larger amount of energy, about 13% compared to 11% in the radiative one. However, this operating mode has also caused a high increase in water evaporation (20% of the energy compared to 8%). They found also that energy losses in the radiative simulation were much higher than in the convective one, mainly in stationary state. The results of a design study revealed that energy consumption would be reduced by 0.9% in the one-hour convective process and by 1.3% in the radiative one, mainly because design changes caused the mass to be heated be lower.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	Up to 5.2% specific energy savings by improved oven design 43466 CO_{2e} for industrial bread baking across Europe Improved uniformity of heating may lead to reduction of losses (over- or under-heating)
Quality of scope 1/2 emissions information	Peer reviewed calibrated CFD simulation study on 1 type of oven from 1 research group extrapolated to EU scale, without experimental

	verification of the optimal solution. Numerous CFD studies available, few actual present energy savings numbers.
TRL level	7
Maintainability issues	Mechanical adaptations should be compatible with cleaning requirements.
Legislative concerns	-
Payback time (years)	Depends on cost of optimization studies, investment costs of adding mechanical parts and applicability scale of the changes. No public data available and always very specific.

9.2.8. Fan assisted vs natural convection

Fan-assisted ovens use a fan to circulate hot air evenly throughout the oven cavity, which ensures uniform heating and faster cooking times compared to natural convection ovens. This allows for lower cooking temperatures or reduced cooking times. Forced air circulation also allows heating elements of higher power, up to 3 kW, which ensures shorter preheat times.

To counterbalance the improved heat transfer, appliance manufactures as well as food manufacturers recommend setting the fan oven temperature to 20°C cooler for the same recipe than for natural convection ovens. While the reduction of cooking temperature offers energy saving potentials, this is offset for fan-assisted ovens due to the operation of the fan motor.

In a 2023 study, Campden BRI determined the energy and cost to cook a range of foods in domestic appliances, including electric ovens set to 200°C for natural convection and to 180°C for fan assisted ones. The energy used and cost was determined separately for preheating the appliances and for cooking a range of foods. When preheating the oven to 200°C, the average amount of energy consumed across the three trials performed was 0.388 kWh, for the natural convection oven. For preheating the fan assisted oven to 180 °C, the average amount of energy consumed across the three trials was 0.472 kWh, about 22% higher. Preheating the ovens, has exceeded 2 to 4 times the preheating energy use of other trialled alternative cooking methods like air fryers, electric grills and deep fat fryers. For preparing the various ready-to-cook foods and dishes (sausage, lasagne, fishcake, haggis, bacon, chocolate pudding, baking potato and toffee pudding), the fan assisted oven set at 180 °C consumed 16% to 45% more electricity compared to the natural convection oven set at 200°C (including the cost of preheating the oven).

The authors have concluded that with the energy and costs involved with preheating it could be argued that it might be more efficient to not preheat ovens and, rather than 'waste' the energy in preheating, simply start to cook or heat products without preheating. Though this would result in less energy being required to cook a product, this does not consider the differences in appliance performance. Thus, it would not be possible to rely on the safety of 'on pack' instructions, as they could not take into account the likely variation in preheat times and their effect on required cook times. Also, cooking appliance had a greater impact on cooking energy usage, and therefore cost, than product type and starting temperature – with a fan assisted oven using up to 1.5 times the energy used by the natural convection oven for cooking the same products.

Fan assisted ovens provide a range of cooking functions and modes, offering versatility in the kitchen beyond basic baking and roasting; these ovens are able to perform various cooking techniques, such as grilling, convection and fan cooking, while also allowing for precise temperature control. However, their flexibility and adaptability to different culinary tasks and for handling complex recipes and diverse cooking needs comes at a cost of higher energy use. Campden BRI proposes that cooking energy / cost information could be used by food manufacturers to include options for heating instructions, so that consumers would be able to make an informed choice of product and cooking appliance in the knowledge of the impact on their energy bill.

NB: Fan assisted ovens are mostly electric although there are a few models which are gas heated. Gas fired stoves were recently highlighted as a source of indoor air pollution – cooking with gas emits carbon monoxide, nitrogen oxides, particulate matter and even formaldehyde (Lebel, 2022) and has been associated with an increased risk of asthma among children (Gruenwald, 2023). As of 2023, some US cities and states have passed laws to prevent gas stoves in new buildings for this reason, therefore the gas fired, fan assisted vs natural convection options are not included in this review.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Negative -25%
Quality of scope 2 emissions information	High, supported by experiments under real-life testing conditions
TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	n/a

9.2.9. Hot water for beverages - kettles, hot taps, coffee machines

Kettles

Kettles are usually used for making hot beverages, however they can also be used instead of a hob to heat water for cooking, although this is usually to preheat the water before cooking/boiling on the hob.

There are two ways to save energy with kettles that only require changes in the way they are used. These are;

- Not overfilling. Often kettles are used for one or two cups of tea, but the kettle is often over-filled, boiling more water than is needed. Choosing kettles with low minimum flow rate, e.g. 250 ml which is about a mug of water, will make it easier to only boil what is required. A fill level allows you to ensure that you do not overfill the kettle. However, Engelking et al. (2019) stated that there was no observable effect of the minimum fill level marker on the amount of excess water heated.
- Boiling the kettle more than once is another waste of energy. It is common to boil a kettle and then come back a few minutes later and boil it again.

Engelking et al. (2019) stated that the amount of excess water heated significantly varied by usage purpose as well as the time sensitivity of the usage purpose. They included uncertainty in the need for hot water in the near future, flexibility in the needed volume for a usage purpose, forgetting to use heated water, and concerns about limescale build up. They found that the median overfilling for a hot drink was 0.3 L and for cooking was 0.2 L. According to a survey by the Energy Savings Trust three-quarters of UK households overfill their kettle. In 6 of 14 houses, 10% of the time kettles were reheated within 5 minutes of boiling.

Durand et al. (2022) have shown that it is more efficient to heat as much water as possible, as long as you use it all.

There are a number of different technologies that can be used to make kettles more efficient.

- Double walled skin to keep the heat in. Durand et al. (2022) showed that the average keep-warm power for the insulated model was roughly half that required for a single-wall kettle.
- Immersed rather than concealed heating elements are more efficient (Durand et al., 2022).
- Keep warm features are convenient, however, they increase energy consumption.
- According to Durand et al. (2022), shutting off the kettle as soon as it reaches temperature.
- You can get kettles with different temperature settings, so you do not need to boil water, if a lower temperature is required.

Boiling-water taps

These are different from normal hot water taps, which normally come from the centralised heating system and provide water at approximately 60°C. These taps provide water at close to 100°C (“boiled”, to replace a kettle.

Boiling-water taps do not boil the water as and when needed as kettles do. Instead, they maintain boiled water in a tank underneath the sink. The water is heated and stored at the correct temperature so each time you turn on the tap you get instant “boiled” water.

The energy advantage over a kettle is that any unused water in a kettle will quickly cool down and the energy will be wasted. For a boiling-water tap, the water in the tank will be maintained at temperature, using energy even when water is not required. However, the tank is heavily insulated. For high usages the hot water tap will work out more efficient as extra energy to maintain the hot water in the tank will be less than the repeated cooling down in the kettle. For low usage the opposite will be true.

According to Hobson’s-Choice (2022) a study by Npower stated that boiling a full kettle (0.85 l) 4 times a day will cost 12.6 p/day in UK at 2022 prices. A boiling-water tap costs 3 p/day to maintain temperature and 1 p/day to dispense, therefore 7 p/day total (4 dispenses a day). This indicates a boiling-water tap to use less energy. However, this assumes that a full kettle is boiled each time.

