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D2.3: Food catering road map

Technological road maps for food catering

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Food service road map

ENOUGH

EUROPEAN FOOD CHAIN SUPPLY TO REDUCE GHG EMISSIONS BY 2050

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NOMENCLATURE

AC	Alternating current
AD	Anaerobic digestion
AHU	Air handling unit
AI	Air impingement
AIS	Active insulation system
ASD	Adjustable speed drive
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAT	Best available technology
BAU	Business as usual
BSRIA	Building Services Research & Information Association
CES	Corporate environmental sustainability
CFD	Computational fluid dynamics
CFM	Cubic foot per minute
CH	Chilled horizonal
CHP	Combined heat and power
CHTC	Convective heat transfer coefficient
CI	Carbon intensity
CIBSE	Chartered Institution of Building Services Engineers
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Coefficient of performance
CV	Chilled vertical
DC	Direct current
DCKV	Demand control kitchen ventilation
DRL	Deep reinforcement learning
DSR	Demand side response
DX	Direct expansion system
EC	European Commission
ECE	Electro- caloric- effect
EEB	European Environmental Bureau
EEI	Energy efficiency index
EEV	Electronic expansion valve
EI	Energy intensity
EN	European norm
EN	European standard
EPREL	European Product Registry for Energy Labelling
ERV	Energy recovery ventilator
ETS	Emissions Trading System
EU	European Union
EU	European Union
EU GPP	European Union Green Public Procurement
FAO	Food and Agriculture Organization of the United Nations

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FC	Frequency converter
FC	Fuel cell
FEA	Finite element analysis
FH	Frozen horizontal
FRISBEE	Food Refrigeration Innovations for Safety, consumers' Benefit, Environmental impact and Energy optimisation along the cold chain in Europe
FV	Frozen vertical
FW	Food waste
GHG	Greenhouse gas
GW	Giga Watt
GWP	Global warming potential
HC	Hydrocarbon
HDPE	High density polyethylene
HFC	Hydro fluorocarbon
HFO	Hydrofluoro olefin
HVAC	Heating ventilation and air conditioning
HVAC&R	Heating, ventilation, air conditioning and refrigeration
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IH	Induction heating
IIR	International Institute of Refrigeration
IR	Infra-red
ISO	International standards organisation
kWh	Kilo Watt hour
LCA	Life Cycle Analysis
LDPE	Low density polyethylene
LED	Light emitting diode
LULUCF	Land use, land-use change, and forestry
MDPE	Medium density polyethylene
MEPS	Minimum Energy Performance Standards
MW	Mega Watt
MW	Microwave
PBAT	Poly(butylene adipate-co-terephthalate)
PCM	Phase change material
PFAS	Per- and polyfluoroalkyl substances
PHA	Polyhydroxyalkanoate
PID	Proportional integral derivative
PLA	Poly(lactic acid)
PLC	Programmable logic controller
PP	Poly propylene
PPWD	Packaging and Packaging Waste Directive
PU	Polyurethane
PV	Photo voltaic
PVC	Polyvinyl chloride

PVDF	Poly(vinylidene fluoride)
PZT	Lead zirconate titanate
QSR	Quick service restaurant
RAC	Room air conditioner
RCP	Representative concentration pathway
RD&T	Refrigeration Developments and Testing
RES	Renewable energy source
RORC	Regenerative Organic Rankine
rpm	Revolutions per minute
SDG	Sustainable Development Goal
SEC	Specific energy consumption
SHGC	Solar Heat Gain Coefficient
SME	Small and medium-sized enterprises
SMPC	Stochastic Model Predictive Control
TABE	Thermally anisotropic building envelope
tCO_{2e}	Tonnes of CO_2 equivalent
TES	Thermal energy storage
TEWI	Total equivalent warming impact
TEV	Thermostatic expansion valve
TFA	Trifluoroacetic acid
TPE	Thermoplastic elastomer
TRL	Technology readiness level
UK	United Kingdom
UNRCCC	United Nations Framework Convention on Climate Change
US	United States
USA	United States of America
VAR	Vapour absorption refrigeration
VAV	Variable airflow volumes
VCC	Variable capacity compressor
VFD	Variable frequency drive
VIP	Vacuum insulated panels
VSD	Variable speed drive
VSLC	Variable-speed linear compressor
VT	Visible transmittance
WRAP	Waste & Resources Action Programme
WRI	World Resources Institute

EXECUTIVE SUMMARY

In this roadmap we question how the food service food sector can decarbonise and rapidly reach zero carbon emissions. As part of the work, we provide independent reviews of 60 different technologies/strategies that fast food restaurants could apply to reduce carbon emissions and energy consumption. Scope 1 and 2 emissions are covered which encompass emissions from fuel used on the premises, e.g. gas for heating and cooking and emissions from leakage of refrigerants (scope 1) and emissions from electricity provided from the national grid (scope 2)

Technology/strategy reviews were used to identify the individual technologies/strategies that had the most potential to reduce GHG emissions in fast food restaurants. Only technologies with a high technology readiness level (TRL) were considered which meant that technologies/strategies considered were already available on the market. The carbon emissions from those technologies/strategies that had a low TRL were often not available or had very varied application times and the claimed savings often varied widely. Therefore, these technologies/strategies were very difficult to quantify. 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 grid carbon emission factor as well as the impact of the combined technologies/strategies. Two scenarios were considered for a high usage and medium usage fast food restaurant:

1. Do nothing: the impact of changes due to global warming (an RCP 4.5 climate change scenario was applied) and changes to the electrical grid emission conversion factors were considered.
2. Retrofit: options that could be applied in fast food restaurants to save energy/carbon.

The impact of the scenarios was applied to 6 locations (in the UK, France, Lithuania, Norway, Italy, Poland) which were selected for their varied climatic conditions, grid emission conversion factors and their current use of fuels and refrigerants.

Results from the reviews and modelling identified routes for fast food restaurants to reduce emissions and enabled the creation of a roadmap through to 2050. By 2050, restaurants in Lithuania, the UK, Norway and France were predicted to be almost zero carbon emitters due to the low electrical grid emission factors in the countries (all heating in the restaurants were from grid electricity) even if they made no changes to their current operations. Information on how the grid will decarbonise in Italy was not available and so it is possible that Italy will also follow the same path as other European countries and emissions from the electrical grid in 2050 will also be almost net zero. The country we examined where the electrical grid decarbonises most slowly is Poland and so for restaurants to decarbonise there they would have to also apply carbon reducing technologies. Overall the interventions applied could save 38-52% of the energy and 40-52% of the carbon emissions if applied immediately.

Although restaurants in many countries will have near zero carbon emissions by 2050 just through the grid decarbonising, it is important to consider the rate at which carbon is abated. Applying interventions now will save 40-50% of the emissions by 2050 compared to a ‘do nothing’ scenario.

Our recommendations to reduce carbon in food service restaurants are presented graphically below:

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FOOD SERVICE ROAD MAP

1 ABOUT THIS ROAD MAP

Globally, greenhouse gas emissions (GHG) emissions from the food chain are estimated to account for 33% of the total GHG emissions [1,2]. 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 food service sector. The food service sector covers restaurants, cafes, pubs, bars, fast food outlets, and other establishments (such as schools, colleges, hospitals and other institutional facilities) that serve food and drinks to customers. Fast food chain restaurants often have common designs and are owned by international conglomerates. On the other hand, many smaller outlets such as cafes and restaurants are operator owned or are part of smaller chains operating mainly within a single country.

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 food service sector is feasible.

2 INTRODUCTION

In June 2021, the 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 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, fertilizers 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 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;

[1] Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987-992.

[2] Crippa, M., Solazzo, E., Guizzardi, D. et al. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food (2021).

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- 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 food service sector in Europe generates significant quantities of carbon emissions and so has a major role to play the aimed for 55% reduction target.

Statistics on the number of food service outlets varies but most sources estimate that there are around 1 million businesses across Europe and the UK. These have a market size of €254 bn and employ over 4.5 million people[3]. France, Italy, Germany and the UK have by far the greatest numbers of restaurants and mobile food outlets, and this is probably related to population size [4]. In 2018 the largest 20 operators of food service outlets operate between 1,430 and 44,819 outlets in Europe and those outlets accounted for ~23% of the total outlets[5]. Only Subway, McDonalds, KFC, Pizza Hut, Burger King, Domino's, Spar (Netherlands) and Dunkin' Donuts operated more than 10,000 outlets. A large number of food service operators are small and medium-sized enterprises, and many are micro sized (less than 10 people).

The carbon footprint of food service outlets is claimed to be large. Much of the available data on energy usage originates from around 10 years ago and was collected by a team from the University of reading in the UK. According to this work the total energy consumption of Britain's catering industry is estimated to be in excess of 21,600 million kWh per year (Mudie et al, 2013[6]). If this was pro ratered for Europe the total energy consumed would be 245.4 TWh/year. Work within the ENOUGH project has also estimated energy used in the UK and if this was also pro ratered for the whole of Europe it would result in a smaller but still significant figure of 196.6 TWh/year (which equates to 77.3 $MtCO_2e$/year). Differences may be due to the year of assessment. The Mudie data is from 2013, whereas the ENOUGH data is from 2019 and so equipment may have become more efficient. It is also likely that pro ratering the energy used by number of facilities may not be completely accurate as there may be a predominance of different outlet types and sizes in different countries.

Information on how the total energy used by food service outlet is scarce but it is estimated that 50% of the energy is used in non-commercial catering operations (hospitals, ministry of defence, schools, etc.), 20% is used by hotels and guest house kitchens and the remaining 30% is used by commercial kitchens (restaurants, public houses, cafes, etc.)[7] [8].

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[3] https://www.ibisworld.com/eu/industry/restaurants-takeaway-food-operators/3420/

[4] https://www.statista.com/statistics/684211/number-of-enterprises-in-the-food-and-beverage-service-industry-in-the-eu-by-country/

[5] https://www.statista.com/statistics/665656/leading-european-restaurant-franchises-by-outlet-number/

[6] Mudie, S. A., Essah, E.A, Grandison, A. and Felgate, R. Benchmarking Energy Use in Licensed Restaurants and Pubs. CIBSE Technical Symposium, Liverpool John Moores University, Liverpool, UK, 11-12 April 2013.

[7] Carbon Trust. Food Preparation and Catering—Increase Carbon Savings without Compromising on Quality—CTV035. 6th Floor, 5 New Street Square, London EC4A 3BF, 2008.

[8] CIBSE. TM50—Energy Efficiency in Commercial Kitchens. The Chartered Institution of Building Services Engineers (CIBSE) and Catering for a Sustainable Future Group (CSFG). CIBSE, 222 Balham High Road, London SW12 9BS, 2009.

2.1 Electrical energy use

Energy is used in food service outlets for HVAC, lights, pumps and for operating the appliances located in the kitchen and other areas. These include:

1. Food preparation and cooking (ovens, ranges, fryers).
2. Refrigeration (cold stores, food service refrigerators, display refrigerators, beverage coolers, drink dispensers, ice cream makers, ice makers.
3. Washing (dishwashers, kitchen cleaning and sometimes washing of clothes, serviettes, tablecloths).
4. Storage of hot water water.

Information on how electrical energy is used in kitchens is relatively scarce. Mudie et al (2013[9]) found from monitoring 400 individual appliances over a year that the energy used for cooking and cold storage of food was the dominant use of energy (70% of the building annual energy). Data was also reported by Paillat (2011)[10] (Figure 1). Even this small data set confirms that energy use can vary considerably between facilities but that in all cases cooking, and HVAC are the dominant energy users in food service outlets.

The work by Mudie identified that daily energy used by refrigeration accounted for 70 kWh, fryers accounted for 11 kWh, combination ovens for 35 kWh, Bain Maries for 27 kWh and grills 37 kWh. There were however large differences between the energy used by similar appliances caused by poor maintenance and operational practices. The overall average division of energy between appliances is presented in Figure 2.

[9] Mudie, S. A., Essah, E.A, Grandison, A. and Felgate, R. Electricity use in the commercial kitchen. International Journal of Low-Carbon Technologies 2016, 11, 66–74.

[10] Paillat, E. Energy efficiency in food-service facilities: the case of Långbro Värdshus. Master of Science Thesis Energy Technology 2011, KTH School of Industrial Engineering and Management Division of Sustainable Energy Systems SE-100 44 Stockholm.

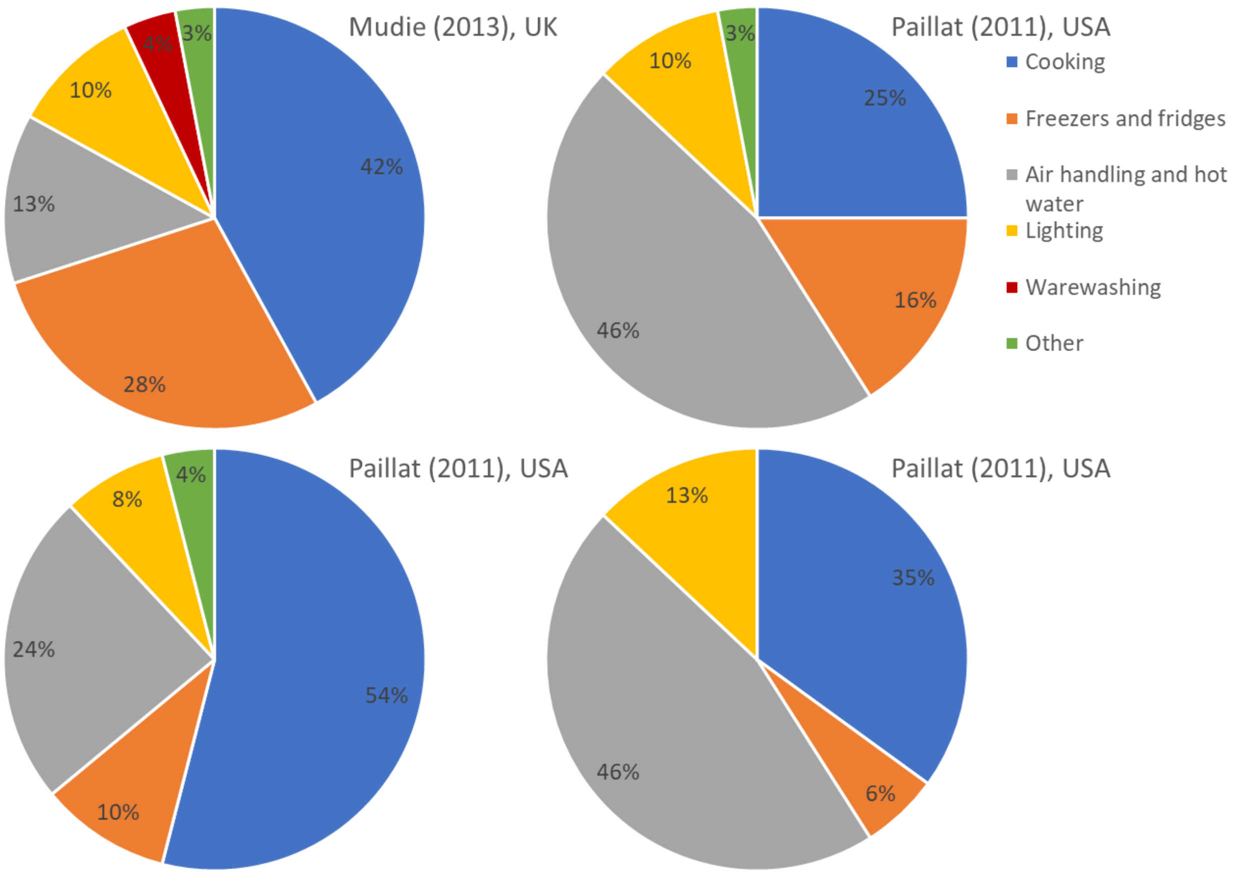


Figure 1. Division of electrical and gas energy between functions in a typical kitchen (Mudie et al, 2013, Pailatt, 2011).

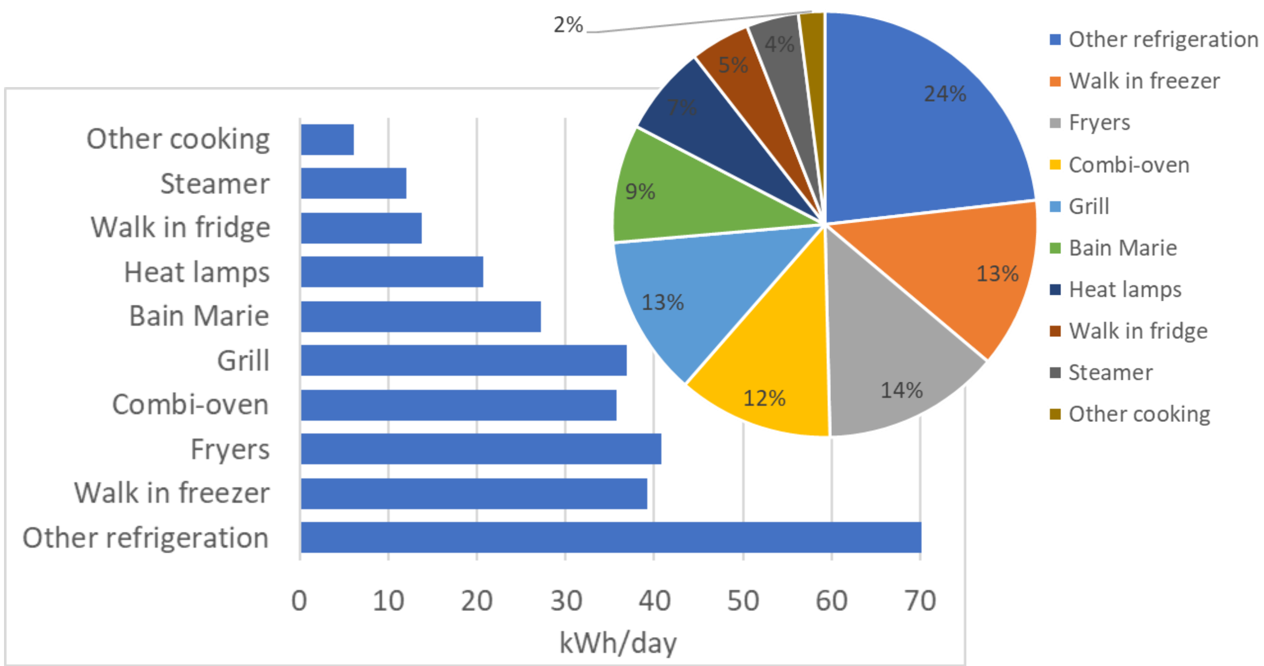


Figure 2. Division of electrical and gas energy between appliances in a typical kitchen (Mudie et al, 2013).

2.2 Benchmarks

Benchmark information exists for food service outlets. Mudie et al provide a range of different specific energy consumption (SEC) benchmarks which can be based on floor area, number of meals served or turnover of the outlet. Those based on floor area vary between 90 and 890 kWh/m^2. Fast food outlets tended to have higher SECs and restaurants lower SECs. Assessing efficiency based on energy used per floor area is a potentially flawed method to compare outlets unless types and how outlets are used are compared directly. Issues also potentially exists that are related to the area for assessment which could just include the kitchen or all the restaurant seating area. Some outlets may also operate for different times during the day. For example, a hotel may only provide breakfast whereas another may also provide food throughout the day. This probably explains the wide variation in SEC figures available.