Cotrell (2023) say that only 20% of the energy is used boiling one cup than a full kettle, therefore, the kettle would be more energy efficient if it was not overfilled.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	No data

Quality of scope 2 emissions information	Poor
TRL level	9
Maintainability issues	
Legislative concerns	
Payback time (years)	

9.2.10. Manual rather than pyrolytic cleaning (high temperatures to burn off grease)

The inner walls of conventional electric ovens are seldom heated to temperatures higher than 200 °C but any fats deposited on the oven walls are easily oxidised, polymerised to a viscous mass at this temperature. A pyrolytic oven is a self-cleaning appliance that utilises high temperatures to incinerate food residue and grease, eliminating the need for manual scrubbing. Pyrolytic ovens usually have a dedicated cleaning cycle or program that can be selected from the oven's control panel. During the cleaning cycle, which reaches temperatures as high as 400 to 450 °C, the oven locks its door and converts organic matter into ash. This process effectively removes stubborn stains, baked-on spills, and grease from the oven's interior, including walls, racks, and the door. The oxidation catalysts may include manganese dioxide, nickel oxide and colloidal platinum, together with a polymerisation inhibitor like antimony trioxide, aluminium and zinc oxides and silicates (Izuoka and Kusaki, 1979).

Ovens with pyrolytic self-cleaning are highly energy efficient as they are equipped with reinforced thermal insulation, multiple door glazing, and special door seals to ensure they can reach the high temperatures needed to burn the residue away. As a result, these ovens consume up to 19% less electricity than ovens without pyrolytic self-cleaning function when baking and roasting (Brischke 2010). However, they use more energy when running the cleaning cycle.

While the pyrolytic cleaning feature offers convenience and thorough cleaning, pyrolytic ovens do come at a higher cost compared to regular ovens and they consume significant energy during the cleaning process as it can take several hours to complete. A study (Amienyo, 2015) made on a conventional pyrolytic oven versus a Highly Efficient oven (HEO), featuring a stainless-steel cavity with high reflectivity and a sol–gel coating to prevent the loss of reflectivity owing to metal oxidation, evaluated the electricity consumed and oven cleaning over its lifetime. The conventional oven can be cleaned either by using chemicals (aerosol oven cleaners or traditional dish-washing detergents) or a built-in pyrolytic self-cleaning cycle. The HEO can be cleaned using traditional dish-washing detergents. For the use stage, 110 use cycles and 10 pyrolytic cleaning cycles were assumed annually over 19 years for both types of oven.

The conventional oven consumed 0.69 kWh electricity per cooking cycle and 3.5 kWh of electricity over 75 minutes for the short pyrolytic cycle, or 6.5 kWh of electricity over 120 minutes for the long pyrolytic cleaning of stubborn soils, both are carried out at 440 °C. Such usage pattern resulted in a lifetime electricity consumption of 1442 kWh for cooking and an additional 665 kWh (additional +46%, or 32% of the combined electricity use) for the short pyrolytic cycles or 1235 kWh (additional +86% or 46% of the combined use) when using the long pyrolytic cycles.

A pyrolytic oven may use more energy than a conventional oven that does not have the increased insulation in cooking (non-cleaning) mode. However, it would use more energy than an oven with the enhanced insulation that was not operated in cleaning mode.

It is evident that the use of pyrolytic cleaning cycles significantly increases electricity consumption in exchange for user convenience. However, alternatives to pyrolytic cleaning, such as novel interior coatings like the Highly Efficient oven or steam clean ovens, offer viable options. Steam clean ovens utilise hot steam to soften grease and grime, facilitating easier wiping for oven cleaning without the need for burning residue.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Up to 32% (assuming 1 pyrolytic cleaning after 11 typical oven use cycles)
Quality of scope 2 emissions information	Medium – the available study compared only one appliance model.
TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Immediate

9.2.11. Microwaves - inverter technology, combination, improved power supply, improved fan, improved magnetron, reflective surfaces

Modern microwave ovens are not only used to warm food quickly and efficiently, but can also include several other features. For example, convection, baking and roasting is possible, whereas with a quartz or halogen heating light food can be browned. **Inverter technology** allows the microwave output power to be modified. (Bansal et al., 2011).

Bansal et al. (2011) stated that, “The overall energy use in microwaves is reduced by about two-thirds compared to a conventional oven […]”. The reason for this is claimed to be the reduced cooking time.

Uswitch.com has published online articles in which the energy efficiency of cooking appliances is discussed. A list with tips for energy-efficient cooking is provided and states that the microwave is generally the most efficient way to heat up and cook food. Compared to an oven it has the benefit of its smaller size and it only heats up the food and wastes less energy for heating the air around it. (Gallizzi, 2024).

Regarding the cost of usage, a price comparison was carried out. Based on the average power rating of the appliances the microwave is stated to cost €0.33 in 02/2024 per hour and the oven (electric/fan) to cost 0.20 € per hour. (Gallizzi, 2024; Gallizzi, 2023).

Although the period of usage has to be taken into account. A microwave usage of 10 minutes would therefore only sum up to 0.05 €. (Gallizzi, 2024).

Provided data regarding the average usage time states the average time used per week for the microwave was 96 minutes and the oven 180 minutes. (Gallizzi, 2023).

In the following table an overview of the data is given.

Table 7: Cost comparison microwave and oven (Gallizzi, 2023).

Appliance	Average minutes used per week	Cost per hour	Cost per week per household	Cost per year per household
Microwave	96	0.33 €	0.51 €	26.74 €
Oven (electric/fan)	180	0.20 €	0.61 €	31.59 €

There are not only conventional microwaves available on the market but there are also combined systems. Hybrid microwaves combine induction heating with microwave cooking technology. A combined IR-microwave, is where IR and microwave heating are combined, which can according to Sumnu et al. (2005) lead, when compared to conventional baking, to a baking time reduction of 75%, with no quality loss. (Bansal et al., 2011)

Regarding the feasibility of the microwave hybridisation, Bansal et al. (2011) state: "This hybridization required change of typical kitchen infrastructure which resulted in limited market penetration. Induction cook tops and dual cavity ovens are considered as main feasible energy efficiency options since this industry lack the energy standards motivation."

In Morawicki and Hager (2013) different modifications and features for several cooking appliances and their effect on the efficiency are listed. The data for the microwave – which is referenced to the U.S. Department of Energy (DOE, 2008) – is shown in the following table, and includes improved power supply, improved fan, use of reflective surfaces and improved magnetron:

Table 8: Microwave features or modifications and their increase in efficiency (DOE, 2008)

Feature or modification	Increase in absolute baseline efficiency
Improved power supply	2.9%
Improved fan	0.23%
Use of reflective surfaces	0.5%
Improved magnetron	0.9%

Morawicki and Hager (2013) compared the efficiency of different modern cooking methods. . To do this, they used data from various sources (e.g. Pimentel et al., 2009; Warthesen et al., 1984; Lakshmi et al., 2007; Carlsson-Kanyama and Bostrom-Carlsson, 2001; Oberascher et al., 2011):According to Morawicki and Hager (2013) the efficiency of the microwave is influenced by different factors. One factor is the food which is to be prepared. When cooking different vegetables using a microwave compared to boiling on the stove, the energy consumption can be reduced up to 65% (Warthesen et al., 1984; Pimentel et al., 2009), whereas when cooking dry products like grains, rice, and navy beans the efficiency drops significantly and the microwave is stated to be less efficient than other cooking methods (Lakshmi et al., 2007; Warthesen et al., 1984). As a possible reason for this the high energy demand for simmering products in the microwave is mentioned (Carlsson-Kanyama and Bostrom-Carlsson, 2001). Measurements taken by Carlsson-Kanyama and Bostrom-Carlsson (2001) comparing simmering in a microwave oven with a sensor regulated simmering function to a hotplate, indicate 36 to 92% more electricity demand per portion for whole wheat, rice and barley and four times higher power consumption while simmering in the microwave compared to the hotplate kept at simmering. As another influencing factor the volume of fluid or mass of the food product is mentioned. For instance, 250 mL of boiling water was prepared more efficiently in the microwave than on the stovetop, whereas for 1000 mL using the stovetop was more efficient (Oberascher et al., 2011).

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Up to 2/3 less energy consumption when cooking with a microwave compared to cooking with a conventional oven. Although the efficiency is influenced (among other factors) by the food itself and the amount of food which is to be prepared.
Quality of scope 2 emissions information	Good
TRL level	L (regarding conventional microwaves in general)
Maintainability issues	8-9 (regarding conventional/standard microwaves)
Legislative concerns	n/a
Payback time (years)	4 years (see ovens section)

9.2.12. Oven light control

The EU's Energy-Related Products Directive (ErP Directive 2009/125/EC) is intended to encourage manufacturers and importers to provide consumers with products that are more energy and resource efficient.

A difference can be made between the interior oven light (lamp) and the warning lights or indicator lights that are present on the oven. Those lights indicate that oven is preheating, desired temperature is achieved, or a technical problem has occurred.

BJB GmbH (www.bjb.com) has developed 'LED oven lights' with the advantage of low power consumption, durable lighting solution, small plate cutouts to reduce energy losses. Variants are available for steam, pyro and microwave or their combination. Also, different light colours or 'tunable white' is possible.

Vossloh-Schwabe (www.vossloh-schwabe) is provider of LED solutions and lamp holders for ovens, steam ovens, pyrolytic ovens and microwaves.

J&V (jv-cn.com) has developed LED oven lamps since 2015. They offer LED low voltage high temperature lights and LED high voltage lights for ovens. The company has developed a series of low-voltage consumer LED oven lights that are more stable than halogen lamps, longer live with similar cost.

TEMPOMATIC (www.tempomatic.net) uses an innovative thermal management (AIRPASS technology) for the led oven lamps.

Solidur LEDs (Solidur® LEDs | SCHOTT) encapsulate sensitive LED chips in packages made entirely from non-aging materials, which makes them highly resistant to temperature, humidity, chemicals, pressure, vibrations and UV radiation.

Indicator Light (www.indicatorlight.com) provides oven indicator lights that are energy-efficient and environmentally friendly.

Slim (www.slim.it) supplier of electromechanical components for domestic ovens produces LED indicator and warning lights for use in ovens.

Compared to incandescent lighting halogen or LED bulbs use 7 times less energy (Mathias, et al, 2023).

Specific saving values on oven light control are not found. Replacing incandescent bulbs by halogen or LED reduces the energy consumption and also the CO2 footprint.

Scope 1 emissions savings (% or another quantifiable metric)	LED 85 % - 90 % less energy than incandescent lamp and last 30 times longer
Quality of scope 1 emissions information	M
Scope 2 emissions savings (% or another quantifiable metric)	unknown
Quality of scope 2 emissions information	n/a
TRL level	8-9
Maintainability issues	None
Legislative concerns	ErP Directive 2009/125/EC
Payback time (years)	Unknown

9.2.13. Pre-heating oven

It is normally recommended to pre-heat an oven before cooking. Some meals may benefit from pre-heating, for example baking, but not all. The pre-heat instruction is not necessarily because the oven needs to be pre-heated, but that ovens do not heat up at the same rate, so it is not possible to provide the same cooking time for different ovens unless, the oven is preheated. Therefore, it is possible to save energy by cooking the product whilst the oven is preheating.

According to Cernela et al (2014) 10–15 min was required to reach the air-temperature set point. HomeConnect (2023) state that the oven wastes 20% of the energy, however, they provide no reference to back up this statement.

If we assume a 12-minute pre-heat and a 60-minute cook time, the pre-heat is 20% of cooking time. Putting the food in at the beginning of pre-heating would not save the entire time of the cooking, as the oven will not be at the correct temperature. If we assume a linear rate of heating, we might expect the food to cook in twice the time during pre-heat than it does during cook. Therefore, we can conclude that placing food in the oven at beginning of pre-heat could save approximately 10% of the cooking energy.

It is not always possible to know when the oven is fully heated, so either you could put your food in too early, meaning the food might not fully cook, or too late, wasting energy. Some ovens come with an indicator light, which informs the operator when the oven has reached temperature. The oven could also be turned off a few minutes before the end of the cooking, as the oven will remain hot for some time.

Scope 1 emissions savings (% or another quantifiable metric)	10% based on a simple calculation for a gas oven
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	10% based on a simple calculation for an electric oven
Quality of scope 2 emissions information	Low
TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Unknown

9.2.14. Pressure cooking

Pressure cookers have traditionally been used for preparing food for preservation or when long cooking times are required (Sonesson, 2003). Steam gets trapped within the appliance while cooking. A tight lid ensures that pressure builds within the equipment which enables the temperature to get higher in comparison to other pots. This results in reduced cooking times and potentially less energy usage. Finally, a weighted valve is lifted when maximum allowed pressure is reached (Sonesson, 2003; Chin, 2023). Pressure cookers use less water to be boiled which reduces energy consumption (PotsandPans, nd). The temperature gradient from the cooking surface to the interior of the food is greater which causes a faster heat transfer within the food (Sonesson, 2003).

Reported energy and carbon savings range from 22 to 70% and 22% respectively compared to other cooking methods (PotsandPans, nd; Fissler, nd). Higher energy savings are linked to the type of appliance, as pressure cookers operating on electricity are about 50% more energy efficient than those using a stovetop (Franskowska, 2020). For electric pressure cookers 0.287 kg CO_2e/kWh can be assumed (Franskowska, 2020). However contradictory evidence on energy savings can be found. Pressure cookers are not always found to be more efficient than other cooking methods and this could be dependent on the food cooked. For instance, Oberascher (2011) found that the energy needed to cook potatoes was greater in a pressure cooker than that when a pot with lid was used. In the same example a pressure cooker does outperform a steam oven and a pot used without a lid. Likewise, Sonesson (2003) found a similar result for boiling potatoes using a pressure cooker on a hotplate.

Scope 1 emissions savings (% or another quantifiable metric)	Not applicable
Quality of scope 1 emissions information	Not applicable
Scope 2 emissions savings (% or another quantifiable metric)	More energy to 70% saving dependent on comparison between cooking methods, appliance type and food type
Quality of scope 2 emissions information	Open for debate as some authors don't find differences in energy savings
TRL level	9

Maintainability issues	None
Legislative concerns	None
Payback time (years)	Not possible to calculate as savings not clear.

9.2.15. Slow cookers

Slow cooking is an alternative cooking method where the meals are prepared at a low temperature level over a long period of time. For using this technique special appliances, so called slow cookers, are used. They consist of one pot which is filled with the ingredients of the meal and closed with a lid. The pot is electrically heated for several hours, the time depending on the type of meal that is prepared. Compared to ovens, several websites agree that slow cookers require much less energy (Christie, 2013).