Mudie et al examined a number of potential benchmarking options for electricity use in food service outlets. Most had little inter-relationship with energy used. The best relationships for energy used were the kitchen size (~4,000 kWh/year/m^2 of kitchen), meals served (4.02±2.32 kWh/meal) or annual turnover (~0.2 kWh/£ of turnover). Gas usage was not included in these benchmarks but was estimated to be 1.28 times greater (in kWh) than electricity. Paillat (2011)[11] assessed the energy used in a Swedish restaurant and found that the outlet used 5.9 kWh/meal when considering the total energy use of the facility and 4.1 kWh/meal excluding the HVAC systems. Other surveys reported by Paillat have found energy use per meal of 4.8 kWh/meal in Japan (when excluding HVAC energy use) and of 2.77 kWh/meal in two-star hotels and 7.86 kWh/meal in three star hotels in France.

Paillat reported that the energy used per restaurant area was 581 kWh/m^2/year. This compared to figures of 814 kWh/m^2/year and 1,095 kWh/m^2/year in the USA, 1,669 kWh/m^2/year in Japan and 596 kWh/m^2/year for an average Swedish restaurant.

CIBSE (2021[8]) also report benchmarks for a range of food service outlets. These benchmarks originate from a 2012 report and so may not be completely reflective of the current market. Reported energy used per m^2 varied considerably between 33 and 1,250 kWh/m^2 per year. Energy per meal produced also had huge variation of between 0.80 to 12.92 kWh/meal (Table 1).

[11] Paillat, E. Energy efficiency in food-service facilities: the case of Långbro Värdshus. Master of Science Thesis Energy Technology 2011, KTH School of Industrial Engineering and Management Division of Sustainable Energy Systems SE-100 44 Stockholm.

Building type	Annual energy consumption benchmark (kWh/m²)				Energy per meal produced (kWh/meal)			
	Good practice		Typical practice		Good practice		Typical practice	
	Fossil fuels	Electricity	Fossil fuels	Electricity	Fossil fuels	Electricity	Fossil fuels	Electricity
Restaurant, coffee shop	1,110	650	1,230	730	0.90	0.53	1.03	0.60
Fast food outlet	480	820	670	890	0.53	0.90	0.74	0.98
Hotels								
- business/ holiday	262	80	400	140	4.23	2.43	8.46	3.39
- luxury	300	90	460	150	5.29	2.43	9.53	3.39
- small	240	80	360	120	3.18	2.43	6.35	3.39
Schools								
- primary	113	22	164	32	0.68	0.13	0.98	0.19
- secondary	108	25	144	33	0.65	0.15	0.86	0.20
Hospital	-	-	-	-	0.50	1.50	-	-

Table 1. Annual benchmarks (kWh/m²) for as range of food service outlets.

2.3 The food service roadmap

The focus of this report is to assess the technologies and strategies available to the food service sector to reduce their carbon emissions. This covers the emissions that they generate today and also how emissions moving forward to 2050 could be reduced to ultimately assess how a food service outlet could become zero carbon. During the work, 60 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, cooking and HVAC systems.

3 CURRENT TRENDS

3.1 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 high levels of warming were observed across Eastern Europe, Scandinavia and the eastern part of Iberian Peninsula.

United Nations Framework Convention on Climate Change (UNFCCC) 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[12].

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

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

particular concern are north-eastern Europe, northern Scandinavia and inland areas of Mediterranean countries, whereas western Europe, especially in the United Kingdom, 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 cooling systems. Many reports over the last summer stated that food service refrigeration systems were breaking down due to the hot ambient temperatures and that some restaurants and cafes were closing as customer areas were excessively hot due to a lack of air conditioning. Even if the food service outlets can continue to keep working, warmer ambient temperatures are having a major impact on costs to operate the 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%[13]. 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 service outlets, consumers and the environment as the additional costs will have to be absorbed and food may be wasted if refrigeration systems can no longer cope with the warmer conditions.

Options are available to prevent refrigeration breakdowns and reduce temperatures in food kitchens. Good maintenance and monitoring can make sure refrigeration plant and AC systems have the best operational performance before they are stressed by warm conditions. Staff behaviour (such as switching off equipment when not in use), maintenance and using equipment appropriately all have significant impacts in reducing heat build-up in kitchens and reducing breakdown of equipment. As most food service equipment is expected to have an operating lifetime of 15-20 years, there is a need to make sure new 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 equipment, 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.

3.2 Sustainability

The food service sector is a significant contributor to food waste and environmental pollution. Refrigeration is a critical tool to reduce food waste. There is a growing demand for more sustainable practices, such as reducing food waste and using eco-friendly packaging. This put additional costs and pressure on businesses which are often struggling to survive.

'Green issues' within the food service sector are often poorly understood and in the past, there has been reticence to introduce new technologies or practices. This is often due to initial cost to apply new technologies even if they have rapid paybacks. However, the increasing cost of energy has made investment in energy saving technologies more attractive (CIBSE, 2021[8]).

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

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

for personalisation of food where consumers use technology to select foods that suit their health, welfare and lifestyle choices[14].

In Europe the voluntary European Union Green Public Procurement (EU GPP) was established to encourage better environmental procurement in the public sector. GPP is defined as '…a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured'[15]. GPP schemes are available at all levels from EU, national, regional and local levels. The schemes can cover a variety of areas, including food service and catering and include aspects such as:

- Procurement of livestock products with high welfare standards,
- Procurement of seasonal products,
- Procurement in bulk or in packaging that has a high recycled content,
- Use of reusable cutlery, crockery, glassware and tablecloths,
- Use of environmentally friendly paper products,
- Selective waste collection and staff training,
- Minimisation of the use of hazardous chemicals and the use of environmentally friendly cleaning and dishwashing products,
- Procurement of water and energy efficient kitchen appliances,
- Improvement of transport routes and energy efficiency and reduction of emissions by vehicles used to carry out the catering services,

The EU is currently revising the Packaging and Packaging Waste Directive. The current Packaging and Packaging Waste Directive (PPWD – Directive 94/62/EC) lays down measures to prevent the production of packaging waste, and to promote reuse of packaging and recycling and other forms of recovering packaging waste. In addition, it sets out the requirements that all packaging placed on the EU market must reduce the disposal of packaging waste and promote a more circular economy. The PPWD also sets recovery and recycling targets for packaging waste (and from 2008, for different materials of packaging). The 2018 revision of the directive introduced higher targets for overall recycling for packaging (65% in 2025 and 70% in 2030), and higher material-specific targets (such as 55 % for plastic by 2030) (Table 2).

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

[15] Neto, B. and Gama Caldas, M., 2018. The use of green criteria in the public procurement of food products and catering services: a review of EU schemes. Environment, development and sustainability, 20(5), pp.1905-1933.

Table 2. Recycling targets set in the Packaging and Packaging Waste Directive.

	Recycling target deadlines		
	31 December 2008	**31 December 2025**	**31 December 2030**
All packaging waste	Between 55% and 80%	65%	70%
Glass	60%	70%	75%
Paper and cardboard	60%	75%	85%
Metals	50%	70% (ferrous metals) 50% (aluminium)	80% (ferrous metals) 60% (aluminium)
Wood	15%	25%	30%
Plastic	22.5 % (counting exclusively material recycled back into plastics)	50%	55%

The updated directive aims to further reinforce reuse and recycling. Operators placing packaging on the market would have to ensure that a system for re-use of such packaging is in place. Operators would have to participate in re-use schemes and would have to recondition or re-use packaging e.g., by cleaning and washing in accordance with hygiene standards. Targets specifically affecting food service companies would include targets for beverages and take away food (Table 3).

Table 3. Re-use and refill targets related to food service.

	From 1 January 2030	From 1 January 2040
Cold or hot beverages (filled into a container at the point of sale for take-away)	Share of beverages made available in reusable packaging or by enabling refill, 20%	Share of beverages made available in reusable packaging or by enabling refill, 80%
Take-away ready-prepared food (intended for immediate consumption with no need of any further preparation, and typically consumed from the receptacle)	Share of products made available in reusable packaging or by enabling refill, 10%	Share of products made available in reusable packaging or by enabling refill, 40%

3.3 The move to low GWP refrigerants

The move to low GWP refrigerants has been driven primarily by legislative pressures from the European F-gas regulations (Regulation on the Use of F-Gases (EU 517/2014, 2014))[16] to reduce the GWP of refrigerants used. The F-gas regulation has a step-by-step reduction plan that calls for a 79% reduction in GWP-related emissions from the use of hydro fluorocarbons (HFCs) by 2030, using 2010 as the reference year. The clauses that relate to food service cover refrigerators and freezers for commercial use[17] (hermetically sealed equipment) and stationary refrigeration equipment.

[16] https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-legislation-control-f-gases_en.

[17] 'Commercial use' means used for the storage, display or dispensing of products, for sale to end users, in retail and food services.

Hermetically sealed refrigerators and freezers for commercial use cannot contain a fluorinated refrigerant with a GWP of greater than 150. Stationary refrigeration equipment, that contains, or whose functioning relies upon HFCs, cannot use a refrigerant with a GWP of 2,500 or more (unless designed to cool products to temperatures below -50°C). A clause which covers multipack centralised refrigeration systems for commercial use with a rated capacity of 40 kW or more may very occasionally apply to larger cold rooms in food service outlets. In these cases, a refrigerant with a GWP of less than 150 must be applied. Currently regulations affecting the use of refrigerants apply across the EU and the United Kingdom (UK). Even though the UK is no longer part of the EU, the UK has to date mirrored the European legislation.

For the smaller integral refrigeration systems that are commonly used in kitchens and catering outlets there has been a significant move to the use of propane (R290) in Europe in recent years due to its inherent efficiency and low GWP of 3 (AR4). Hydrocarbon (HC) 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). The newer IEC 60335-2-89:2019 allows a higher charge of a flammable refrigerant of up to 1.2 kg, depending on the exact refrigerant applied. For cold storage rooms and HVAC systems in food service outlets the refrigerant applied is unlikely to be a HC and most likely will be a HFC with a GWP of less than 2,500.

European legislation on the use of F gases is due to be updated and proposed amendments were published in April 2022. These new regulations are designed to strengthen the previous measures and introduce new measures. In particular the proposal is intended to enhance the ambition of the regulation by a tighter quota system for HFCs which will reduce the HFCs placed on the market by 98% by 2050 (compared to 2015, based on GWP). It will also improve enforcement and implementation and apply harsher penalties for non-compliance. Monitoring will be more comprehensive with enhanced reporting and verification procedures. The proposed regulation also includes hydrofluoro-olefins (HFOs) (alongside HFCs) for prevention of emissions, leak checks, record keeping, recovery and labelling. The main clauses affecting food retail systems are presented in Table 4.

Table 4. Main impacts of proposed new F-gas regulation.

Clause	Category	Requirement	Date	Notes
11	Refrigerators and freezers for commercial use (self-contained equipment)	- that contain other fluorinated greenhouse gases with GWP ≥150	1 January 2024	Now includes 'other fluorinated greenhouse gases'
12	Any self-contained refrigeration equipment	- that contains fluorinated greenhouse gases with a GWP of ≥150	1 January 2025	New clause
14	Stationary refrigeration equipment	- that contains, or whose functioning relies upon, fluorinated greenhouse gases with GWP of ≥2,500 except equipment intended for application designed to cool products to temperatures below – 50°C	1 January 2024	Now includes 'other fluorinated greenhouse gases'
15	Multipack centralized refrigeration systems for commercial use	- with a rated capacity of 40 kW or more that contain, or whose functioning relies upon, fluorinated greenhouse gases listed in Annex I	1 January 2022	Link to Annex 1 added

Clause	Category	Requirement	Date	Notes
		with GWP of ≥150, except in the primary refrigerant circuit of cascade systems where fluorinated greenhouse gases with a GWP of < 1,500 may be used		

3.4 Economic pressures

The financial crisis has impacted both food service operators and 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 COVID-19 pandemic had a huge impact on food service outlets with many businesses struggling to stay afloat. Many restaurants have had to close down due to reduced demand, while others have had to cut back on staff and services. In an economy where it is challenging to find new employees and where salaries are increasing it has been very difficult for many businesses to survive. These issues combined with reduced consumer spending (7-8% below pre-pandemic levels[18]) has meant that in counties such as the UK, restaurant insolvencies jumped by more than 60% in 2022[19]. Information from accountancy firm UHY Hacker Young showed that 1,406 restaurants closed in the UK in the 12 months to May 2022 (an increase of 64% on the previous year). The closures are not just small businesses but include larger chains who are consolidating their estates to cope with heavy financial losses.

3.5 The labour market

The food service sector is experiencing significant shortage of skilled labour across Europe and the UK. Some of this has been exacerbated by the COVID-19 pandemic where workers returned to their home countries and have not been replaced in the labour market. The food service sector became unstable during the COVID-19 pandemic when many businesses closed or were not active for a period. Many workers looked for opportunities elsewhere and many older employees decided to retire.

Compared to 2020 levels, the EU industry is lacking 10-20% of the required workforce[20]. This level has been continually rising since the beginning of 2020. Due to reduced unemployment, there is now more choice of occupations available to the many relatively unskilled young workers who previously worked in food service.

At the same time the food service industry is changing, with companies needing to be more active online in terms of marketing, social media and greater demands from customers for more sustainable products. This is changing the skills required from employees who may be less willing to work long and unsocial hours in food service when other better paid employment opportunities are available. It also opens up the need for training of employees (for example apprenticeships and skills passports) and

[18] https://www.npd.com/news/blog/2022/the-situation-for-the-foodservice-industry-in-europe-no-more-restrictions-but-issues-remain/

[19] https://www.theguardian.com/business/2022/jul/25/uk-restaurant-insolvencies-closures-rise-data

[20] Hotrec. September 2022. Labour shortages in the hospitality sector: forward-thinking and practices sharing.

career pathways that will encourage employees to join the sector either from within Europe or though legal migration[21].

3.6 Energy costs

Reducing energy consumed also saves operational costs. With increases in global energy price, the need to improve efficiency is never more relevant. Irrespective of refrigerants and systems selected, it is vital to apply a systems-based approach to the whole supermarket design, installation and operation. Reducing loads through use of energy saving technologies has a major role to play in both retrofit and new installations. An overall integrated approach is essential to assess the whole system to ensure that interactions between equipment and energy saving technologies have overall energy reductions for food service facilities as a whole.

One issue in kitchens is that often the layout is not designed for energy efficiency. Refrigerating appliances can be in close proximity to a heat source (ovens, grill, etc.) and are placed for convenience rather than energy conservation. Such practices have been shown to raise energy consumption by 30% in some cases (Mudie et al, 2016)[9].

3.7 Legislation

In the food service industry regulations apply to both the food supplied and the equipment applied. The EU has strict regulations regarding food safety and hygiene. Additionally, there are regulations regarding allergens, nutrition information, and sustainability.

Legislation also applies directly to carbon emissions from certain equipment applied in the food service sector through Ecodesign and energy labelling.

3.7.1 Energy labelling

The Ecodesign Directive is considered one of the most successful regulations applied in Europe. A recent report from the European Environmental Bureau (EEB) estimated that Ecodesign could account for a third of the total emissions reductions needed to achieve the 55% greenhouse gas reduction target by 2030[22].

Professional refrigerated storage cabinets are the main products currently covered under Ecodesign that are relevant to food service outlets. Lighting, fans and motors are also covered but will often be part of other equipment.

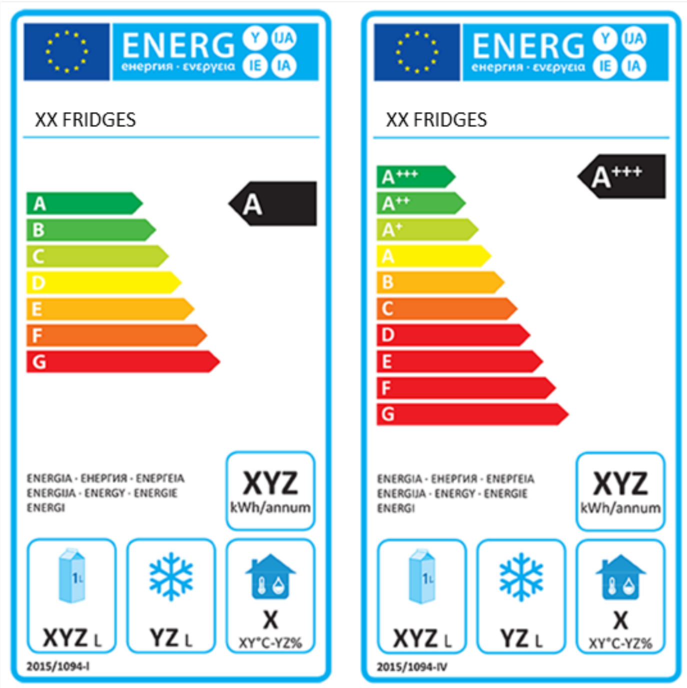


Figure 3. Energy label for professional refrigerated storage cabinets.

[21] Hotrec Hospitality Europe. Labour shortages in the hospitality sector: forward-thinking and practices sharing, September 2022.

[22] Schweitzer, J-P, Toulouse, E. and Zill, M. Delays in ecodesign implementation threaten 55% climate target and cost citizens billions, Brussels, September 2021. EEB, ECOS and CoolProducts.

The energy used by professional refrigerated storage cabinets is legislated via energy labelling and the application of Minimum Energy Performance Standards (MEPS). Regulations for professional refrigerated storage cabinets came into force on July 2016 and are covered by:

- Commission Delegated Regulation (EU) 2015/1094 of 5 May 2015 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of professional refrigerated storage cabinets.
- Commission Regulation (EU) 2015/1095 of 5 May 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for professional refrigerated storage.

The regulations are expected to lead to EU annual energy savings of about 1.8 TWh in 2020 and 4.1 TWh in 2030, corresponding to 0.7 and 1.4 million tonnes CO_2e, as compared with what would happen if no measures were taken.

The regulations cover vertical chilled, vertical frozen, counter chilled and counter frozen cabinets. There is a legal requirement to label the energy efficiency of all 4 types of professional refrigerated storage cabinets (and provide energy used by blast cabinets) if they are sold in Europe (the UK has similar regulations that currently mirror the EU regulations). Professional refrigerated storage cabinets are labelled from A+++ to G (A+++ being the most efficient and G the least). The label is calculated as an energy efficiency index (EEI) using the EN 16825 'Refrigerated storage cabinets and counters for professional use - Classification, requirements and test conditions' test standard.

Although the Energy Labelling directive focuses on energy use, it can also cover the consumption of other resources and impacts, for example water consumption, noise levels during use, or the GWP of refrigerants. Generally, with most refrigeration equipment, the use phase has the greatest environmental impact and so tends to be the focus of regulation. Generally, refrigerant leakage is not directly addressed in eco-design as it is considered to be tackled via F-gas regulations (see above). Therefore, the focus is usually on MEPS and energy labelling.

4 FUTURE ISSUES AND TRENDS

4.1 Increased use of renewables

Using of renewable energy in food service outlets is feasible if sufficient roof area or land adjacent to the outlet are available. Recent increases in energy costs have made the benefits of solar panels greater. If the energy generated can also be stored (electrically or thermally) there is the potential to benefit from demand side response (DSR) periods or use the stored energy at periods when energy costs are higher. The energy demanded by the food service outlets can be quite varied over time and economically there is an optimum level of renewable power that can be justified. The output from renewables can also be quite variable and there is a need to align production and usage. The share of the energy produced with the PV panels can be increased dramatically (20 to 70%) by applying some form of energy storage[23].