Uswitch.com published an online article with the title “Energy-efficient cooking”, in which various energy saving tips regarding the kitchen are mentioned. According to the: “Slow cookers are also an energy-efficient cooking appliance - they use just a little more energy than a traditional light bulb, and you can leave your food to cook slowly throughout the day while you’re at work or when you need to get on with other things.” (Gallizzi, 2024; Christie, 2013)

The article also mentions energy cost per hour of use. According to that, the oven costs around 0.20 € in 02/2024 whereas the average-sized slow cooker only costs 0.11 € – which is equal to a claimed energy consumption of 1,3 kWh per meal. Despite that, one must consider the longer cooking time when using a slow cooker. Regarding the electric power, a slow cooker (rated at only 200 watts) requires far less than an oven. When having access to own solar panels, it is an advantage to use the slow cooker during the day, to make most use of the electricity generated by the panels (Gallizzi, 2024).

In contrast to the above-mentioned energy consumption of 1,3 kWh per meal, Christie (2013) quotes a better energy consumption of only 0,7 kWh in a period of 8 hours usage. Grey Power Electricity (n. d.) claim that slow cookers require roughly only half the energy of a conventional oven without a fan and mention the benefit of the starting price for entry level devices, which is stated to be below approx. 30 €.

Regarding meals with very long cooking durations, using a slow cooker can cut the energy consumption. When preparing for instance a meatloaf, only one third of the energy compared to an oven is needed. (Amann et al., 2007).

Scope 1 emissions savings (% or another quantifiable metric)	When compared to other entirely electrically heated appliances: None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	When cooking meatloaf (slow cooker compared to oven): 2/3 of energy and therefore emissions can be saved. Depends on several factors (e.g., the literature and alternative cooking appliance to which it is to be compared).
Quality of scope 2 emissions information	
TRL level	8-9

Maintainability issues	n/a
Legislative concerns	n/a
Payback time (years)	Depends on a variety of factors (model prize, electricity prize, user behaviour, device to which it should be compared, …)

9.2.16. Temperature control (monitoring of the core temperature)

Hager et al. (2013) reported on temperature monitoring of the core temperature by cooking rice and stated that energy savings of 15% to 50% can be achieved during the process.

The use of intelligent control systems in electric cooking appliances, such as hobs, can result in significant energy savings. These systems automatically regulate the energy supply to cooking elements based on the temperature of the pan's contents. This can potentially achieve energy savings of at least 40% compared to conventional cooking methods. (Newborough et al., 1987)

The study of Batchelor et al. (2018) presents the feasibility of using solar photovoltaics (Solar photo voltaic (PV)) as the energy source for cooking with special focus on the loss mechanisms. If the heat loss is minimised, to reduce the temperature losses, it is possible to cook with a low power source less than 500 W. The Research on solar e-cooking highlights the importance of maintaining the core temperature of food, rather than the energy flow. By minimising heat loss and keeping the temperature inside the cooker, the cooking process can be made highly energy efficient, even with a low power source (Batchelor et al., 2018).

Scope 1 emissions savings (% or another quantifiable metric)	15 up to 50 % (when directly burning fuel for cooking)
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	15 up to 50 %
Quality of scope 2 emissions information	Medium
TRL level	8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Depends strongly on usage and domestic prices for energy

9.2.17. Viewing windows - level of glazing (single, double, triple)

Double or triple glazed doors in domestic ovens are a feature designed to improve insulation and energy efficiency while cooking.

1. Insulation: double or triple glazing provides better insulation compared to single-pane doors. This helps in retaining heat within the oven cavity, ensuring more even cooking and preventing heat loss.

2. Energy efficiency: by reducing heat loss, ovens with double or triple glazed doors can be more energy-efficient. They require less energy to maintain the desired cooking temperature (Table 9).
3. Safety: the additional layers of glass can also contribute to the safety of the oven. The outermost layer of glass stays cooler to the touch compared to single-pane doors, reducing the risk of accidental burns.
4. Condensation: double or triple glazing can help minimise condensation buildup on the oven door during cooking. This can provide better visibility into the oven cavity, allowing you to monitor the cooking process more easily.
5. Noise reduction: while not a primary benefit, the multiple layers of glass can also help in reducing noise from the oven, although this may not be a significant factor for most users.

Overall, double or triple glazed doors can enhance the performance, safety, and energy efficiency of domestic ovens, making them a desirable feature for many consumers.

Burlon (2015) states that optimising the glazing of the oven door can save 4 to 12% energy use (Table 9).

Table 9. Technical solutions and their energy saving potential (from Burlon, 2015).

	Design Option	Energy saving	Consumer Response	Test in prototype
1	Improve thermal insulation (a, b)	0-11	Acceptable	Yes
2	Improve cavity thermal insulation	7-8	Acceptable	Yes
3	Reduce mass of oven structure	10-18	Acceptable	Yes
4	Unglazed door	7-25	Unacceptable	No
5	Optimized glazed door design	4-12	Acceptable	No
6	Passive cooling for glazed door	0-8	Acceptable	No
7	Optimised vent flow	8 or 12	Acceptable	No
8	Aluminium foil on cavity walls	7-10	Acceptable	No
9	Reduce cavity volume	0-4	Acceptable	Yes
10	Reduce cavity opening access	0-4	Acceptable	No
11	Control with smaller oscillations	15	Acceptable	Yes
12	Reduce auxiliary energy	1-4	Acceptable	No

Scope 1 emissions savings (% or another quantifiable metric)	4-12%
Quality of scope 1 emissions information	N/A
Scope 2 emissions savings (% or another quantifiable metric)	-
Quality of scope 2 emissions information	Peer reviewed literature
TRL level	9
Maintainability issues	Cleaning issues
Legislative concerns	-
Payback time (years)	-

9.3. Other/ancillaries

9.3.1. Dishwashers

Recent research has demonstrated the considerable potential of utilizing heat pumps in household dishwashing processes, leading to the emergence of dishwashers equipped with heat pump technology (vapor-compression) in today's consumer market. Flück et al. (2017) conducted a comprehensive investigation into the application of heat pumps in dishwashers. Their study showed a heat pump design using R134a as the refrigerant implemented in a dishwasher, which is specifically engineered to fit within the dimensions of a Standard Euro Niche. The heat pump utilises a latent heat storage containing water, which can be regenerated within 20 hours by ambient air at 22°C and 55% Relative humidity (RH). If a new washing program is initiated before finishing the regeneration, the heat pump operates at lower efficiencies due to lower evaporation temperatures. During the regeneration of the latent heat storage, the surrounding ambient air undergoes cooling. However, in the overall energy balance, more energy is supplied to the ambient air, attributable to the waste heat from the electrical compressor and the cooling of the warm dishwasher. Results from Flück et al. (2017) revealed that the heat pumping system could effectively reduce energy consumption during the dishwashing cycle by up to approx. 50%. Here, next to the integrated vapor-compression heat pump (VCHP) an open dish drying process ("open dishwasher door") was also used. Additionally, the implementation of a bivalent heat pumping system, combining both a heat pump and an electrical resistance heater in parallel, resulted in a shortened dishwashing cycle duration due to enhanced overall heating capacity. Despite achieving notable energy savings compared to dishwashers relying solely on electrical resistance heating, the energy reduction achieved with the bivalent system was found to be lower than that of a monovalent heat pumping system.

Kütük (2019) investigated a heat pump for use within a dishwasher using R600a as refrigerant and ambient room air the heat source. He found that the energy consumption for the dishwashing process can be decreased from 853 Wh (needed by a dishwasher using an electric resistance heater) to 551 Wh (corresponding to a reduction of approx. 35 %). However, noise increased to 46.8 dB(A) due to compressor and fan. According to Kütük (2019) the increased noise does not cause discomfort as it is within the range of refrigerators which might be installed in the same room as the dishwasher. As dishwashers using heat pumps are more costly than "conventional" dishwashers, Kütük (2019) estimates an amortization time of approx. 14 years. However, the amortization time strongly depends on domestic prices for electrical energy as well as usage.

Stoeckel et al. (2023) implemented a heat pump (using ambient air as heat source) in a "conventional" dishwasher using an electric resistance heater and investigated the impact on efficiency when using different refrigerants. For the refrigerant screening, R290 was chosen as a reference. To provide comparative points between using a heat pump or an electric resistance heater, Stoeckel et al. (2023) defined three intervals within the transient rinsing cycle of the "Eco" program (resembling three water inlet temperatures 40 °C, 45 °C and 50 °C at a constant water temperature difference of 2 K) and carried out three measurements each interval. When using R290, it was found that the electrical power for the dishwashing process reduced on average by 57 % compared to the "conventional" "Eco" program. When using a binary zeotropic refrigerant blend of Di methyl ether (DME) and R600a (molar ratio of 0.94 DME), the electrical power was reduced by approx. 63 % compared to the conventional eco program.

Bengtsson and Berghel (2017) investigated further energy efficiency improvements in dishwashers using heat pumps by utilizing a new drying method. The investigated system used a latent heat storage containing water as the heat source. Instead of an open drying method, they recirculated the wet air using a fan over the latent heat storage tank in which – after the washing process – ice was present leading to condensation of water from the wet air. They found that this drying method results in a decrease of electrical energy consumption by 39 Wh per drying cycle as lower drying temperatures are needed (in comparison to a dynamic open drying method using a fan circulating ambient air through the dishwasher (Bengtsson and Berghel (2017).

The presented studies show that using heat pumps in dishwashers can result in a decrease of electrical energy consumption for dishwashing processes. However, noise increases and today, prices for these novel types of dishwashers are still high.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	up to 63 %
Quality of scope 2 emissions information	The information was retrieved from online articles, peer reviewed journal papers, and manufacturer's webpages.
TRL level	8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Depends strongly on domestic prices for electrical energy and usage; e. g. 14 years according to Kütük (2019)

9.3.2. IoT and AI

The use of information and communication technologies such as Artificial Intelligence (AI), in particular machine learning, and the Internet of Things (IoT) opens up great prospects in the management of food at home. In particular they can be applied to refrigeration and cooking[34,35,36,37].

Some examples of such applications are the following:

- IoT sensors can detect which foods are in the refrigerator or freezer, what their quantity is and what their expiry date is.
- A machine learning system can learn the eating habits of the family.

[34] https://theaicuisine.com/eco-friendly-culinary-innovations-the-role-of-ai-in-food-sourcing/

[35] https://forwardfooding.com/blog/foodtech-trends-and-insights/feeding-the-future-ais-role-in-sustainable-agrifoodtech-solutions/

[36] https://hpgconsulting.com/commercial-kitchen/how-ai-can-help-create-a-more-sustainable-food-system/

[37] https://blog.mindmeldwithminesh.com/ai-to-solving-modern-culinary-problems-cd88b580a450

- Based on this information, it can be suggested which foods should be consumed first and which should be purchased instead.
- Based on this information, the temperatures of the refrigeration systems as well as the cooking temperature and time can be controlled and adjusted.

The main consequence of adopting these solutions is a drastic reduction in food waste, which among other things also has a beneficial impact on GHG emissions. Furthermore, regulating the temperature of refrigeration and cooking devices has a direct impact on reducing energy consumption and therefore also in this case on reducing GHG emissions.

On the other hand, when AI and IoT technologies are adopted in smart homes, there is obviously additional energy consumption due to the use of these technologies. Consequently, the use of these technologies produces indirect emissions that should be taken into account.

Therefore, the advantage deriving from the use of these technologies lies in the fact that the reduction in emissions obtained, by reducing waste on the one hand and optimising conservation and cooking on the other, is greater than the emissions that these technologies introduce. However, although there are many works in the literature that discuss such advantages, to the best of our knowledge, there are no works that quantify the saving of GHG emissions. Most of the works focus on waste reduction Onyeaka et al, 2023, Namkhah et al, 2023, Kansaksiri et al, 2023).

As a consequence, the table below reports the overall GHG emissions savings through adopting AI and IoT technologies and the scope 2 emissions savings adopting green AI and IoT technologies. However, it should be noted that the values reported consider the overall emissions savings in a smart home (heating, lighting, etc.) and do not refer exclusively to food management.

Scope 1 emissions savings (% or another quantifiable metric)	Not applicable.
Quality of scope 1 emissions information	Not applicable.
Scope 2 emissions savings (% or another quantifiable metric)	One can save 30% of GHG emissions (Mehdi and Roshchin, 2023; Sepasgozar et al, 2020)
Quality of scope 2 emissions information	One can save up to 38% of energy consumption using both voltage control and shifting in appliances (Elma, and Selamogullari, 2015; Sepasgozar et al, 2020).
TRL level	4-9
Maintainability issues	No particular issues
Legislative concerns	EU AI Act (under approval, European Parliament (2023).
Payback time (years)	The EU actively cooperates with industry, organisations, and academia to unleash the potential of IoT (European Commission, 2023).

9.3.3. Solar electricity

The generation of energy through photovoltaic solar panels is one of the main alternatives for local energy generation and consumption. The photovoltaic sector has developed intensively in recent years and the average cost of this energy source has decreased significantly (Jager-Waldau, 2019). Household generation of energy through solar panels is one of the main strategies to reduce electricity bills and greenhouse gas emissions (Hesselink and Chappin, 2019). From a financial point of view, electricity generation by means of photovoltaic solar panels has proved to be feasible, as it is able to reduce the unit cost of energy consumed by households from the 0.28–0.29€/kWh for traditional supplies to 0.15–0.21€/kWh for household generation (García-López et al., 2023). It has been found that when consumers install solar panels, rather than offsetting existing electricity consumption on a one-for-one basis with solar generation, consumers increase consumption by nearly one-third of the amount generated by their panels. Put another way, solar generation averages around 56% of the pre-adoption consumption amount, but post-adoption draw from the electric grid drops by only 40% because solar customers use 16% more electricity than they did prior to panel installation (Beppler et al, 2023).

The household simple payback time period with net metering at various sizes of investment grants applied, from 50 €/kWp to 200 €/kWp varies from 7.9 to 5.6 years respectively (Trypolska and Rosner, 2022). As a result, an increasing share of the cost of the PV system, and the resulting electricity, arises from the balance of systems and not the solar module (Nelson et al., 2014).

Like other households, households with PV systems can reduce their demand for energy through the efficient use of energy-consuming equipment and by investing in energy-efficient appliances. An additional option for households with PV is to influence the kind of electricity they use by influencing the respective shares of electricity from the grid and electricity from their PV system. The latter is also called the self-consumption and is defined as the electricity produced by the PV system that is directly consumed by the producer. Two options can be used to increase the self-consumption: technical solutions such as battery storage systems and behavioural options by load shifting, also called demand side management (DSM). Load shifting refers to shifting the demands for electricity consumption to the times during which electricity is produced. The two options can also be combined for a further increase in the self-consumption. Analysing battery storage systems and DSM, the self-consumption can be increased by 13–24% with battery storage systems and 2–15% with DSM (Wittenberg and Matthies, 2016; Huld et al., 2014). Households also shift their consumption to the time periods when solar electricity production is higher (Aydin et al., 2023).

The results indicate that kitchen energy consumption is a significant proportion of households' (in Scotland). The findings indicated that the kitchens consumed 41% (mean) of household electricity; however, the range of household consumption varied significantly between 20 and 72% (Foster and Poston, 2023).