[23] Franco, A.; Cillari, G. Energy Sustainability of Food Stores and Supermarkets through the Installation of PV Integrated Plants. Energies 2021, 14, 5678. https://doi.org/10.3390/en14185678.

4.2 Integration (of heating and cooling)

A food service outlet should be considered as a complete energy system (including the building HVAC, hot water, lighting and refrigeration) and the best overall energy use evaluated[24]. This includes the integration of systems to share heat and coolth efficiently.

Currently there seems limited consideration of thermal integration within food service outlets. Equipment in kitchen generates considerable amounts of heat that are removed using HVAC systems. It is feasible to reclaim heat and use this heat for generating hot water, door curtains or to heat customer areas within an establishment. Similar systems have been applied in other sectors of the food chain and generally have reclaimed heat from CO_2 refrigeration systems where the opportunities for heat reclaim are greater. In supermarkets the annual energy demand for commercial refrigeration could be reduced by heat recovery from the refrigeration plant and energy recovery from exhaust air (Hafner et al., 2012[25]; Sawalha, 2013[26]). Most food service refrigeration systems are disparate and not interconnected due to a predominance of plug-in integral systems. Systems also tend to not currently use CO_2 as the refrigerant. Therefore, integration is not simple in existing outlets as they have not been designed for thermal integration. However, thermal integration could be designed into new facilities and with increasing energy costs such systems will have greater commercial feasibility.

4.3 Increased use of robotics and automation

Automation and robotics are now a far more viable option in the food service sector. With increased staff costs and issue with recruiting staff, the use of automation looks more attractive. Robots can chop, slice, mix, and cook ingredients with precision and consistency ensuring uniform quality for meals. Generally, automation works better when large numbers of similar meals are produced. This works best for large fast-food companies. For example, Nandos has installed a robotic chip fryer line that can produce 550 portions of chips per hour in a restaurant in London[27].

Automation works best when there are repetitive tasks and where products are consistent. In such cases the cooking time can be optimised and ultimately this can lead to efficiency gains and also improved food hygiene. Automated systems can also control portion sizes exactly and so can be useful to control measurement of ingredients, toppings, and condiments. Robots can also be used for washing and cleaning operations.

More complex automation tasks such as food waiter robots have proved less effective as the robots often lack the fine manipulative skills required to serve customers. For more repetitive tasks there have been examples of robot chefs used to prepare drinks and even whole meals[28].

[24] EN environment, RTOC Montreal protocol on substances that deplete the ozone layer. 2022 Report of the refrigeration, air conditioning and heat pumps technical options committee.

[25] Hafner, A., Poppi, S., Nekså, P., Minetto, S. and Eikevik, T.M., 2012, June. Development of commercial refrigeration systems with heat recovery for supermarket building. In Proceedings of the 10th IIR Gustav Lorentzen Conference on Natural Refrigerants, Delft, The Netherlands (pp. 25-27).

[26] Sawalha, S., 2013. Investigation of heat recovery in CO2 trans-critical solution for supermarket refrigeration. International journal of refrigeration, 36(1), pp.145-156.

[27] [27] Foodservice Equipment Journal, May 2023, Issue 99.

[28] Garcia-Haro, Juan Miguel, Edwin Daniel Oña, Juan Hernandez-Vicen, Santiago Martinez, and Carlos Balaguer. "Service robots in catering applications: A review and future challenges." Electronics 10, no. 1 (2020): 47.

Automation can also be part of inventory management by checking stock, tracking expiry dates and even placing orders for new stock. Although automation potentially has huge potential it is not suitable for all restaurants as not all facilities have the scale to make automation commercially viable.

Simpler automated systems that convey orders to the kitchen have become more popular, partly due to restriction during the covid pandemic. For fast-food outlets they also can reduce waiting times and provide simple transactions when purchasing meals.

The greater use of automation generates a new need for training and skills to program, operate and manage such systems. This requires upskilling of employees who will have completely different skills to those of current employees.

4.4 Increase in home delivery

In 2022 there were an estimated 211.1 million users of online meal delivery platforms in Europe. This was an increase of 85% since 2017[29]. This follows similar increases in home delivery Worldwide. The growth has been primarily driven consumer preferences for convenience and also due to home delivery being developed during the pandemic by restaurants as a new revenue stream. The increased use of home delivery has increased competition between restaurants. Increasingly restaurants have to differentiate themselves through quality, unique offerings and the efficiency of their delivery systems. It also creates issues around branding and customer experience. The restaurant no longer has a face-to-face experience with the customer and removes the personalised experience that may make a customer visit the restaurant.

Potentially home delivery provides restaurants with new revenue streams. Most restaurants partner with a delivery platform as this provides them with a ready-made platform and potential to expand outside of their existing customer base. However, most home delivery services charge commission for each order. Although potentially home delivery can increase sales and revenue it may reduce margin per meal sold. Restaurants may also have to compete against dark kitchens where food is prepared away from a formal restaurant setting in a cheaper industrial unit. This removes many of the overheads that a restaurant has and reduced costs and increase margins for the operators.

In the future drones and autonomous vehicles are a new area for the food service sector. These are under development and may provide new efficient methods to deliver food directly to customers.

4.5 Integration into electricity grid

Potential exists for all electricity users to better integrate into the grid. Demand side response (DSR) is when electricity users switch off appliances to help balance the grid. Most DSR periods are requested by grid operations at peak energy usage times (typically early evening). Although DSR does not save energy, it enables the more carbon intensive power generation facilities to be turned off/down during DSR periods and so carbon is saved. Operators are paid to remove load from the grid making DSR an economic proposition. Most DSR periods are approximately 30 minutes but may last for up to an hour. Other sectors of the food chain have recently embraced how they can benefit from integrating into national electrical grids. Retailers as whole estates of hundreds of supermarkets can provide significant reductions to grid demand if switched off. For food service operators to do the same thing they would either have to have considerable numbers of outlets or would have to link together to provide a consolidated load reduction. Potential exists for food service operators to switch off refrigeration systems in the same way as retailers and cold store operators do. Potential also exists to incorporate thermal storage or battery energy storage into food service outlets to enable cooking appliances to be

[29] Statista. https://www.statista.com/forecasts/1297721/users-online-food-delivery-europe

removed from the grid or to extend DSR periods for refrigeration systems. However, we could not find any evidence that this has been commercially applied yet.

4.6 Management

One issue that is paramount in many food service outlets is the ability for operators and owners to be able to make sustainable choices. Many food outlets are leased and so the operators have little impact on the building they operate from and can make only limited changes to the structure. Leases may also be relatively short terms and so operators may be reluctant to invest in fixed equipment that they would have to remove at the end of the lease period.

In many institutional facilities such as hospitals, schools, office canteens and government facilities the operator may be a contractor and have no influence over the equipment provided by the host. Contractors often are not responsible for the energy bill and so have limited incentive to save energy or use equipment in an efficient and sustainable manner.

4.7 Training and skills

The way food service facilities are managed is often related to training of the operators. Mudie et al (2016)[9] found that kitchens rarely reduced the consumption of appliances during quiet sales periods. Fitting simple time clocks or motion sensors and increasing staff training would yield substantial energy savings but are rarely applied[30]. In domestic cooking appliances such as ovens, hobs and range hoods standby and off-mode functions can also be responsible for much of the total power consumption. These functions are part of the minimum energy performance requirements in Ecodesign[31] but have not yet been applied to commercial appliances.

Mudie et al (2016)[9] found that behavioural issues and poor maintenance in kitchens were a major contributor to excessive electricity usage. In work they carried out they found potential savings of 70% for particular pieces of equipment that could be operated better and savings of 45% for equipment that could be maintained better. Catering appliances were found not to encourage efficient use and the often-high pressure environment in kitchens did not engender efficient behaviours from staff. However, training could certainly be applied both in work environments and in catering colleges to help staff better appreciate where energy could be saved.

Another area examined by Mudie et al (2016)[9] covered correct sizing of refrigeration equipment. Storage facilities were often not fully utilised and better logistics and planning could have significant impact to save energy. Generally, there is a shortage of skilled technicians, and in particular refrigeration engineers with skills and experience of natural refrigerants. Lack of skills in these areas is a serious barrier to the uptake of natural refrigerants (such as R744 and R290)[32].

Critically a recent article stated that 30% of restaurants do not feel they have the right resources to increase skills and 25% claimed that they do not have the finances to invest in training of their staff[27].

[30] Batty, W., Conway, M. A., Newborough, M., et al. Effects of operative behaviours and management planning on energy consumptions in kitchens. Applied Energy, 1988;3:205–20.

[31] Commission Regulation (EU) No 66/2014 of 14 January 2014 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for domestic ovens, hobs and range hoods.

[32] https://www.thebesa.com/news/skills-gap-threatens-cooling-sector-s-safety-and-environmental-aims/

4.8 Circular economy and food waste

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 there is now a shift in 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.

Clowes, Mitchell and Hanson (2018)[33] found that food waste is not typically measured as part of standard food service operating procedures. Even when information is collected, it is rarely communicated back to the food service team. By making efforts to reduce food waste the authors found that on average food waste could be reduced by 36%. This had a huge economic gain as the investments made to reduce food waste were easily outweighed by the cost benefits. Technologies such as smart weighing scales and training of staff in measuring wastes and techniques to reduce waste had paybacks of less than 12 months in 64% of cases evaluated (86 sites were part of the assessment). The main steps to reduce waste were:

1. Measurement and quantification of waste.
2. Engaging staff, rewarding waste reduction, training and good leadership to engender good habits.
3. Developing pilot projects to test procedures and find issues before rolling out more extensively.
4. Reduce overproduction through identifying poorly selling dishes and staff identifying where food was most wasted. Better forecasting of sales was also beneficial.
5. Repurpose excess food in other meals (for example use excess breakfast items in a lunch menu), use previously wasted peels, seeds, skins and bones usefully into meals (e.g. soup and stock). Other options included food donation and customers taking food they did not eat home to eat at a later time.

5 BEST AVAILABLE TECHNOLOGY (BAT)

What are the most efficient food service appliances currently available? Figure 4 shows the proportion of professional storage cabinets falling within each energy label class on the European Product Registry for Energy Labelling (EPREL) as of March 2023. According to the EPREL, 1% of storage cabinets are G-

[33] Clowes, A, Mitchell, P. and Hanson, C. The business case for reducing food loss and waste: catering. A Report on Behalf of Champions 12.3. 2018.

class and 4.3% are F-class. Many of the worst performing storage cabinets on the EPREL were labelled incorrectly, being commercial cabinets with glass doors or blast cooling cabinets. Chillers had a better energy class than freezers.

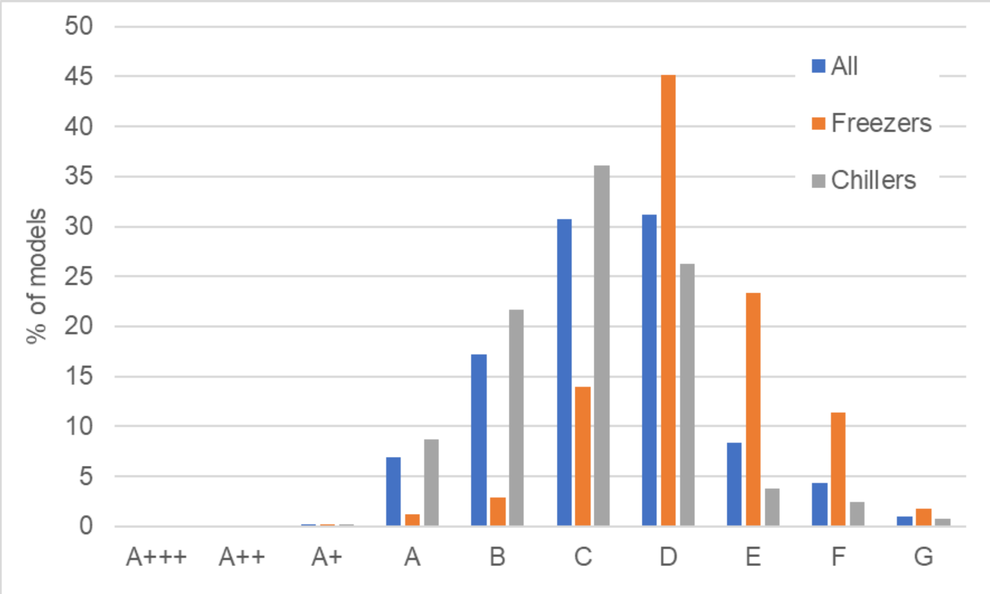


Figure 4. Proportion of professional storage cabinets (%) falling within each label on EPREL as at March 2023.

The EPREL does not allow searching by cabinet type (apart from chilled and frozen volume), so it is not possible to tell how many cabinets within each label class are vertical or horizontal. Therefore, information on 175 appliances were extracted from the web site of a major UK supplier of professional refrigerated cabinets (https://www.nisbets.co.uk/) was searched and label classes for different cabinet types (chilled vertical (CV), frozen vertical (FV), chilled horizonal (CH) and frozen horizontal (FH)) were collected (Table 5).

Table 5. Energy label and percentage of cabinets (in brackets) in that label from a UK retailer of professional refrigeration.

	Top label class (%)	Modal label class (%)	Bottom label class (%)
CV	A (4)	C (52)	F (4)
CH	A+ (7)	B (36)	E (1)
FV	B (16)	D (22)	E (10)
FH	B (12)	D (76)	D (76)

This data correlated well with the EPREL data showing most cabinets falling in the C and D class and chillers performing better than freezers. However, this data also shows a difference between the different model types, with CV providing label class one higher than CH which were one higher than FV and FH.

The Eco-design ECO scenario aims to lead average cabinets to a B-class by 2040 (MEErp, 2011)[34]. For all cabinets this is already achievable for all cabinet types. However, it would be more difficult for freezers than chillers. For CH type, this would probably be too lenient, as the modal class is already a

[34] MEErp, 2011. Methodology for ecodesign of energy-related products (MEErP 2011) Methodology for ecodesign of energy-related products (MEErP 2011) - Publications Office of the EU (europa.eu)

B. The most recent Ecodesign study for the EC (Kenma et al., 2022)[35] has suggested changing the calculation of the energy efficiency index (EEI) and changing the threshold for the labelling. The revised policy change (ECO scenario) is predicted to reduce energy consumption of storage cabinets up to 2050 and is shown in Table 6 along with the current business as usual scenario (BAU scenario). The ECO scenario is predicted to reduce emission of professional refrigeration by 19% in 2030 and 41% by 2050.

Table 6. Total energy consumption and greenhouse gas (GHG) emissions from professional refrigeration in the EU projected to 2050 under different scenarios.

	Scenario	2020	2030	2040	2050
Electricity (TWh/year)	BAU	85	92	97	104
	ECO	-	-8.1	-23.8	-30.5
GHG emisisons ($MtCO_2$/year)	BAU	18.1	13.1	7.3	6.3
	ECO	-	-1.2	-1.8	-1.9

6 TECHNOLOGIES/STRATEGIES

Energy saving technologies/strategies were initially identified and listed. In total 60 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 included all available published information, or any information obtained directly from manufacturers of the equipment. 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 GHG 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 TRL were listed if available. If a technology was not currently available, the approximate time until it could be deployed was estimated (Table 7).

Most of the 60 technologies and strategies had potential to be applied relatively rapidly. Some were direct retrofit options, but others would be more appropriately applied to a new facility. Whether savings were scope 1 or 2 were assessed. The TRL level of the technology is noted in Table 8. Only options with a TRL of 8-9 are considered for full assessment as it is not possible to guess the impact that lower TRL technologies might have in the future.

> **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.*

[35] Kenma et al. Professional Refrigeration Ecodesign and Energy Labelling: Review Study Phase 1.1 & 1.2 Technical Analysis DRAFT 2nd INTERIM REPORT. European Commission. 20221221_Professional refrigeration review study_second interim report.pdf (ecoprorefrigeration.eu).

Table 7. Review summary information included at the end of each review.

Information	Comments
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 8. List of technologies/strategies assessed, when they can be applied and the type of emission saving.

Technology	Sector in restaurant	TRL level	Where applied:		Carbon savings	
			Retrofit	New	Scope 1	Scope 2
Refrigerated appliances						
Acoustic refrigeration	Refrigeration	1-4		✓	✓	✓
Advanced controls	Refrigeration	5-7	✓	✓	✓	✓
Charge optimisation	Refrigeration	8-9		✓	✓	✓
Dampers	Refrigeration	1-4		✓		✓
Defrost control (e.g. on demand)	Refrigeration	8-9	✓	✓		✓
Door open warnings	Refrigeration	8-9	✓	✓		✓
Dual-loop system	Refrigeration	1-4		✓		✓

Technology	Sector in restaurant	TRL level	Where applied:		Carbon savings	
			Retrofit	New	Scope 1	Scope 2
Dynamic demand	Refrigeration	8-9	✓	✓		✓(grid)
Efficient compressor technology	Refrigeration	8-9		✓		✓
Electrocaloric refrigeration	Refrigeration	1-4		✓	✓	✓
Evaporator and condenser optimisation	Refrigeration	8-9		✓		✓
Fan-assisted condenser	Refrigeration	8-9		✓		✓
Heat pipes and spot cooling	Refrigeration	5-7		✓		✓
Improved door gaskets	Refrigeration	8-9	✓	✓		✓
Improved insulation e.g. vacuum insulation panels	Refrigeration	5-7		✓		✓
LED lighting	Refrigeration/ general	8-9	✓	✓		✓
Liquid line solenoid	Refrigeration	8-9		✓		✓
Magnetic refrigeration system	Refrigeration	1-4		✓	✓	✓
Maintenance and servicing	Refrigeration	8-9	✓	✓	✓	✓
Nanoparticles	Refrigeration	1-4	✓	✓		✓
Phase change materials	Refrigeration	1-4		✓		✓
Refrigerants	Refrigeration	8-9	✓	✓	✓	✓
Stirling coolers	Refrigeration	1-4		✓	✓	✓
System optimisation	Refrigeration	8-9		✓	✓	✓
Thermoelectric refrigeration	Refrigeration	1-4		✓	✓	✓
Thermionic refrigeration	Refrigeration	1-4		✓	✓	✓
Two-stage system	Refrigeration	8-9		✓		✓
Vortex tube	Refrigeration	1-4		✓		✓
Wide glide refrigerants	Refrigeration	1-4		✓		✓
Ovens:						
Air impingement	Cooking	8-9		✓		✓
Automatic shutdown	Cooking	8-9	✓	✓		✓
Control of exhaust hood	Cooking	8-9		✓		✓
Doors instead of open front/back	Cooking	8-9		✓	✓ (gas)	✓ (elec)
Efficient/improved oven design	Cooking	1-4		✓	✓ (gas)	✓ (elec)
Improved combustion efficiency (gas/oil)	Cooking	8-9		✓	✓	
Improved oven control e.g., active exhaust control	Cooking	5-7		✓	✓ (gas)	✓ (elec)
Keep oven loaded	Cooking	8-9	✓		✓ (gas)	✓ (elec)
Motor efficiency (mixers, conveyors etc.)	Cooking	8-9		✓		✓
Position away from chillers/freezers	Cooking	8-9	✓		✓ (gas)	✓ (elec)
Recover exhaust heat	Cooking	1-4		✓	✓ (gas)	✓ (elec)
Reduce heating up time	Cooking	8-9		✓	✓ (gas)	✓ (elec)
Reduce thermal mass of tins	Cooking	5-7	✓		✓ (gas)	✓ (elec)
Switch off conveyors when not in use	Cooking	8-9	✓		✓ (gas)	✓ (elec)
HVAC:						
Air conditioning	HVAC	8-9		✓	✓ (gas)	✓ (elec)
Cold air retrieval	HVAC	8-9		✓		✓

Technology	Sector in restaurant	TRL level	Where applied:		Carbon savings	
			Retrofit	New	Scope 1	Scope 2
Controls (advanced)	HVAC	8-9	✓	✓		✓
Boilers with higher efficiency	HVAC	8-9		✓	✓ (gas)	✓ (elec)
De-stratification fans	HVAC	8-9	✓	✓	✓ (gas)	✓ (elec)
Door air curtain	HVAC	8-9	✓	✓	✓	✓
Fan motors with higher efficiency	HVAC	8-9		✓		✓
Heat pumps, heat reclaim and radiant heat	HVAC	8-9		✓	✓	✓
Variable frequency drives	HVAC	8-9		✓		✓
Other/ancillaries:						
Building fabric optimisation	Ancillaries	8-9			✓ (gas)	✓ (elec)
Building glazing optimisation	Ancillaries	8-9	✓	✓	✓ (gas)	✓ (elec)
Building lighting efficiency	Ancillaries	8-9	✓	✓		✓
Maintenance and operational practices	Ancillaries	8-9	✓	✓	✓	✓
Renewable energy (solar electricity)	Ancillaries	8-9		✓	✓ (gas)	✓ (elec)
Renewable energy (solar thermal)	Ancillaries	8-9		✓	✓ (gas)	✓ (elec)
Packaging – low carbon options	Ancillaries	8-9	✓	✓	✓ (gas)	✓ (elec)
Waste technologies and impact of changes (landfill, AD, incineration etc)	Ancillaries	8-9		✓	✓ (gas)	✓ (elec)

6.1 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 whole supermarket:

Potential to save carbon:

Low (L): <5% potential saving

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

High (H): >10% saving

Payback time:

<1 year

1 to 3 years

3 to 5 years

>5 years

Neutral/limited information

Negative payback

Technologies and strategies were then divided into sectors of relevance (Figure 5). Those in:

- Category 1 have the highest carbon savings potential and shortest payback and so 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.