Solar energy thus can help to mitigate carbon emissions by replacing more carbon intensive sources of power. Power generation by PV systems manufactured in Europe and deployed in southern Europe using c-Si, multi crystalline silicon and CdTe systems incur 38 gCO_2/kWh, 27 gCO_2/kWh and 15 gCO_2/kWh, respectively. Around 5 gCO_2/kWh of this is embedded in the BoS (Nelson et al., 2014).

Scope 1 emissions savings (% or another quantifiable metric)	Unknown
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	n/a

Quality of scope 2 emissions information	n/a
TRL level	7-9
Maintainability issues	No specific requirements. On-grid systems must have operating electricity grid.
Legislative concerns	EU Solar Energy Strategy (Brussels, 18.5.2022 COM (2022) 221 final)
Payback time (years)	5,6-7,9 years

9.3.4. Solar thermal hot water

Solar energy can be used to heat water so that it can be used for various household tasks. Here, the solar heater absorbs the heat from the sun and then it transmits the heat to the water tank which results in heating up the water.

In practical domestic solar hot water systems, the solar hot water system is usually run in conjunction with, rather than instead of, a backup conventional boiler and as a result the the carbon intensity of the combined system is high relative to other renewables, at some 100-200 gCO_2/kWhth. Moreover, the high efficiency of modern condensing gas boilers, which can convert over 90% of the calorific value of the fuel into useful heat, means that the carbon intensity of these heat sources is relatively low at 200-300 gCO_2/kWhth. As a result, domestic solar water heating systems are a relatively expensive way of mitigating carbon emissions when they replace heat from efficient modern boilers. The abatement cost would be lower if the solar hot water system were compared against an electrical immersion heater powered by high-carbon generation. Abatement costs are also helped when the solar systems are installed in new buildings rather than retrofitted to existing ones (Nelson et al., 2014).

Solar energy assisted heat pump systems (SAHP) have been used for space heating and domestic hot water, showing promising results with improved coefficient performance compared to conventional systems (Sezen and Gungor, 2023). The efficiency of a domestic solar water heater is influenced by its Solar Collector Efficiency (SCE) and Coefficient of Performance (COP). Photovoltaic/thermal-solar assisted heat pump systems integrate photovoltaic modules with a heat pump, providing improved performance coefficient and overall efficiency for hot water generation. Compared to the other hot water technologies that use either conventional or non-conventional energy resources, this system is more energy efficient (Vaishak and Bhale, 2019); Dual tank solar-assisted heat pump (SAHP) systems for domestic hot water heating provide significant energy savings compared to traditional systems, with potential for further energy and cost savings for larger loads (Banister and Collins, 2015). In contrast, heat pumps have relatively higher energy utilization efficiencies, with most systems operating in the COP range of 1.8–2.5, but potential technological updates could increase COP to a range of 2.8–5.5 (Willem and Lekov, 2017).

Solar-based heat pump water heaters are considered environmentally friendly due to their use of solar radiation and ambient energy (Venugopal et al., 2022). A techno-economic study evaluating a photovoltaic-assisted compact heat pump water heater showed a reduction in non-renewable primary energy consumption by 79% and CO_2 emissions by 82% compared to a boiler (Aguilar et al., 2019). A life cycle impact assessment of a solar heat pump system for domestic hot water and space heating showed lower environmental impacts compared to systems operating on electricity only, especially when the electricity used derives from renewable sources (Eicher et al., 2014).

Scope 1 emissions savings (% or another quantifiable metric)	100-200 gCO_2/kWhth
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	7-9
Maintainability issues	No specific requirements
Legislative concerns	No concerns
Payback time (years)	0.5 to 18 years

9.3.5. Waste utilisation

According to the Food and Agriculture Organization of the United Nations (FAO), around 1.3 billion tons of food is lost and squandered every year, costing the world economy 750 billion dollars (Withanage et al., 2021). It has been estimated that 30–50 % of the total food produced is either discarded or not consumed and food losses and waste have a negative environmental impact due to the water, land, energy and other natural resources used to produce them, the post-consumption disposal costs (Esteban and Ladero, 2018, López-Gómez et al., 2020) and the contribution to greenhouse gas (GHG) emissions worldwide (López-Gómez et al., 2020). The EC has proposed legally binding targets to reduce food waste by 2030, including a 30% reduction for households, restaurants, and retail, but organisations and lawmakers warn it does not match international ambition to halve food waste.

Presently, there are several chemical, biological, and thermochemical recycling methods for common organic waste (Prajapati et al., 2021). Bioprocesses were explored as possible sustainable techniques for converting food waste to diverse products such as chemicals, biofuels, fertilisers, and animal feed (Singhania et al., 2022). Overall, kitchen wastes are often treated as municipal wastes by incineration, landfill, composting, and AD (anaerobic digestion). It is essential to both reduce their generation and to upgrade their treatment to add value within a bioeconomy strategy. More recently, the cascading biorefineries for the recovery, recycling and/or generation of high-value compounds have been proposed (Carmona-Cabello et al., 2018) to promote a transition to a sustainable bioeconomy (Mahjoub and Domscheit, 2020). This circular approach has a positive impact on the environment, and builds long-term resilience, generating business, new technologies and jobs (Cris Garcia-Saravia Ortiz-de-Montellano et al., 2023).

Kitchen waste consists of post-consumption residues from household and food service sector, heterogenous in composition and highly variable depending on the particular origin, which are often treated as municipal (Esteban-Lustres et al., 2022). Kitchen wastes from households and hospitality sector are biodegradable, highly heterogeneous waste, normally collected by municipal or charter services, accounting for 30–60 % of solid urban residue (Esteban and Ladero, 2018). Food and kitchen wastes are available worldwide and could be an excellent source of value-added products (Sindhu et al., 2019) and a good candidate as biorefinery raw material.

The high organic content, carbohydrates, proteins and lipids makes kitchen waste a good substrate for chemical and biotechnological conversion into biobased products and platform chemicals, more profitable than fuel and electricity (Trivedi et al., 2020; López-Gómez et al., 2020).

Conventional strategies of food-waste management such as composting, incineration, use as animal feed are not efficient and environmentally unsafe to process large quantities of waste. Food waste is becoming a sustainable source with the significant potential to be used as feedstock for the synthesis of chemicals due to the presence of diverse chemical components such as carbohydrates, proteins, and fatty acids. The processes reported till date for food waste valorisation are mostly tested at laboratory scale, and R&D work for their scale-up is required for making industrially viable processes for utilisation of large quantities.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	3-9 depends on selected food waste treatment technology
Maintainability issues	n/a
Legislative concerns	None
Payback time (years)	n/a

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11. ENERGYPLUS MODELLING

The aim was to assess the impact of various opportunities to reduce energy use and carbon emissions from a domestic kitchen in 6 different European countries and to determine how close to carbon neutrality could be achieved by 2050. The work presents results from an EnergyPlus™ building model (U.S. Department of Energy, 2024) that examines the impact of external and internal environmental conditions on energy consumption and carbon emissions when new carbon saving technologies were applied. The environmental impact was characterised by the total equivalent warming impact (TEWI).

11.1. Domestic kitchen modelling

A baseline case study was simulated using a typical-sized domestic kitchen in the UK. The total energy consumption for the modelled scenarios was calculated using EnergyPlus™ V22.2.0. SketchUp Pro (Trimble Inc.) 2023 was employed for drawing purposes and creating the geometry of the model, while OpenStudio V1.5.0 (by NREL, ANL, LBNL, ORNL, and PNNL) served as the graphical interface for EnergyPlus™. It was employed to add and modify a range of factors including weather files, construction, materials, occupancy, internal loads, schedules, and HVAC systems, ultimately presenting the simulation results.