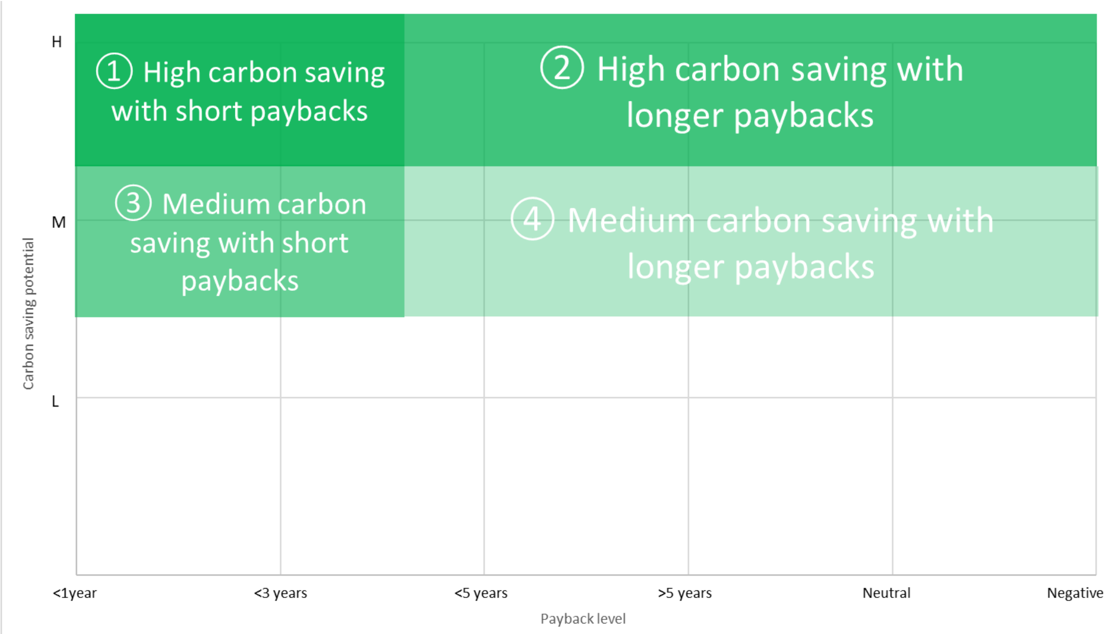


Figure 5. Potential carbon savings and payback sectors.

Technologies with a TRL of 8-9 were assessed using the above methodology. Results are presented in Figure 6, Figure 7 and Figure 8. It should be noted that several technologies had overlapping impacts or could not be applied in tandem. In these cases, the technology with the greatest benefit was considered in the modelling.

It was clear that most of the reviewed technologies were available today. Those that had a lower TRL were difficult to assess as there was very limited information on the of performance the technologies. It was therefore not possible to assess looking forward when the lower TRL technologies would be applied or their benefits.

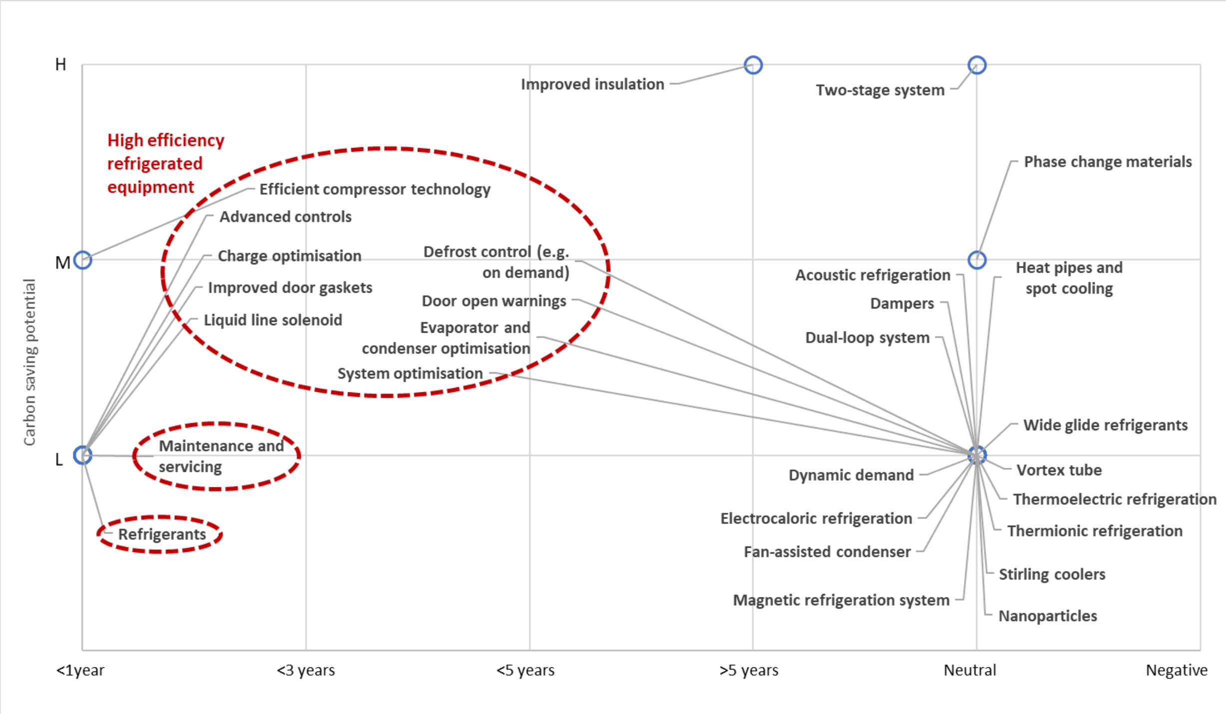


Figure 6. Refrigeration options.

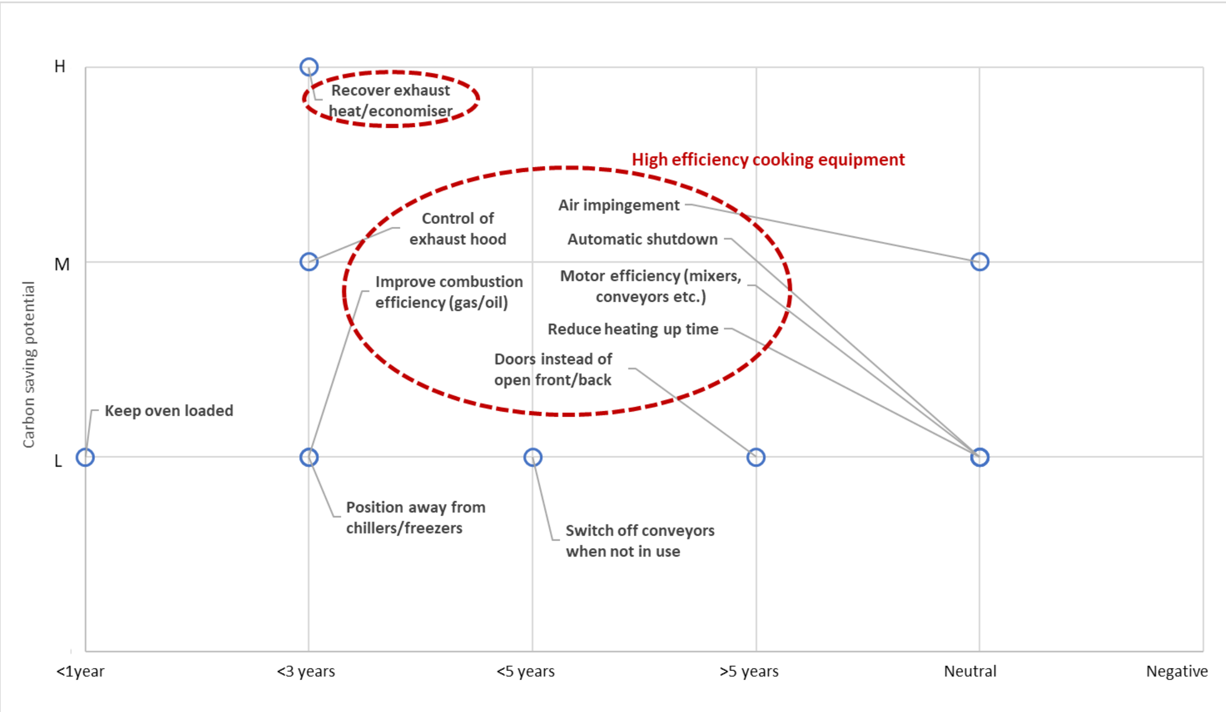


Figure 7. Cooking options.

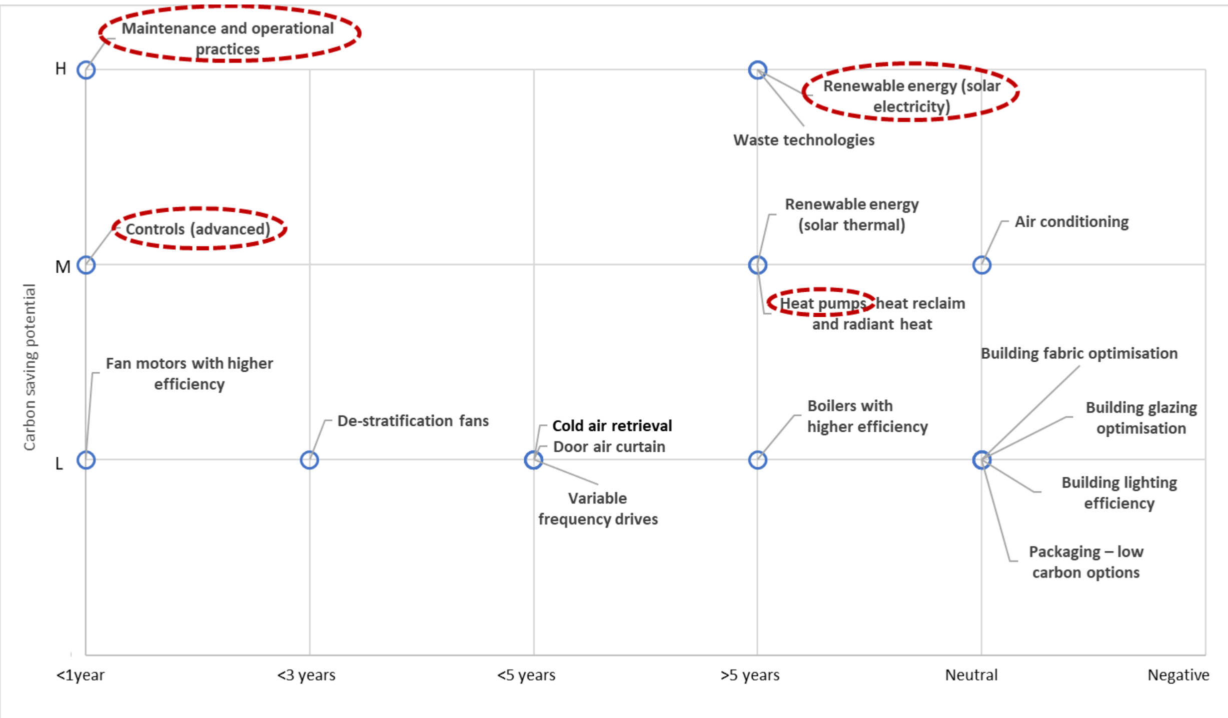


Figure 8. Options for Air conditioning, building fabric and miscellaneous options.

7 WHAT STRATEGIES SHOULD WE APPLY TO GET TO ZERO CARBON IN FOOD SERVICE OUTLETS?

The options with the most potential were then applied into an EnergyPlus™ model of typical European high usage quick service restaurant and another one with a medium usage in 6 European countries (UK, France, Lithuania, Norway, Italy, Poland) to assess their individual and combined potential to reduce carbon emissions.

7.1 Scenarios

In the modelling a scenario comparing 'do nothing' with one that applied new technologies and systems were considered.

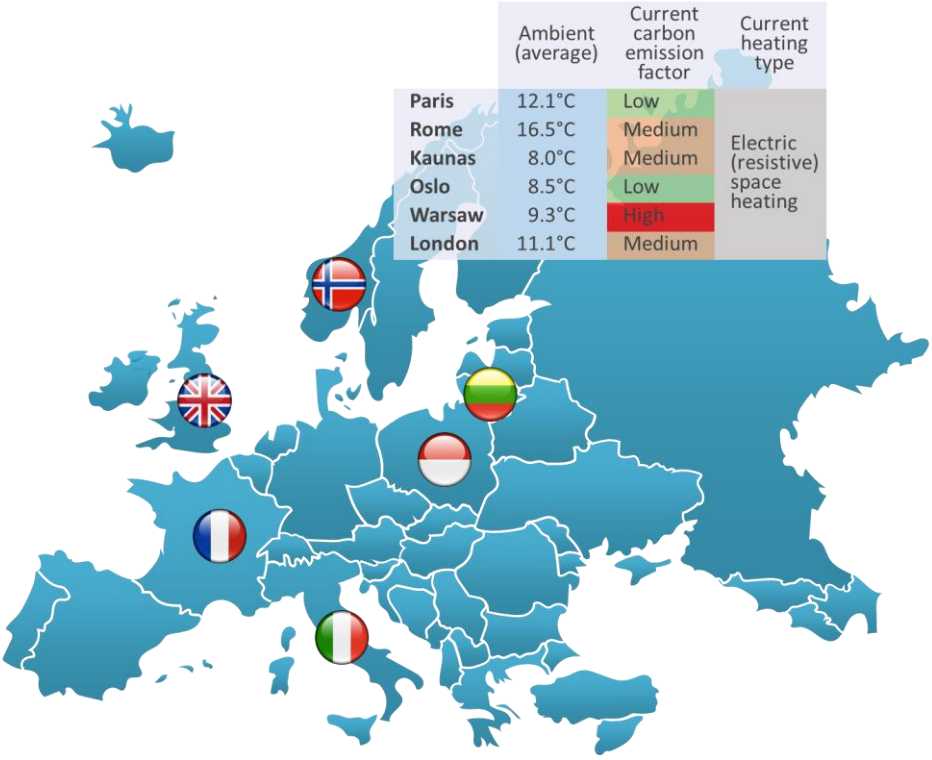
WHY WE MODELLED A QUICK SERVICE RESTAURANT

To be able to assess the technologies and strategies for a facility we need to consider the interactions between all the heating and cooling systems in a facility and also whether there are interactions between individual technologies. For example, one technology may reduce the need for cooling, but at the same time increase the need for heating. Technologies interact and so you cannot just assume that you can add the benefits of each technology together. Outputs can also be dependent on 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 systems, cookers and cooking equipment, HVAC (heating and cooling) and other items such as space heating for the customer areas.

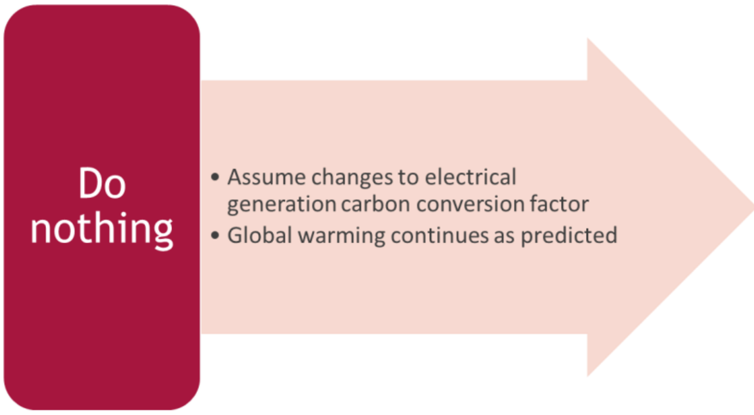
The impact of building a completely new facility was not considered as it was technically possible to retrofit all the technologies/strategies considered.

7.1.1 Do nothing

This considered the carbon savings if the food service outlets did nothing above what would occur naturally and there were no changes to current regulation and legislation. The impact of changes due to global warming and changes to the electrical grid emission conversion factors were applied for 2020, 2030, 2040 and 2050. An RCP 4.5 climate change scenario was applied. This is described by the Intergovernmental Panel on Climate Change (IPCC) as a moderate scenario in which emissions peak around 2040 and then decline. Where possible the grid conversion factors for energy resources were applied forward to 2050. It was not possible to identify predicted electrical grid conversion factors into the future for Norway or Italy and so it was only possible to assess impact for the 2020 scenario for these countries.



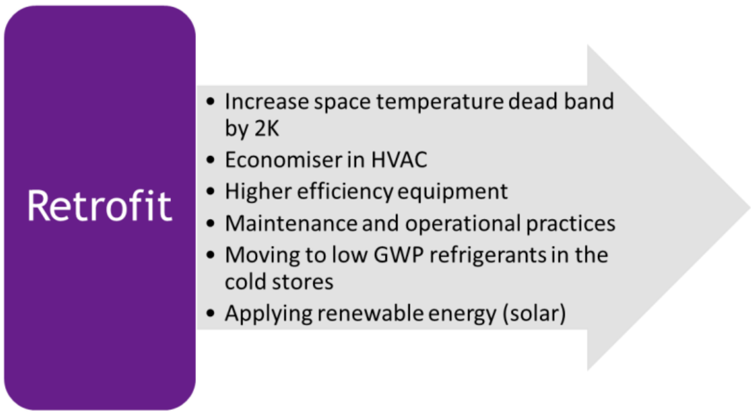
	Ambient (average)	Current carbon emission factor	Current heating type
Paris	12.1°C	Low	Electric (resistive) space heating
Rome	16.5°C	Medium	
Kaunas	8.0°C	Medium	
Oslo	8.5°C	Low	
Warsaw	9.3°C	High	
London	11.1°C	Medium	



The impacts of climate change and changes to the grid emission conversion factors were assessed individually and if applied together. In all cases the impact on energy consumption and carbon emissions were assessed.

7.1.2 Retrofit

The modelling in the 'do nothing' scenario was extended to the retrofit options identified as being most useful to reduce carbon with the best paybacks. These were:



1. Increase space temperature dead band by 2K.
2. Economiser in HVAC.
3. Higher efficiency equipment.
4. Maintenance and operational practices.
5. Moving to low GWP refrigerants in the cold stores.
6. Applying renewable energy (solar).

Each retrofit option was applied from 2020 onwards to the ‘do nothing’ scenario, individually to assess benefits for each store type, location and over the same time periods as in the ’do nothing’ scenario. Technologies were then applied together to assess the impact of interactions and to identify the overall benefits for energy and carbon reduction.

7.2 How to interpret the results

Results from the predicted carbon emission savings can be used to assess reductions in emissions over time. When integrated, this shows accumulated carbon emissions reductions. Although there are ambitions to reduce 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 more important than reaching zero carbon emissions by a fixed date. By applying the 3 scenarios, we calculated the total carbon savings from a food service restaurant, that can be achieved from 2020 to 2050 and the impact of accelerating the move to low GHG emission technologies. For example, the accumulated carbon emissions from 2020 to 2050 in a worked example would be for (Figure 9):

Do nothing: 1718 tCO_{2e}

Minor retrofit: 1042 tCO_{2e}

Major retrofit: 375 tCO_{2e}

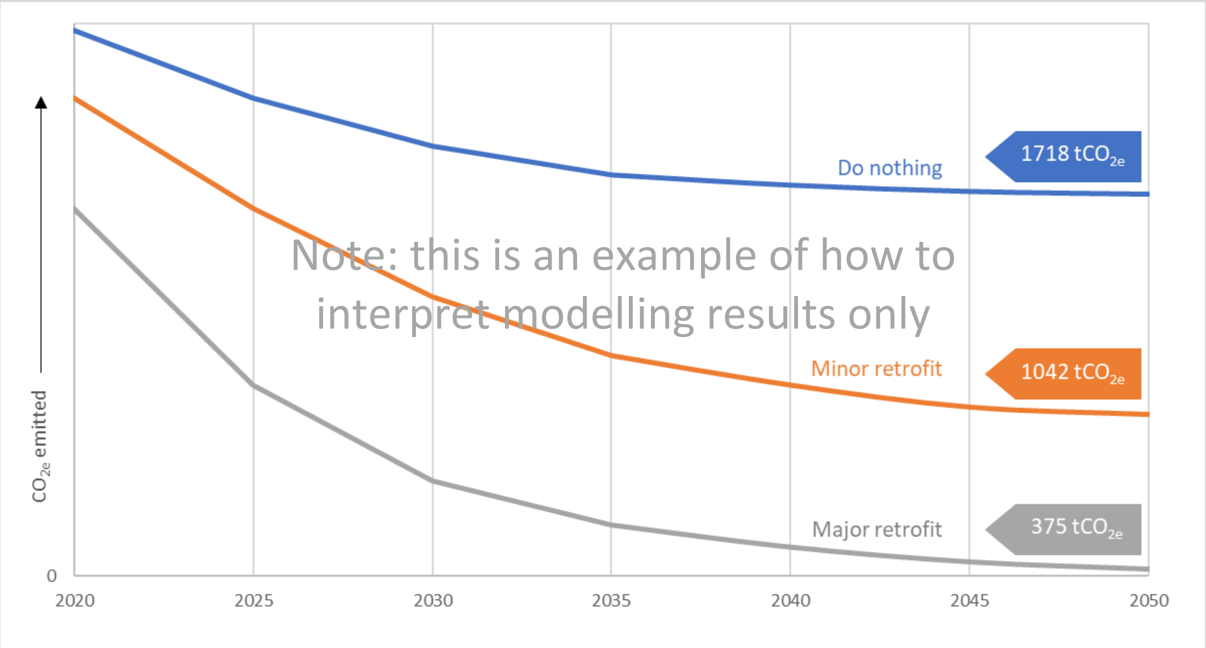


Figure 9. Diagram showing impact of when technologies are applied (example only).

Other options can then be selected to assess impacts of when changes are made on accumulated carbon savings (Figure 10). For example:

- If the facility did nothing until 2030 and then caried out a major retrofit the accumulated carbon emissions would be 747 tCO_{2e} (option 1).
- If they did nothing until 2025, then applied minor retrofit and in 2035 and carried out a major retrofit the accumulated carbon emissions would be 780 tCO_{2e} (option 2).
- If they carried out a minor retrofit immediately and then a major retrofit in 2025 the accumulated carbon emissions would be 475 tCO_{2e} (option 3).

This demonstrates that it is imperative to apply technologies as quickly as possible and that delays have significant impacts on accumulated carbon emissions.

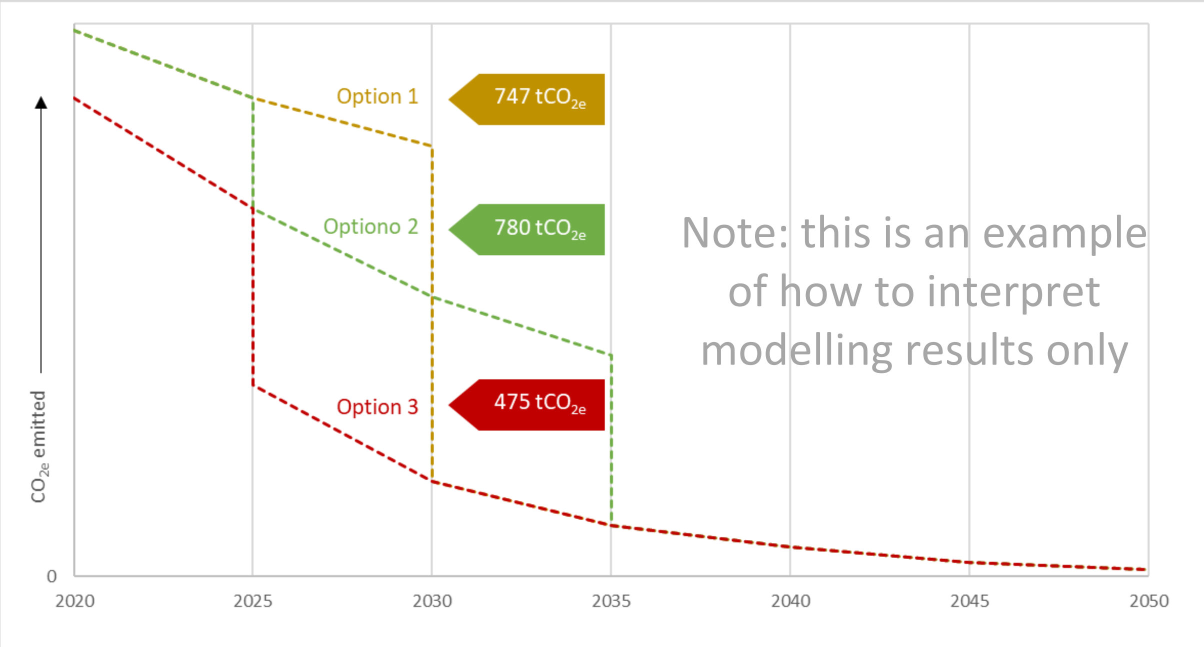


Figure 10. Diagram showing impact of when different scenarios are applied (example only).

7.3 Assumptions applied in the modelling

EnergyPlus[TM] with Openstudio as the "front end" was used to simulate the heat flow in the supermarket and thus allow carbon emissions to be calculated. Complete information on the modelling approach is shown in Section 14.

The modelling was based on a typical high usage fast-food outlet and an adapted moderate usage one. The inputs to the model are shown in Section 14.4.8.

These two facilities were then modelled at 6 other locations, where the weather file, (changing ambient conditions), of a different location was used. The 6 locations were, London (UK), Kaunas (Lithuania), Warsaw (Poland), Oslo (Norway) and Rome (Italy).

7.4 Scenario 1: do nothing

The impact of climate change and grid electricity emission factor were considered individually to assess impact and whether there was any benefit in assessing the additive impacts.

Impact of climatic temperature change: Figure 11 (high usage quick service restaurant) and Figure 12 (medium usage quick service restaurant) shows the impact of climatic temperature change on energy consumption for the 6 locations in 2020 and 2050. The graphs present information divided into heating, cooling (HVAC), lighting, interior equipment, fans, pumps, water systems and refrigeration (storage cabinets and cold stores).

Overall differences between energy consumed in 2020 and 2050 were small (less than 0.6% for the high usage quick service restaurant and up to 0.8% in the medium usage quick service restaurant). The low impact on increasing climatic temperature was due to a balance between the heating and cooling demands on the restaurants. As climatic temperatures increased there was less heating demand, but this was balanced by the increased A/C and refrigeration demand. In some cases, energy was slightly reduced (up to 0.2% in the high usage quick service restaurant and up to 0.5% for the medium usage quick service restaurant) for the same reasons.

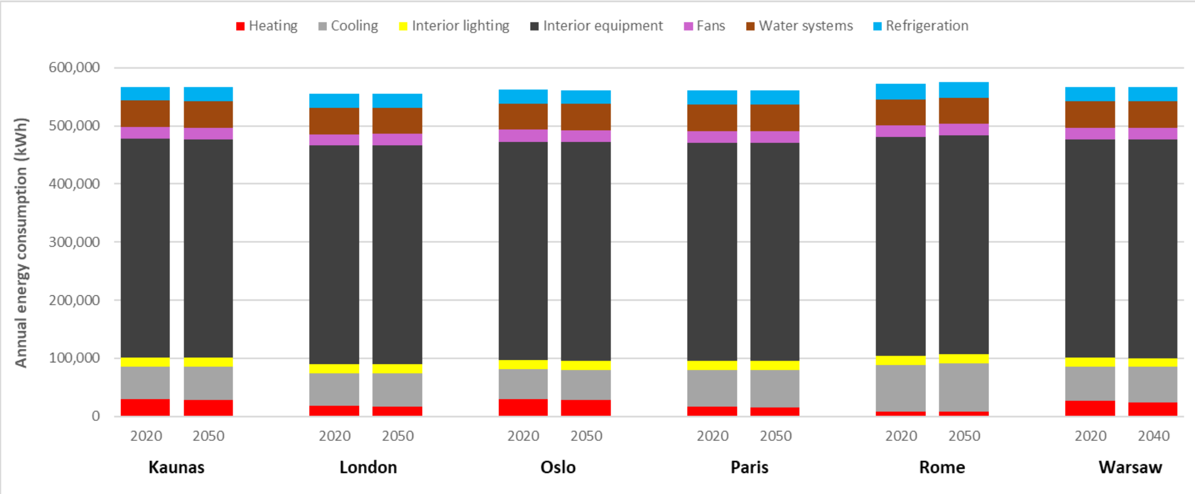


Figure 11. Impact of climatic temperature change between 2020 and 2050 for the high usage quick service restaurant in the 6 locations studied.

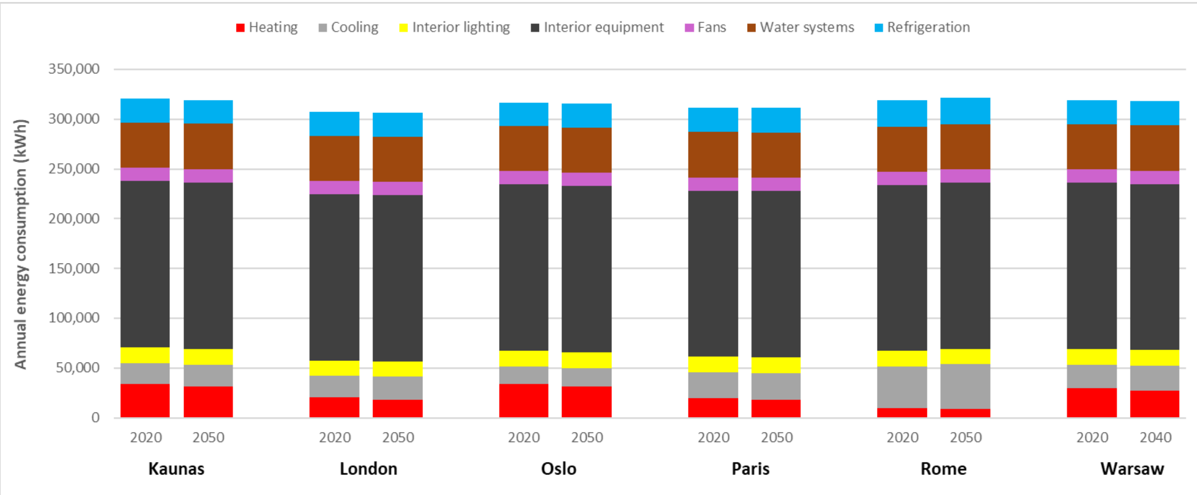


Figure 12. Impact of climatic temperature change between 2020 and 2050 for the medium usage quick service restaurant in the 6 locations studied.

Impact of changes to electrical grid emission factors: over time the carbon intensity of the nation's electrical grids are predicted to decrease considerably. Figure 13 presents (where available) the changes to the grid intensity factors in the 6 counties. As can be seen, the grid intensity factors reach almost zero in Lithuania, the UK and France by 2050. No information on future grid intensities was available for Italy and Norway. However, Norway already has a very low grid intensity that is the lowest of the 6 countries considered. Poland has the highest intensity in 2020 and although it is predicted to reduces considerably it is still the highest of the 6 countries considered in 2040 (no data was available for later dates).

The significant changes to carbon intensity over time had a major impact on emissions for the restaurants studied (Figure 13). Figure 14 presents the total carbon emissions for the high usage quick service restaurant and Figure 15 presents the total emissions for the medium usage quick service restaurant. Carbon emissions in both restaurant types reached almost zero in France, the UK and Lithuania by 2050 as the restaurants were powered by electricity and the grid carbon emissions factors were all predicted reduce to very low levels by 2050. Although forward emission figures for Norway were unavailable, the restaurants in Norway would also be close to zero emissions in 2050 as it seems unlikely that the 2020 carbon intensity would increase. The only locations where the carbon emissions might not reduce to near zero were Italy and Poland. Although there were still emissions from the refrigerant applied to the cold stores in 2050, this had minimal impact on carbon emission as the refrigerant charge was so low.

The accumulated carbon emitted between 2020 and 2050 when the 'do nothing' scenario was applied are presented in Table 9 for the restaurant configurations. Clearly Paris had the lowest accumulated carbon emissions and Warsaw the highest.

DO NOTHING SCENARIO

If the case study restaurants make no changes to how they operate between 2020 and 2050 it is possible to reach close to net zero if the grid carbon conversion factor is almost zero. As all restaurants were powered by electricity the grid carbon conversion factor was the primary driver in reducing emissions. Althougb there were still fugitive emissions from the refrigerant (R448A) used in cold stores the refrigerant charge applied was low and so refrigerant leakage had minimal impacts on overall emissions.

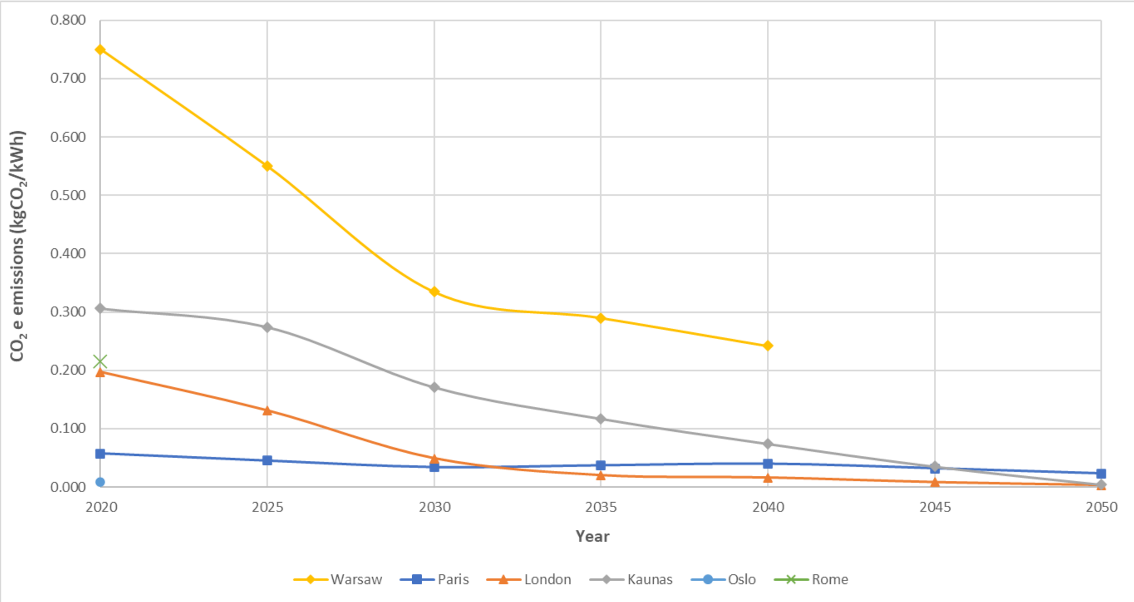


Figure 13. Grid electrical carbon conversion factors for the 6 countries studied (where available).

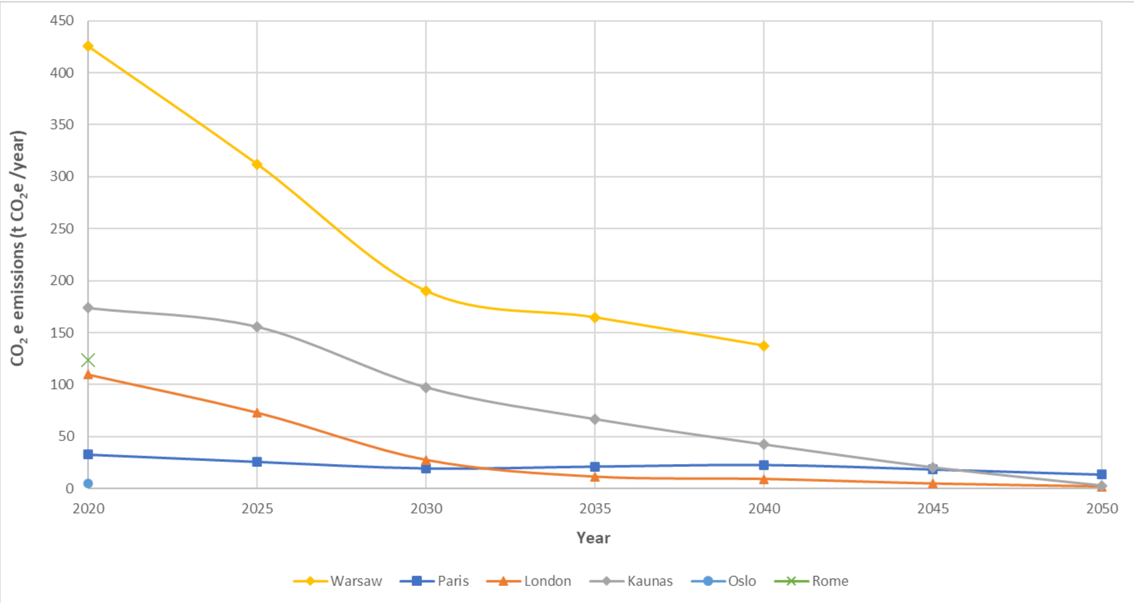


Figure 14. Impact of grid carbon emission factor change on total carbon emitted by high usage quick service restaurant in the 6 locations studied.