The workflow of the software used throughout all the work is presented in Figure 29.

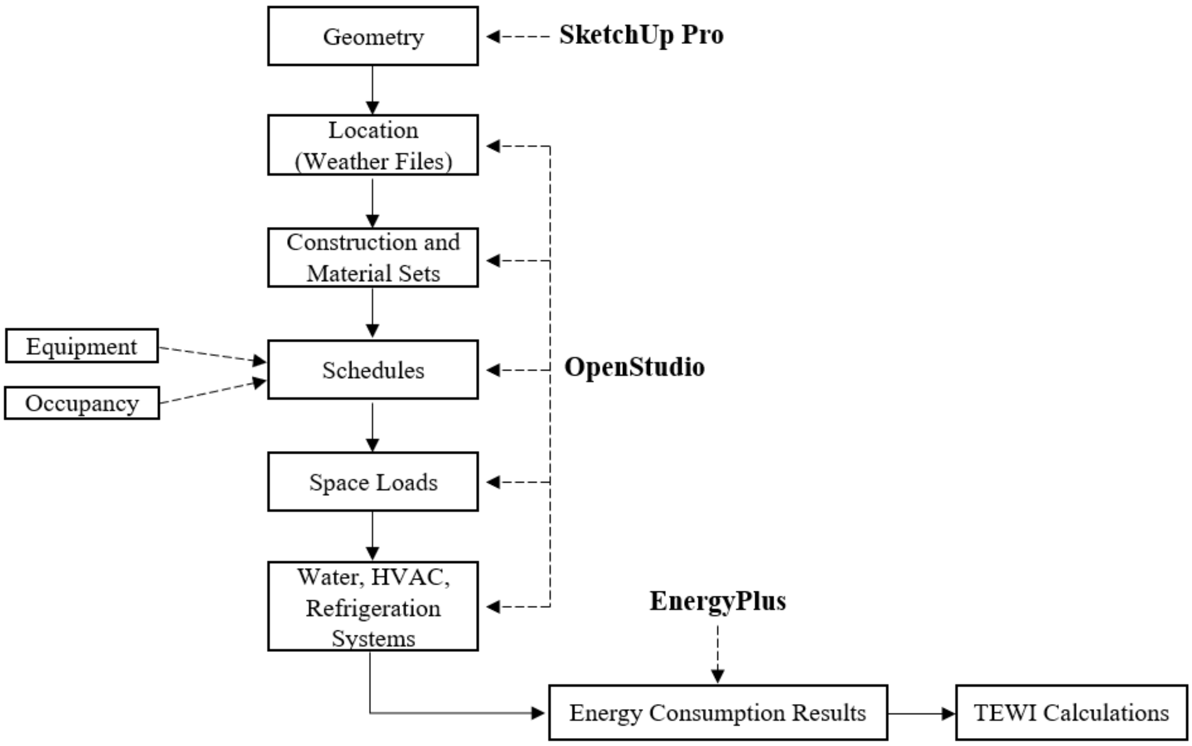

Figure 29. Methodology of the work for modelling and simulating the case studies

11.1.1. Geometry

This geometry was created in SketchUp and designed to represent a typical-sized domestic kitchen commonly found in the UK. According to Statista (2024), the average kitchen size in the UK has been 13.4 m^2 since 2000. Therefore, the modelled domestic kitchen had a floor area of 13.4 m^2 and a height of 2.5 m. It included two internal walls, two exterior walls, an interior door, and an exterior window. Additional specifications regarding the construction can be found in the model inputs section below.

Figure 30 shows the geometry of the kitchen adopted in the simulation.

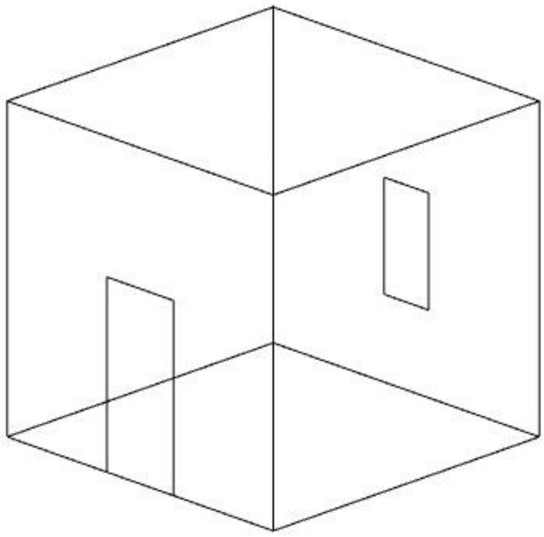

Figure 30. Geometry of the domestic kitchen

11.1.2. *Assumptions for baseline simulations*

The ambient conditions and therefore the weather drives a significant part of the energy going in and out of a building. EnergyPlus contains weather values at many locations throughout the world. However, the EPW files available from the EnergyPlus website were created over a range of years before 2009. To use weather files related to 2020 and 2050, https://weathershift.com/ was used to shift the historical EnergyPlus weather files to 2020 and forward to 2050. To simulate the baseline kitchen simulations in various locations, weather files from 6 different locations were used. These locations were London (UK), Paris (France), Kaunas (Lithuania), Warsaw (Poland), Oslo (Norway) and Rome (Italy).

The baseline simulations across the 6 countries varied solely based on the heating and cooking sources employed. Other equipment (dishwasher, microwave, kettle, refrigerator) were all electrical. Table 10 presents the differences in the baseline simulations for the different countries.

Table 10. Differences in the baseline simulations across the 6 countries

	Heating	Cooking
UK	NG	NG
France	NG	Resistive
Lithuania	Biomass	NG

	Heating	Cooking
Poland	Coal	NG
Norway	ASHP	Resistive
Italy	NG	NG

Detailed information of the model inputs is presented in Table 11.

11.1.3. Model inputs

Equipment was added into OpenStudio as input loads. The internal heating loads in spaces are a function of the schedules, which usually varies with the time of day and day of the week.

Each surface has an associated construction set which is composed of layers of materials. Each material layer has properties related to its heat transfer characteristics, specifically the thermal conductivity. To define the envelope of the domestic kitchen, a standard construction for a domestic house was created. It is important to highlight that the wall containing the door, as well as one adjacent wall and the roof, were treated as adiabatic in terms of construction, given that they formed the internal structure of a domestic house.

OpenStudio offers a wide range of HVAC system designs. All HVAC types in OpenStudio contain a defined arrangement of sub-components. By default, HVAC systems and components within OpenStudio are "auto sized," meaning that properties such as flow rates, heating and cooling capacities are automatically determined by the EnergyPlus™ engine using sizing algorithms. These are derived from heating and cooling loads at design conditions from the weather files. The HVAC aims to control each thermal zone via a thermostat set point. The kitchen was heated using various fuels depending on the country. For the sake of a direct comparison in transitioning to heat pumps, we used a packaged rooftop unit equipped with a heating coil, a cooling coil, and a supply fan. According to Invictus Mechanical (2018), a Mintel report indicated that only 0.5% of UK households possess air conditioning units installed. Consequently, the study did not take cooling the kitchen into account. Hence, our study included heating only. Furthermore, we neglected the consumption of heating fans since their presence in domestic houses is uncommon. The capacities of the heat pumps and the other fuel boilers were sized the same to insure a fair comparison across the countries. The COP of the heat pump was calculated based on the outside dry-bulb temperature using a cubic equation from default values in EnergyPlus™:

$$COP_{T,\ heating} = \frac{COP_{rated,heating}}{1.192 - 3.004\text{e}{-2}\, T_d + 1.037\text{e}{-3}\, T_d^{\,2} - 2.333e{-5}\, T_d^{\,3}} \qquad \text{Eq. (1)}$$

where $COP_{T,\ heating}$ is the COP at different temperatures, $COP_{rated,heating}$ is the COP at rated conditions (outdoor air dry-bulb temperature of 8.33°C) and T_d is the outdoor air-dry bulb temperature in °C.