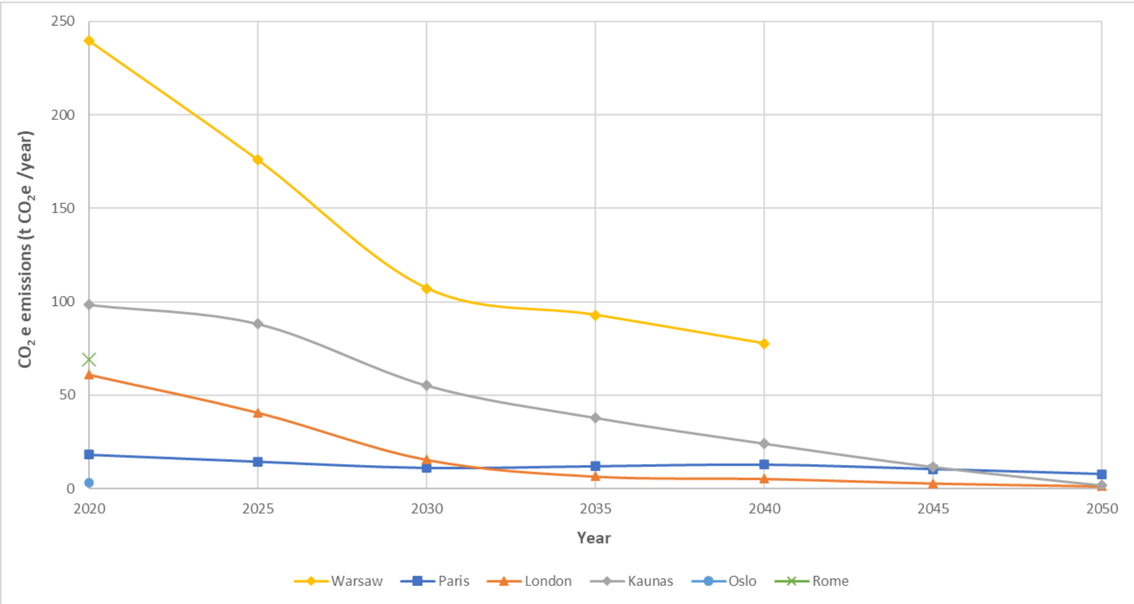


Figure 15. Impact of grid carbon emission factor change on total carbon emitted by medium usage quick service restaurant in the 6 locations studied.

Table 9. Accumulated carbon emitted between 2020 and 2050 for the Kaunas, London, Paris and Warsaw.

	Accumulated tCO_2e emitted between 2020 and 2050	
	High usage quick service restaurant	Medium usage quick service restaurant
Kaunas	6,478	1,343
London	904	506
Paris	651	367
Warsaw (note: data for 2050 extrapolated using trend)	4,773	2,690

7.5 Scenario 2: retrofit

Initially each retrofit technology was applied individually to the 2 restaurant formats (high/medium usage quick service restaurant) and the impact assessed to 2050 assuming the same changes as applied in the 'do nothing' scenario. The following assumptions were made:

Increase dead band by 2K: The restaurant set point was adjusted by 1K (decrease and increase) depending on which option saved carbon (this was dependent on the location of the store).

Economiser in HVAC: An HVAC economiser was applied. Economisers were integrated into the HVAC of both the kitchen and dining areas. These used outside air to provide free cooling when the external air conditions were favourable, instead of relying on the mechanical cooling of the air conditioning.

Higher efficiency equipment: Equipment with 20% less energy consumption was applied (for all equipment).

Low GWP refrigerant: R448A in the cold stores was replaced with a refrigerant with GWP of 150.

Maintenance/operational practices: A 10% overall savings for all equipment was applied.

RES (solar PV): The available annual energy from covering all the store roof with solar PV was calculated for each location using RetScreen. The available energy from the solar PV was removed from then annual energy consumed by the store. It was therefore assumed that all solar PV generated could be used by the store.

The impact of the retrofit options (alone and in combination) is shown in Figure 16and **Error! Reference source not found.** for energy consumption and Figure 18 and Figure 19 for carbon emissions. The impact of the combined technologies to 2050 are shown in Figure 20 for the high usage quick service restaurant and Figure 21 for the medium usage quick service restaurant.

Energy and carbon emissions for each scenario are presented in Table 6 and Table 7 shows the total cumulative carbon emissions between from 2020 to 2050 when implementing the 'combined retrofit' scenario for the two restaurant configurations.

Increase dead band by 2 K:

ENERGY: Increasing the dead band range reduced energy consumption by up to 1.9% in the high usage restaurant and 3% in the medium usage restaurant. The impact was slightly greater in the medium usage restaurant as there was less equipment in the restaurant.

CARBON EMISSIONS: As all energy consumption was electrical (and fugitive emissions low), the percentage reduction in carbon emissions mirrored the percentage change in energy consumption.

Economiser in HVAC:

ENERGY: Applying an economiser had a greater impact in the high use restaurant due to the greater need for air conditioning (due to heat generating electrical equipment). Savings of up to 7.5% were predicted for the high use restaurant and 4.3% for the medium usage restaurant.

CARBON EMISSIONS: As above, all energy use was electrical (and fugitive emission were low) the percentage reduction in carbon emissions mirrored the percentage change in energy usage.

Higher efficiency equipment:

ENERGY: Up to 15.6% of the energy was saved in the high usage restaurant. This was higher than in the medium usage restaurant (savings of up to 11.7%) due to a greater density of electrical equipment in the high usage restaurant.

CARBON EMISSIONS: As above all energy use was electrical the percentage reduction in carbon emissions mirrored the percentage change in energy usage.

Low GWP refrigerant:

ENERGY: No changes were seen in energy usage as it was assumed that the cold stores would have the same energy consumption as with R448A refrigerant.

CARBON EMISSIONS: The only country where changing the refrigerant had significant impacts was Norway as the fugitive emission was a greater impact due to the extremely low grid electrical carbon emission factor in the country. Otherwise carbon savings of 0.1-2% were calculated. Savings were low as the refrigerant charge in the cold stores was low.

Maintenance/operational practices:

ENERGY: Savings of up to 7.8% for the high usage restaurant and 5.9% for the medium usage restaurant were predicted. Savings in the high usage restaurant were slightly higher due to the greater density of electrical equipment sued for cooking and cold storage.

CARBON EMISSIONS: As above all energy use was electrical the percentage reduction in carbon emissions mirrored the percentage change in energy usage.

RES (solar PV):

ENERGY: Applying solar PV reduced net energy consumption (this assumes if PV is higher than consumption at any time, the exported energy is removed from the imported energy) by between 11% and 30%. Greatest savings were seen in countries closer to the equator with more sunshine. Greater savings were seen in the medium usage restaurant as the roof area for both the high and medium usage restaurants was the same, but the medium usage store used less overall energy and so percentage savings were greater.

Combined impact

ENERGY: The impact of the combination of the above were overall energy savings of 38% to 52% were predicted.

CARBON EMISSIONS: overall carbon savings of 40% to 52% were predicted. Overall percentage combined savings did not vary hugely between countries. Savings were slightly higher in Rome due to the impact of RES. Overall the emissions were almost all related to electrical energy use and the impact of reducing refrigerant emissions was relatively low as the refrigerant charge was so low.

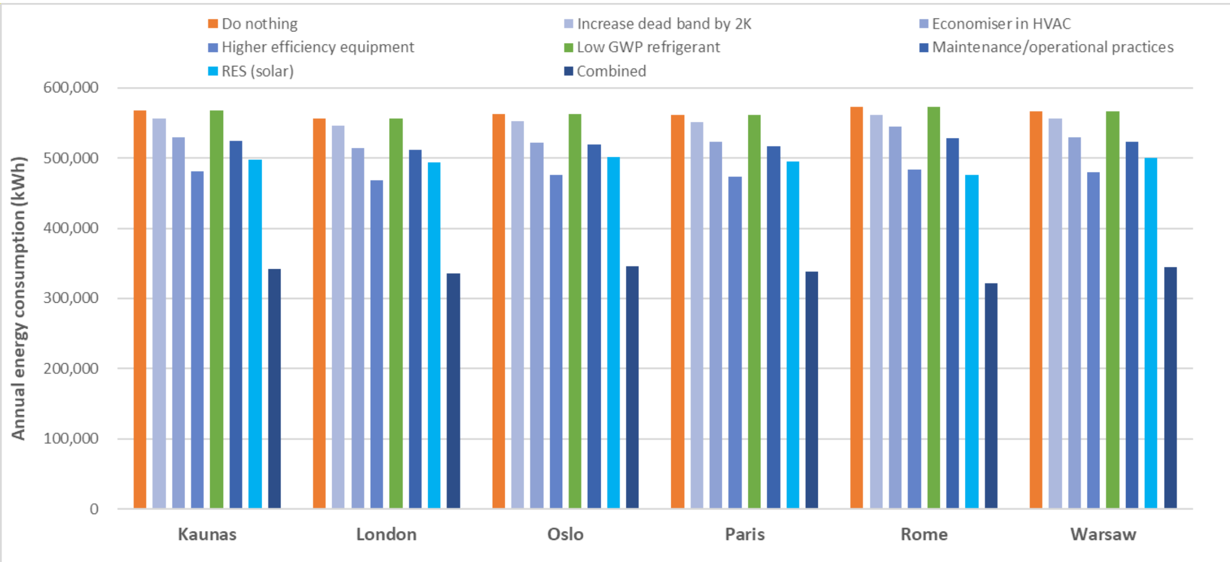


Figure 16. Impact on energy consumption of retrofit options individually and applied together for the high usage quick service restaurant in the 6 locations.

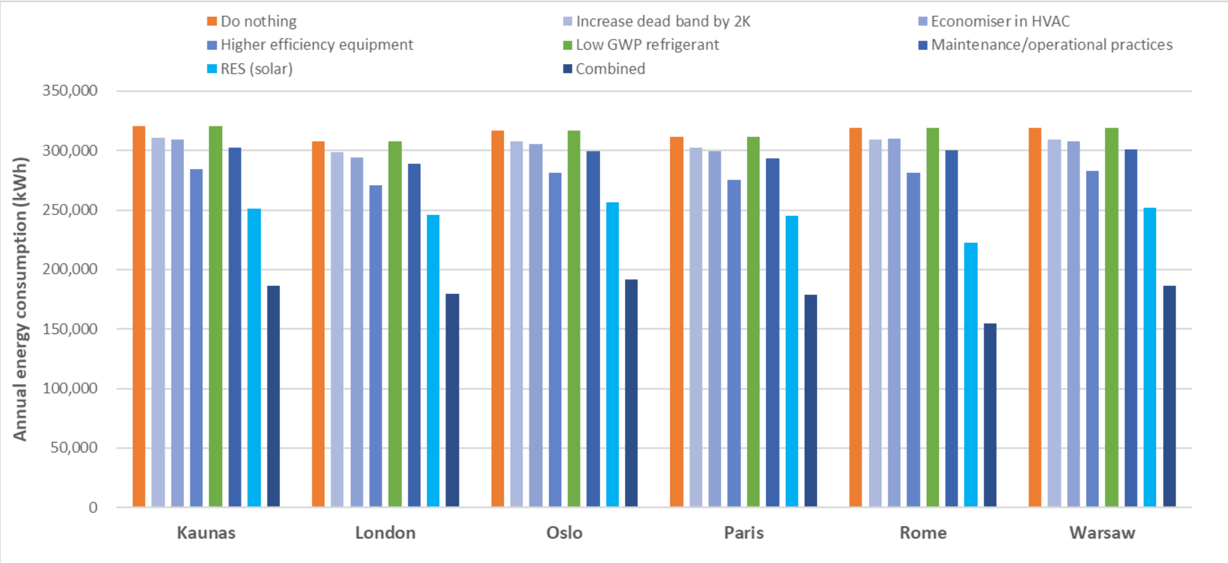


Figure 17. Impact of energy consumption retrofit options individually and applied together for the medium usage quick service restaurant in the 6 locations.

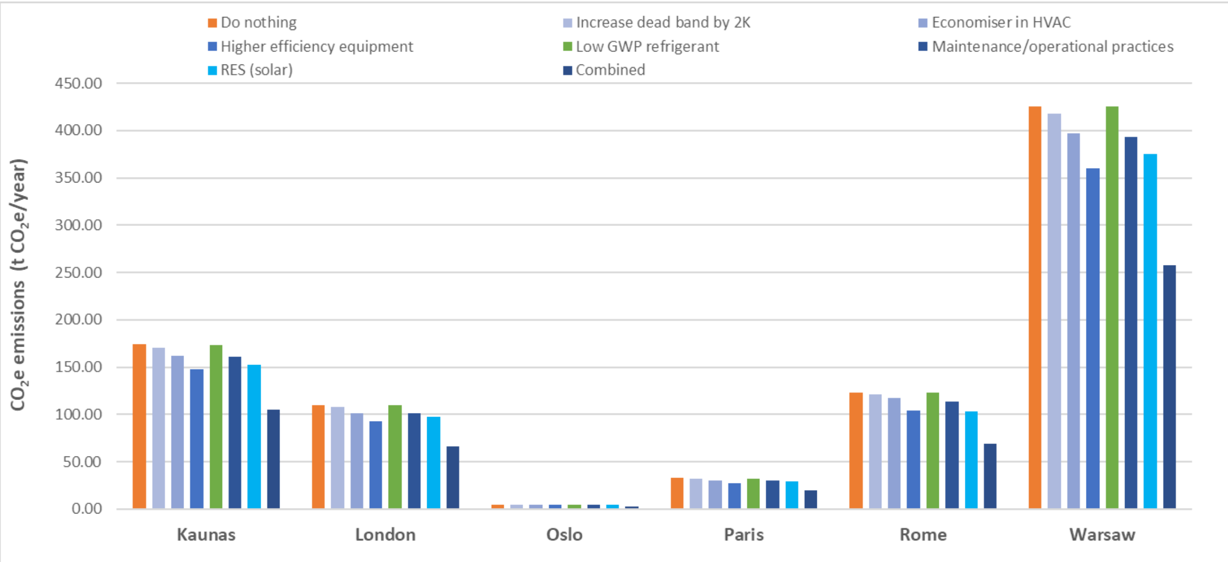


Figure 18. Impact on carbon emissions of retrofit options individually and applied together for the high usage quick service restaurant in the 6 locations.

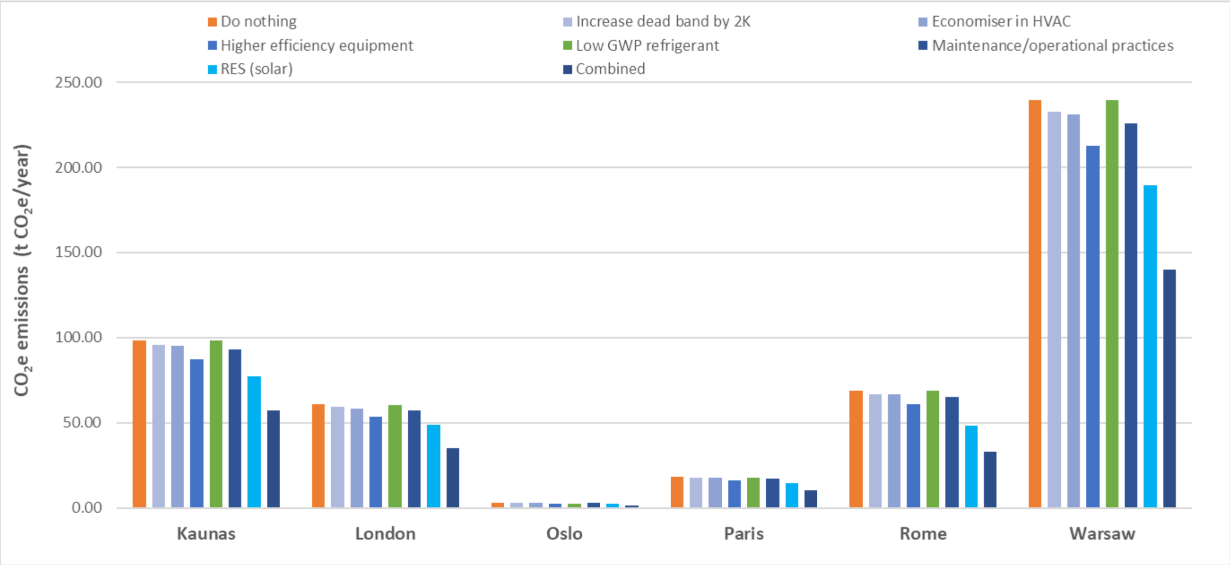


Figure 19. Impact on carbon emissions retrofit options individually and applied together for the medium usage quick service restaurant in the 6 locations.

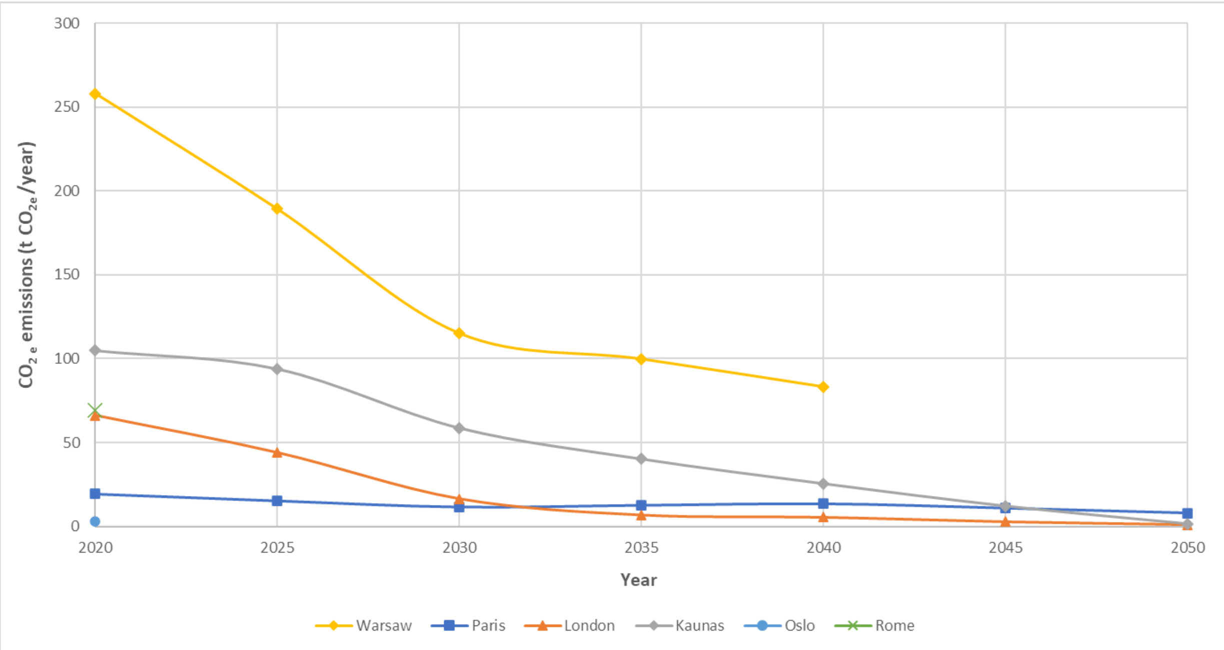


Figure 20. Impact of grid carbon emission factor change on total carbon emitted in the 'combined retrofit' scenario in the high usage quick service restaurant in the 6 locations studied.

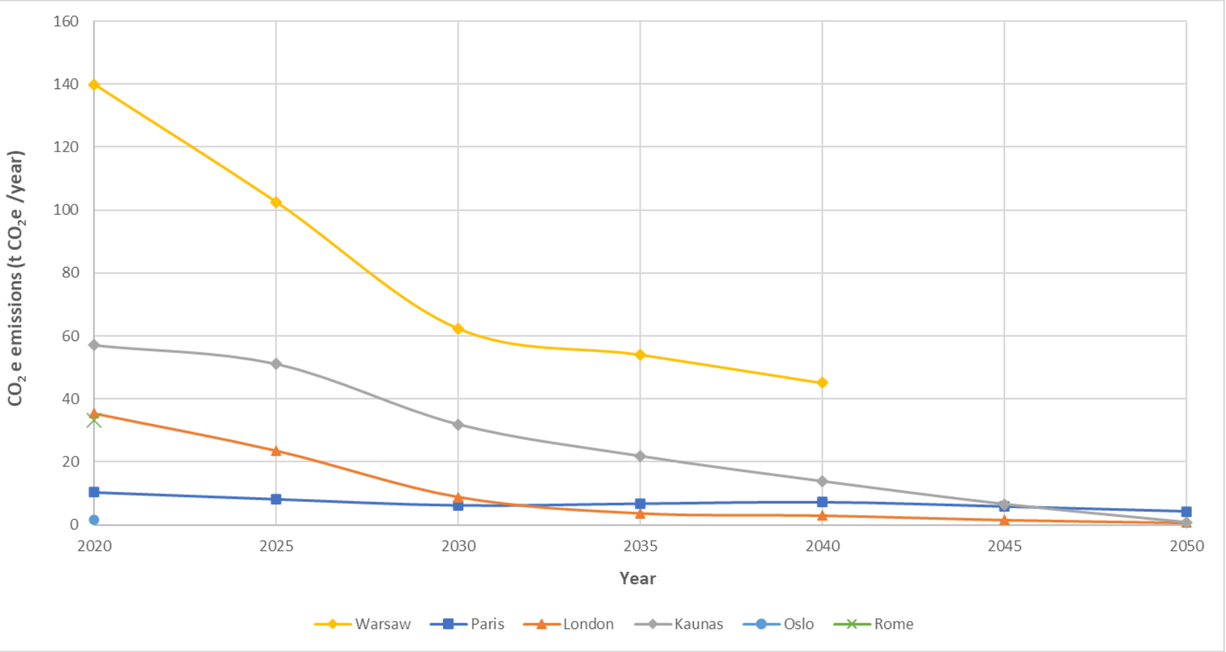


Figure 21. Impact of grid carbon emission factor change on total carbon emitted in the 'combined retrofit' scenario in the medium usage quick service restaurant in the 6 locations studied.

Table 10. Energy use and carbon emissions for retrofit scenarios in 2020.

		High usage quick service restaurant						Medium usage quick service restaurant					
		Kaunas	London	Oslo	Paris	Rome	Warsaw	Kaunas	London	Oslo	Paris	Rome	Warsaw
Do nothing	kWh/year	567,041	555,618	562,263	560,984	572,235	566,685	320,408	307,380	316,875	311,450	318,948	318,884
	tCO2e/year	173.9	109.9	4.9	32.6	123.4	425.4	98.5	61.0	2.9	18.3	69.0	239.6
Increase dead band by 2K	kWh/year	556,667	546,000	551,989	551,114	561,497	556,422	310,767	298,703	307,397	302,511	309,339	309,408
	% change	1.8%	1.7%	1.8%	1.8%	1.9%	1.8%	3.0%	2.8%	3.0%	2.9%	3.0%	3.0%
	tCO2e/year	170.8	108.0	4.8	32.0	121.1	417.7	95.5	59.3	2.87	17.74	66.9	232.5
	% change	1.8%	1.7%	1.7%	1.7%	1.9%	1.8%	3.0%	2.8%	2.6%	2.8%	3.0%	3.0%
Economiser in HVAC	kWh/year	528,900	513,944	522,378	523,631	545,325	529,069	309,564	293,989	305,378	299,675	309,767	307,686
	% change	6.7%	7.5%	7.1%	6.7%	4.7%	6.6%	3.4%	4.4%	3.6%	3.8%	2.9%	3.5%
	tCO2e/year	162.3	101.7	4.6	30.4	117.7	397.2	95.1	58.3	2.9	17.6	67.0	231.2
	% change	6.7%	7.5%	6.5%	6.6%	4.7%	6.6%	3.4%	4.3%	3.1%	3.7%	2.9%	3.5%
Higher efficiency equipment	kWh/year	480,597	468,592	476,198	473,514	483,320	479,801	284,605	271,114	281,325	274,932	281,381	282,766
	% change	15.2%	15.7%	15.3%	15.6%	15.5%	15.3%	11.2%	11.8%	11.2%	11.7%	11.8%	11.3%
	tCO2e/year	147.5	92.7	4.2	27.5	104.3	360.3	87.5	53.8	2.7	16.2	60.9	212.5
	% change	15.2%	15.6%	14.0%	15.4%	15.5%	15.3%	11.1%	11.7%	9.7%	11.5%	11.7%	11.3%
Low GWP refrigerant	kWh/year	567,04	555,618	562,263	560,984	572,235	566,685	320,408	307,380	316,875	311,450	318,948	318,884
	% change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	tCO2e/year	173.6	109.5	4.5	32.2	123.1	425.1	98.1	60.6	2.6	17.9	68.6	239.2
	% change	0.2%	0.3%	7.3%	1.1%	0.3%	0.1%	0.4%	0.6%	12.2%	2.0%	0.5%	0.2%
Maintenance/ operational practices	kWh/year	523,770	512,048	519,200	517,204	527,746	523,193	302,461	289,212	299,048	293,156	300,147	300,792
	% change	7.6%	7.8%	7.7%	7.8%	7.8%	7.7%	5.6%	5.9%	5.6%	5.9%	5.9%	5.7%
	tCO2e/year	160.7	101.3	4.6	30.0	113.9	392.8	93.0	57.4	2.8	17.2	64.9	226.0
	% change	7.6%	7.8%	7.0%	7.7%	7.7%	7.7%	5.6%	5.9%	4.8%	5.7%	5.9%	5.7%
RES (solar PV)	kWh/year	497,650	493,985	501,492	495,041	475,691	499,880	251,017	245,747	256,104	245,507	222,404	252,079
	% change	12.2%	11.1%	10.8%	11.8%	16.9%	11.8%	21.7%	20.1%	19.2%	21.2%	30.3%	20.9%
	tCO2e/year	152.7	97.7	4.4	28.8	102.7	375.3	77.2	48.8	2.5	14.5	48.2	189.5
	% change	12.2%	11.1%	9.9%	11.6%	16.8%	11.8%	21.6%	19.9%	16.5%	20.7%	30.1%	20.9%
Combined	kWh/year	342,425	336,135	346,270	338,353	321,716	343,985	186,177	179,307	191,547	178,937	154,440	186,395
	% change	39.6%	39.5%	38.4%	39.7%	43.8%	39.3%	41.9%	41.7%	39.6%	42.5%	51.6%	41.5%
	tCO2e/year	104.8	66.3	2.8	19.4	69.2	258.0	57.0	35.4	1.6	10.3	33.3	139.8
	% change	39.7%	39.7%	42.6%	40.3%	43.9%	39.3%	42.1%	42.0%	46.3%	43.6%	51.8%	41.6%

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

Table 11. Accumulated carbon emitted between 2020 and 2040/2050 for Kaunas, London, Paris and Warsaw for the combined retrofit scenario.

	Accumulated tCO_2e emitted between 2020 and 2050	
	Hgh usage quick service restaurant	Medium usage quick service restaurant
Kaunas (2050)	3,207	775
London (2050)	541	289
Paris (2050)	386	205
Warsaw (accumulated emissions to 2040)	2,894	1,568

7.5.1 Impact on carbon emissions of making changes

The total carbon emitted between 2020 and 2050 for the high and medium usage quick service restaurants in Warsaw, Kaunas, London and Paris are shown in Figure 22 and Figure 23 respectively.

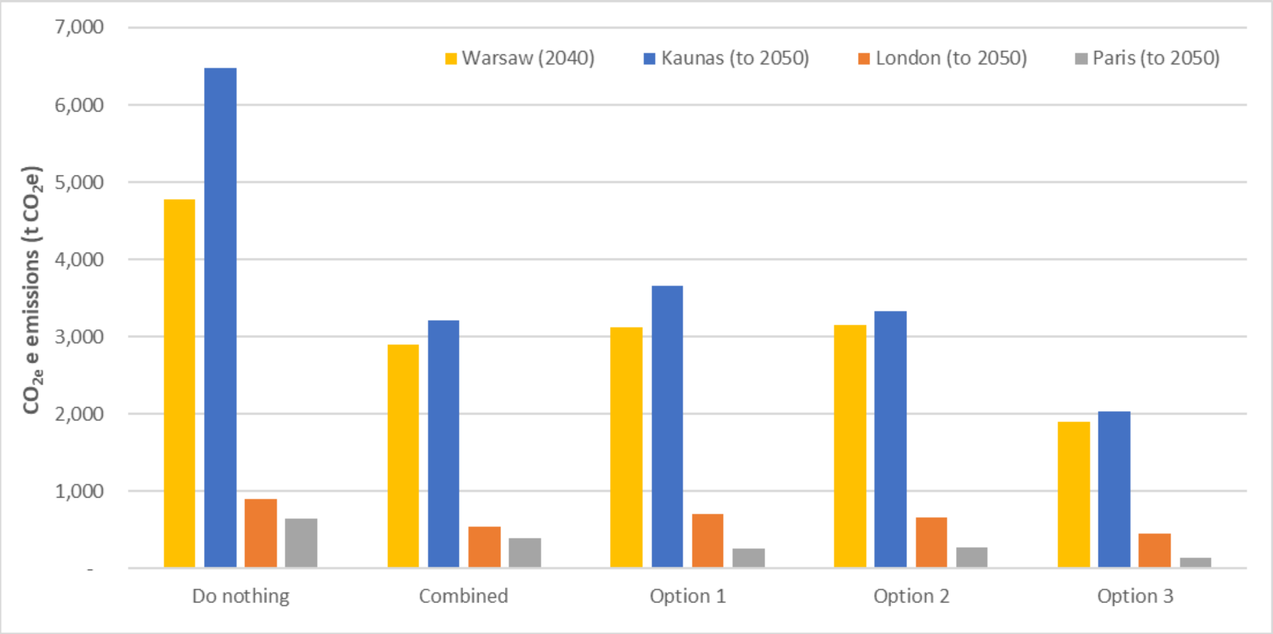


Figure 22. Carbon emitted by the high usage quick service restaurant in different locations from 2020 to 2040/50.

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

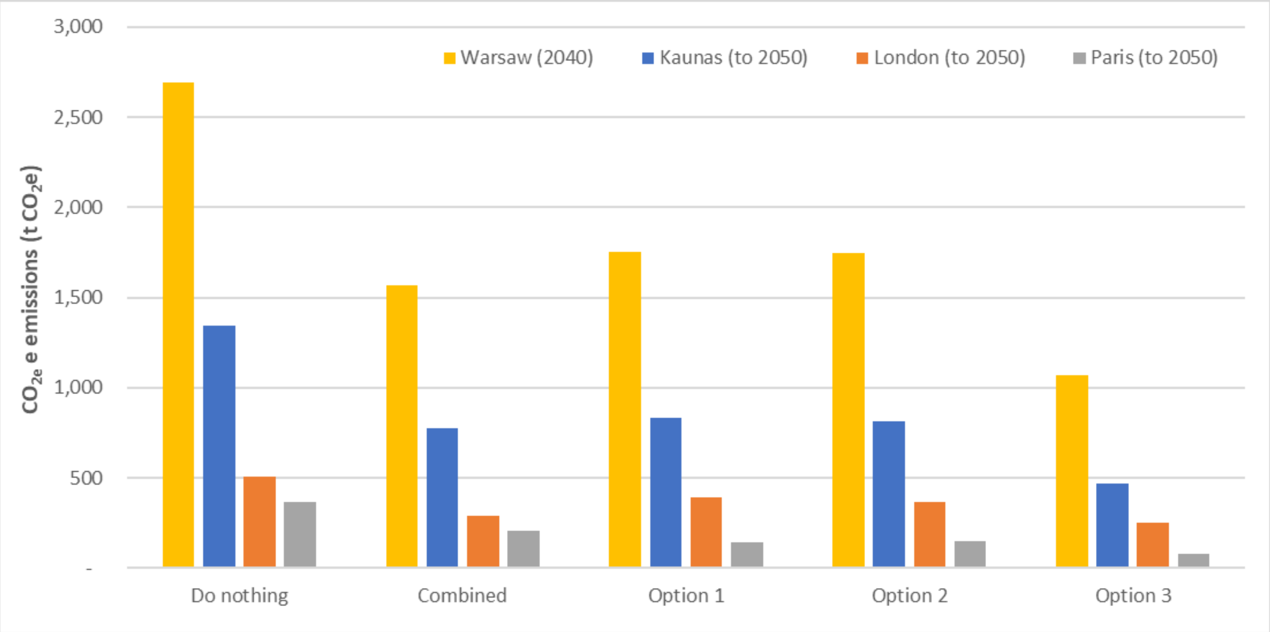


Figure 23. Carbon emitted by the medium usage quick service restaurant in different locations from 2020 to 2040/50.

8 RECOMMENDATIONS

The modelling of the varied technological options in the 6 locations provided a direct comparison between the impact of each intervention in each location.

A great deal of decarbonisation should occur naturally (without intervention from the food service sector) through dramatic reductions in the electrical grid emission conversion factors. In Lithuania and the UK, these are predicted to reach almost zero by 2050. France already has a low electrical grid carbon emission intensity, and this will not change dramatically through to 2050. Although we were unable to find how grid carbon intensity would change in the future in Norway the grid carbon intensity 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 grid emission factors carbon

OUR RECOMMENDATIONS

- *Apply technological interventions as rapidly as possible to ensure cumulative carbon emissions are maximised.*
- *Always purchase the most efficient equipment that is available on the market.*
- *Check operation of plant through regular auditing, maintenance and automated monitoring.*
- *Consider the use of renewable energy resources (especially solar in sunnier climates).*
- *It is good practice to apply natural refrigerants, if possible, in new restaurants.*
- *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 GWP of refrigerants that are applied. Therefore, always consider individual situations.*

intensity in Norway will remain low moving forward. No official information on grid carbon intensity was available for Italy. The trend in Italy over the past 20 years has been for electrical grid carbon intensities to decrease and if this trend continues then Italian quick service restaurants will also be much lower carbon emitters in 2050[36]. The country that stands out as not achieving the low grid carbon intensities as fast as other European countries 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).

Decarbonisation of the electrical grid has a huge impact on carbon emission from quick service restaurants in most European counties. Although in many locations the carbon emissions will; be almost zero in 2050 it is important to reduce cumulative emissions as well. Therefore applying technological interventions will enable carbon emissions to be reduced more quickly and reduce the accumulated emissions over time. Modelling of the most promising interventions identified in the technical reviews demonstrated that 38-52% of the energy and 40-52% of the carbon emissions could be saved if all the interventions were applied. The technologies with the greatest reductions in energy and carbon were the use of an economiser, the application of high efficiency equipment, applying best maintenance and operation practices and applying solar panels. Due to the interactions between how the restaurants were heated and cooled, the combined emissions were less than the total of each intervention alone. Generally, the restaurant kitchens needed to be cooled as there was a high density of cooking and refrigeration equipment that generated heat. This was greater in the high usage quick service restaurant than the medium usage restaurant as the higher usage equated to a greater density of heat generating equipment to service the high number of meals being produced. Therefore, any intervention that reduced the heat load in the kitchen was valuable. The customer areas of the restaurants had minimal equipment generating heat and so the main heat loads were from customers and through transmission and infiltration. In the winter the area required heating and so the energy usage for the area was very related to the location of the restaurant (i.e. more heating was needed in Kaunas and Oslo which were the coldest locations).

We would always recommend the application of low GWP or natural refrigerants, assuming no increase in energy consumption. However, in the quick service restaurants the impact of immediately moving to a low GWP refrigerant was marginal as we assumed that all kitchen (not cold stores) equipment already used natural refrigerants and so the only opportunity to remove high GWP refrigerants was in the chilled and frozen cold stores. The refrigerant charge in both stores was relatively low and so although it would be technically feasible to use a lower GWP refrigerant, the impact on reducing carbon was only currently significant (in comparison to the total carbon impact of the store) in Norway where the grid carbon emission factor was very low. Although this is the case now, as the grid in other countries decarbonises the proportion of total emissions associated to refrigerant leakage will become more significant and moving to a low GWP refrigerant will be more important in reducing carbon emissions.

The road map investigated the options which were assessed as being most economic. Some technologies may develop in the next few years and provide greater energy savings. These could include even more efficient components, advanced control systems and greater levels of automation. There is also greater emphasis being placed on operation practices, maintenance and controls. Much of the savings in the future may come from these initiatives which rapidly identify operational issues and enable rapid remedial action and correction.