Table 11. Model inputs for the domestic kitchen.

Parameter	Value	Reference
Construction		
Exterior wall (brick, insulation, air space, gypsum) M01 brick		Erikas Grig, 2022 EnergyPlus library

Parameter	Value	Reference
Roughness	Medium rough	
Thickness (mm)	100	
Conductivity (W/m.K)	0.89	
Density (kg/m^3)	1920	
Specific heat (J/kg.K)	790	
Thermal absorptance	0.9	
Solar/Visible absorptance	0.7	
I02 insulation board		EnergyPlus library
Roughness	Medium rough	
Thickness (mm)	0.05	
Conductivity (W/m.K)	0.03	
Density (kg/m^3)	43	
Specific heat (J/kg.K)	1210	
Thermal absorptance	0.9	
Solar absorptance	0.7	
Visible absorptance	0.5	
F04 wall air space		EnergyPlus library
Thermal resistance (m^2.K/W)	0.15	
G01 gypsum board		EnergyPlus library
Roughness	Medium smooth	
Thickness (mm)	0.019	
Conductivity (W/m.K)	0.16	
Density (kg/m^3)	800	
Specific heat (J/kg.K)	1090	
Thermal absorptance	0.9	
Solar absorptance	0.7	
Visible absorptance	0.5	
Interior floor (concrete + carpet pad)		Weber, 2024
Normal weight concrete floor		EnergyPlus library
Roughness	Medium rough	
Thickness (mm)	100	
Conductivity (W/m.K)	2.31	
Density (kg/m^3)	2322	
Specific heat (J/kg.K)	832.55	
Thermal absorptance	0.9	
Solar/Visible absorptance	0.7	
CP02 carpet pad		EnergyPlus library

Parameter	Value	Reference
Roughness Thermal resistance (m^2.K/W) Thermal absorptance Solar absorptance Visible absorptance	Smooth 0.216 0.9 0.7 0.8	
Exterior window (double-glazing) U-factor (W/m^2.K) Solar heat gain coefficient, G-value	 1.2 0.78	 Norrsken, 2024 Aguilar-Santana et al., 2020
Occupancy		
Number of people Schedule Monday to Saturday Sunday	1 7h to 9h, and 18h to 19h 12h to 13h	Assumption Assumption
Internal heat loads		
Oven cooking Power (W) – Natural Gas Power (W) – Resistive Power (W) – Induction Schedule October to March April to September	 3270 2130 1850 30 mins – 5 evenings at 18h, and Sunday at 12h 30 mins - Monday to Wednesday at 18h	 Khalid and Foulds, 2020 Khalid and Foulds, 2020 Khalid and Foulds, 2020 Assumption based on Khalid and Foulds, 2020
Microwave Power (W) Schedule Monday and Wednesday	 1250 30 mins – at 18h	 Khalid and Foulds, 2020 Assumption based on Khalid and Foulds, 2020
Kettle Power (W) Schedule	 2000[38] 5 mins - every day, twice in the morning (7h and 8h), and twice in the evening (18h and 21h)	 Tameside, 2024 Assumption based on Tameside, 2024
Refrigerator Power (W)	 44.5	 Biglia et al., 2017

[38] In Openstudio, a 1000 W power level was employed for 10 minutes instead of 2000 W for 5 minutes, as the minimum sensible duration was 10 minutes. This adjustment was made to achieve equivalent output.

Parameter	Value	Reference
Schedule	All the time	
Dishwasher Power (W) Schedule	 1800[39] 1h per day at 20h	 Footnote Assumption (footnote)
HVAC		
Heating DX rated COP	3.4	Expert advice
Minimum outdoor dry-bulb T for compressor operation (°C)	-20[40]	Assumption
Boiler efficiency Gas Coal Biomass	 0.9 0.7[41] 0.9	 JL Philips, 2024 Footnote JL Philips, 2024
Heating thermostat (°C)	18 (between 6h and 23h) 16 (between 23h and 6h)	Real kitchen data
Zone equipment		
Natural ventilation Air changes/hour (ACH) Schedule	 0.2 Max between 6h and 22h Half between 22h and 6h	 ASHRAE, 2021
Exhaust fan[42] (cooker hood) Air changes/hour (ACH) Schedule	 4 Only when cooking	 ASHRAE, 2021

11.1.4. Modelling technologies

The impact of various technologies incorporated in the kitchen were examined individually and together in the 6 different locations to assess their effects. The following assumptions were made:

1. Move to air source heat pumps (ASHP) when not already applied.

[39] https://energyusecalculator.com/electricity_dishwasher.htm

[40] In the simulation, it was assumed that the heat pump operates all year, even at cold temperatures as low as -20°C (where applicable in colder countries), to ensure a consistent comparison across all countries, even though it may not always be running in reality.

[41] https://www.open.edu/openlearn/nature-environment/energy-buildings/content-section-3

[42] The consumption of exhaust fans was disregarded in all simulations since it was the same in all the simulations and negligible.

2. Move to resistive cooking when not already applied: it was assumed (based on Khalid and Foulds, 2020) that resistive cooking was 73% more efficient than gas cooking which was assumed to be 47% efficient.
3. Move to induction cooking: it was assumed (based on Khalid and Foulds, 2020) that induction cooking was 84% more efficient than gas cooking, which was assumed to be 47% efficient.
4. More efficient cooking appliances: the cooking appliances (cooker, microwave and kettle) were assumed to use 10% less energy.
5. More efficient refrigeration: the refrigerator was assumed to use 10% less energy.
6. More efficient dishwasher: the dishwasher was assumed to use 10% less energy.
7. ASHP, induction cooking, more efficient cooking, refrigeration and dishwasher all combined.

Initially each technology was applied individually and in combination to the kitchen format and the impact were assessed in 2020 and forward to 2050.

11.2. Total equivalent warming impact (TEWI)

The TEWI characterises CO_2e emissions and is a useful tool to study the impact of systems on global warming. The TEWI combines the direct and indirect emissions of CO_2e. However, as only a refrigerator was considered in this kitchen, using a low GWP refrigerant, direct emissions of CO_2e due to refrigerant leakage were not considered. Therefore, only indirect emissions associated with energy consumption of each fuel used was considered. The TEWI is then determined based on the following relation:

$$TEWI = \Sigma\,(E_{fuel} \times \beta_{fuel}) \quad \text{Eq. (2)}$$

Where *TEWI* is the mass of CO_2e produced during a year (kg); *fuel* is electrical, NG, coal or biomass; $(E_{fuel} \times \beta_{fuel})$ are indirect emissions of CO_2e associated with energy consumption of each fuel; *E* is the energy consumption per year of the domestic kitchen for each fuel (kWh/year); β is the CO_2e equivalent emissions per kWh of energy produced (kg CO_2e/kWh).

Electrical carbon intensity factors for the 6 locations are shown in Figure 14.

Table 12 shows carbon emission factors for different fuels taken from UK Government (2023).

Table 12. Carbon emission factors for different fuels

	NG	Coal	Biomass
β (kg CO_2e/kWh)	0.18	0.35	0.01074

11.3. Bibliography for modelling

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