Some of the opportunities to apply interventions may only be possible in new quick service restaurants. There is often a relatively fast turnover of ownership of this type of restaurant, and this

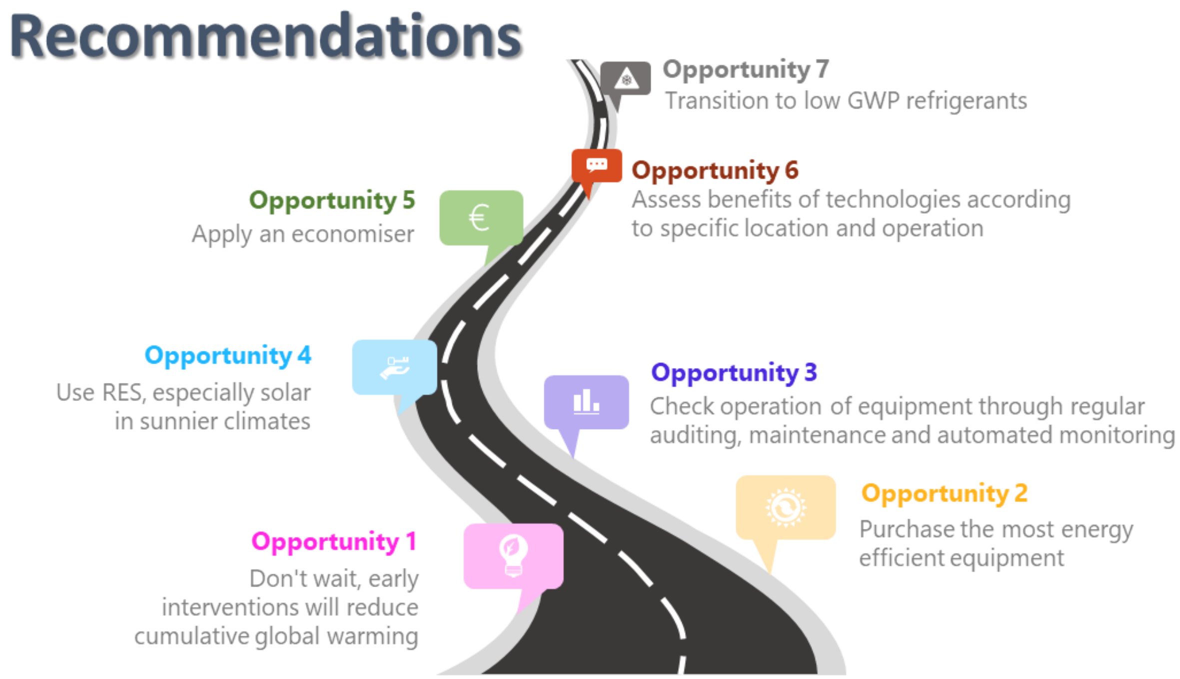
[36] https://www.statista.com/statistics/1290244/carbon-intensity-power-sector-italy/

provides an opportunity for owners to apply the best efficiency equipment. On the other hand, it may also restrict investment as owners may not consider they will see the long term benefits of efficient (and possibly slightly more expensive) equipment. Greater emphasis needs to be placed on the business case to purchase energy efficiency and maintaining that energy efficiency over the life of the restaurant.

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 countries electrical grid carbon intensities and their rate of change over time and the ambient conditions in the location. It should also be noted that the quick service restaurants modelled were example facilities and that results would be different in facilities with different designs, operational practices, and locations. It is essential to assess each quick service restaurant individually to ascertain the most beneficial interventions.

To achieve near net zero carbon emission in quick service restaurants will require a range of initiatives. It was clear from the modelling that 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. Making an assessment of the best technologies for each application is also important to maximise both energy and carbon savings.

Ultimately all the technologies and interventions we examined are available today and so the opportunity to reach near net zero carbon for quick service restaurants exists and is feasible. The diagram below shows what we consider to be the priority areas for cold stores to focus on.



DETAILED TECHNOLOGY/STRATEGY REVIEWS

9 REFRIGERATION

9.1 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 (Poese et al, 2004). 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 commercialisation (Poese et al, 2004). However, since that time there has been no updates on progress.

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.

Potential developments considered over 25 years ago were to be to improve and optimise design and performance (Wetzel and Herman 1997). Developments were 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 has 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)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	No justifiable savings for food service have been found
Quality of scope 2 emissions information	Low
TRL level	4
Maintainability issues	Not known
Legislative concerns	None
Payback time (years)	Not known

9.2 Advanced controls

Applying smart control and logic to food service cabinets has the potential to optimise energy use. Most of the work available is related to domestic refrigerators and so this is presented here as is also applicable to commercial service cabinets.

Most household refrigerators and professional cabinets use conventional controllers for adjusting the compressor and it is claimed to be able to save 2.5% of the energy for active and 4.5% of the energy for passive user-profiles whilst still maintaining the desired cabinet temperatures (Kapici et al, 2022). The 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 more 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)	n/a
Quality of scope 1 emissions information	n/a
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

9.3 Charge optimisation

With capillary based systems the refrigerant charge is never optimal for all conditions. Therefore, the charge has to be optimised for a specific condition that provides the best overall performance. 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.

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 also found that by optimising the charge in a domestic fridge-freezer that they could save 10% of the energy.

Overall savings are dependent on the initial optimisation of the refrigerant charge. There is limited information to suggest that refrigerant charge is poorly optimised, however, the charge for a professional cabinet will be optimised for the test conditions which in Europe are 30°C. If capillary tube expansion is applied this will have an impact on charge optimisation at different ambient conditions and so the refrigerant charge may be poorly optimised if the appliance is not operated in the facilities where the test conditions are not replicated.

Temperature in commercial kitchens and cooking areas has been shown to vary considerably. In a study in the USA Simone et al (2013) found diurnal ranges in temperature from 22.2°C to 36.7°C. In a study in Finland covering a range of catering facilities Heinonen (n.d.) found mean temperatures ranged from 19.5°C to 26.5°C. This indicates that conditions in commercial catering facilities can vary considerably depending on the type of facility and its location.

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.

If operational conditions vary from those used in the test (where it can probably be assumed that refrigerant charge is optimised) the use of an thermostatic or electronic expansion valve can overcome the issue. The negative of this is that the total refrigerant charge needs to be higher to ensure good operation of the valve across all ambient conditions.

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%, but only if issue exists (it is unlikely to be an issue in most appliances/cabinets)
Quality of scope 2 emissions information	Medium
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

9.4 Dampers

Operating a refrigerator with variable temperature compartments from one refrigeration systems has challenges and the system has to operate at the temperature required by the lowest temperature compartment. Control of such systems is more difficult, especially when a refrigerator has a variable 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

9.5 Defrost control (e.g. on demand)

Traditionally defrosting of professional refrigerated appliances is normally initiated by a timer. 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 need for defrost can be achieved using more sophisticated logic 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).

Improved methods of applying defrosts can also be used, such as pulse type defrost that cycles the defrost heater on and off during the defrost cycle. This minimises the total temperature rise in the cabinet and helps to reduce the post defrost cooling load. Work on commercial systems (see commercial; defrost control section) indicated a 9% savings are achievable.

Most research into reducing defrosting energy demand has been caried out on domestic refrigerators. However, much of that can be translated to professional appliances and so is included here.

Adaptive defrost control has been developed which adjust 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 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 accumulation the optimum power required varied and could be optimised.

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)	1.9-9%
Quality of scope 2 emissions information	Medium
TRL level	7-8
Maintainability issues	Unlikely
Legislative concerns	None
Payback time (years)	Not quantified

9.6 Door open warnings

Door open warnings are audible and/or visual alarms which alert the user to a door which has been inadvertently left open.

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)	n/a
Quality of scope 1 emissions information	n/a
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

9.7 Dual-loop system

Most dual compartment refrigerators operate using one refrigeration circuit with one compressor. However, using separate refrigeration circuits 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 of applying two compressors and the space requirements for an additional compressor. Also, the fact that the two compressors will probably have a lower individual efficiency 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.

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 24). This links the operation of the 2 systems and adds efficiency.

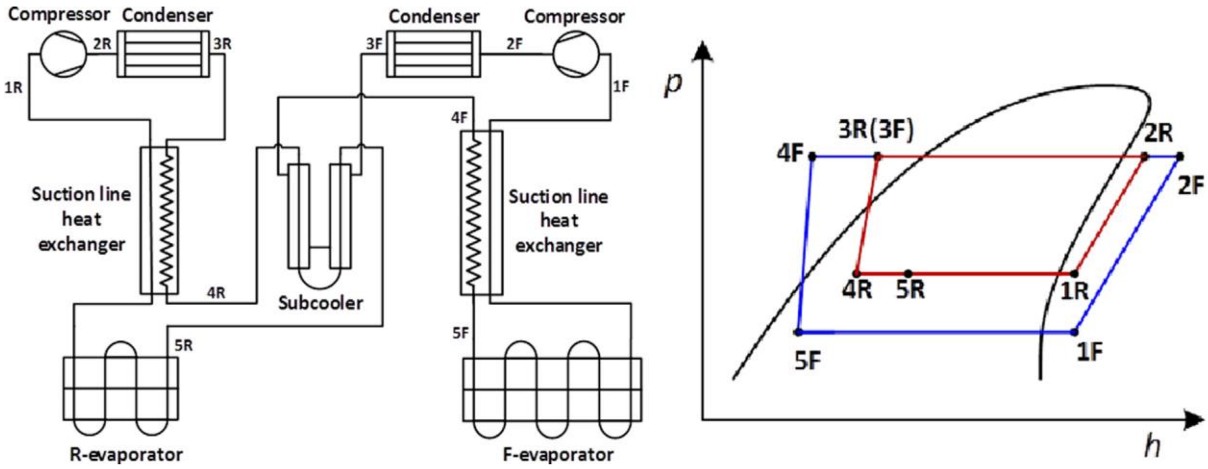


Figure 24. Schematic of coupled dual-loop refrigerator system (left) and p–h diagram (right).

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 25). The cost for the modified system was 21% higher but the energy use was 26-35% lower (depending on condensing temperature).

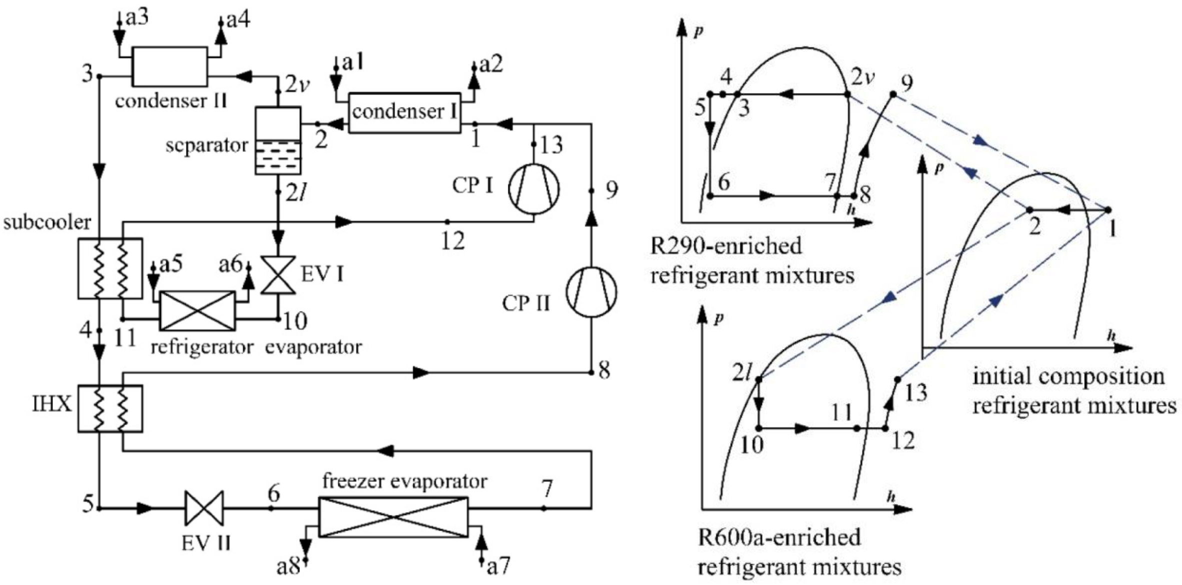


Figure 25. Schematic diagram of modified refrigeration cycle (MRC); (left) Cycle pressure-enthalpy diagram of MRC (right).

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, 2012). The same team (Yoon et al 2012) found that an optimised dual-loop cycle using R600a and 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)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	2-35% (very variable depending on design)
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)

9.8 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 match demand from the grid, wasting renewable resources. This is likely to become more of an issue as the proportion of renewables 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 or low generation.

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. This 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. For example, cold stores can shift load while providing a buffer which can be used to balance off-cycling during peak times. Cold stores, freezers and some professional cabinets can offer flexibility as they can be 'over cooled' and then switched off for 30– 60 minutes, possibly more if not opened.

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 carbon intensity, 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 carbon intensity. The best models were able to predict the peak carbon intensity 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. PCMs enable longer off periods and greater flexibility in shifting off periods. PCMs may also have a positive impact in stabilising the temperature within the appliance during normal operation and can also reduce cycling, increasing efficiency and reducing wear on compressors. PCM application is estimated to add ~$50 per unit for domestic refrigerators (Rodrigues et al, 2022).

One issue with dynamic demand is that once the appliances are brought back into operation they may create high initial demand, if they all come back on at the same time. Control, and protection devices can help overcome these issues. This can also be used to predict demand (based on weather for example) and pre-cool appliances to enhance/lengthen dynamic demand periods. Controllers can also ensure that food remains at safe temperatures and identify best options 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 carbon intensity 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 smaller catering outlets is that they are unlikely to have sufficient capacity to provide any meaningful grid impact. 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	High
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	Medium
TRL level	TRL8-9
Maintainability issues	None
Legislative concerns	Unknown
Payback time (years)	Frequency response 2 years.

9.9 Efficient compressor technology

The majority of refrigerated appliances use constant speed reciprocating compressors. As the load is not constant they maintain temperature by switching on and off based on demand. This cycling can cause losses estimated to be up to 9% (Bjork and Palm, 2006). 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 domestic 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.

Variable-speed linear compressors (VSLC) and variable capacity compressors (VCC) can avoid such cycling by running at reduced speed or capacity. They can also reduce instantaneous evaporator loading and this can contribute to energy reduction if the evaporator temperature can controlled. Both options would require attention to design and control of evaporator and/or condenser fans, as these would also run continuously and offset some of the energy savings.

Optimising the use of variable speed compressors via advanced controls has the potential to save up to 30% of the energy used by a refrigeration system (Binneberg et al, 2002). Savings are achieved through smaller friction losses in the compressor, higher evaporation temperature, lower condensing temperature and a reduction in losses associated with the pressure equalisation on compressor stops. However, good control is required especially if only variable fixed compressor speeds are applied.

Variable speed compressor technologies are already penetrating the domestic 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). As the technology becomes more established it is likely to transfer into the slightly larger compressor used in professional cabinets.

The same manufacturer also claimed compressor energy savings up to 45% when using variable capacity compressors to replace conventional fixed speed reciprocating models. In work by Pedersen et al (2018) they improved the performance of an under counter professional cabinet by 50% (moving it from a C energy label to an A energy label). The major item leading to this improvement was achieved by selecting the best compressor (46%) which was a variable speed drive 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)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	22-45% (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.

9.10 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 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 the journal

'Science' that thin films of perovskite PZT (lead zirconate titanate) 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 poly(vinylidene fluoride) (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 6.5 K temperature difference can be achieved; larger temperature differences (20 to 30 K) have only been measured at much warmer temperatures 350 – 400K (Scott, 2011). However, for commercially available $BaTiO_3$-based multilayer films, it has been claimed that an ideal GEC heat pump could deliver a cooling power of 22.5 $W.kg^{-1}$ and it is hoped that through optimisation of materials and design 2875 W.kg-1 could be achieved (Maidment)

Giant electro-caloric-effects and large- electro-caloric-effects (ECE) have been measured in thin film materials but not at temperatures useful for typical professional refrigeration and not on a scale suitable to meet the cooling demands of professional 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) identifies 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 current opportunities for the technology are limited currently as systems have so far not achieved high enough temperature spans required for food service refrigeration systems (maximum temperature differences of ~14K have so far been achieved).

Scope 1 emissions savings (% or another quantifiable metric)	No refrigerant, so a 100% reduction in emissions
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Currently limited, but potentially high in the future if technology can be commercialised
Quality of scope 2 emissions information	Low
TRL level	1-2

Maintainability issues	Not known
Legislative concerns	Potential issue with lead
Payback time (years)	Not able to quantify, too low TRL

9.11 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. For example, 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. Generally, finned evaporators are applied and so this probably is not a valid real life saving. If the best and worst finned evaporator were compared the saving was ~13%.

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 (and are used in other sectors such as air conditioning), but further research is needed for professional cabinets.

External and fan-assisted condensers, which are the most common type in professional refrigeration 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)	n/a
Quality of scope 1 emissions information	n/a

Scope 2 emissions savings (% or another quantifiable metric)	10-15%
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

9.12 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.

Whitman et al stated that the refrigerant in a non-fan assisted condenser on a domestic refrigerator would typically condense at approximately 110 F (43.3°C). Data from Refrigeration Developments and Testing (RD&T) show a condensing temperature of 37 and 41°C at an ambient temperature of 23 and 29°C respectively for a non-fan assisted condenser. Using a fan assisted condenser the refrigerant may condense at 95 F (35°C). The difference in condensing temperatures would, using a simple COP calculation, generate savings of approximately 12%. Typically, an efficient fan for a condenser would use 2-5 W (Radermacher and Kim, 1996). Therefore, if an appliance uses more than approximately 40 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)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Up to 10%. However. Most professional cabinets already have fan assisted condensers
Quality of scope 2 emissions information	Medium
TRL level	8-9
Maintainability issues	None identified

Legislative concerns	None identified
Payback time (years)	None directly identified

9.13 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. For example, they could be used to spot cool in cabinets.

Very little work is published on heat pipes in small professional refrigerators. Work on heat pipe shelves in open 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%.

One more recent use of heat pipes has been explored by Yian et al (2019). They used heat pipes to overcome the heat transfer limitations of phase change materials (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)	12% but applied to a different cabinet type
Quality of scope 2 emissions information	Low
TRL level	7
Maintainability issues	Not known
Legislative concerns	None
Payback time (years)	No evidence

9.14 Improved door gaskets

Door gaskets for refrigerators are generally based on magnetic strips encased in flexible plastics such as polyvinyl chloride (PVC). PVC is not particularly stable at low temperatures and so alternatives such as thermoplastic elastomer (TPE) in the gasket have been suggested as better alternatives (Liu et al 2021). The main negative of this is higher cost.

The gasket 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.

According to Fine and Lupinacci (1994) heat flow through the gasket region of the cabinet contributes significantly to the total load and FEA analysis has shown that heat flow can be reduced by 50% by minor changes to the design of the flanges on the door and cabinet.

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.

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. On the other hand, Gao et al (2017) estimated that the average effective heat leakage on the door gasket surface was 0.2 $W\ m^{-1}\ K^{-1}$. This equated to 17% of the total load in the fresh-food compartment and 14% in the freezer compartment.

Air infiltration due to deterioration in door seals varied between freezers and chillers. In work carried out by Afonso and Castro (2010) they found that for equivalent air leakage rates, the heat gain 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. With 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 damaged seals.

Direct emissions savings (% or another quantifiable metric)	n/a
Quality of direct emissions information	n/a
Indirect emissions savings (% or another quantifiable metric)	~5%, higher if seal badly damaged
Quality of indirect emissions information	Low
Availability barriers	None
TRL level	9
Maintainability issues	Current seals deteriorate
Legislative concerns	None
Payback time (years)	No quantified evidence but seals are not expensive and are simple to fit

9.15 Vacuum insulation panel insulation

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 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.

Polyurethane has two major benefits which are missing from VIPs; the 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.

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 polyurethane 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. Therefore, 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).

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.

The present cost of VIPs is more than that for PU foam, but the energy savings achievable can still make them an economic option. The cost of VIPs is also reducing as they become more prevalent in domestic refrigerators. Energy savings can be made but unless space is of a high value, the additional cost of the VIP is currently unlikely to be justified alongside the option of adding more PU foam. Paybacks depend on where 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 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 fumes 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 polyurethane (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.

Further work by Hammond and Marques (2014) on another professional cabinet design with drawers modelled and tested the use of VIPs. Energy savings of between 12.4% (refrigerator) and 12.5% (freezer) were found with paybacks of 7.6 and 3.1 years for the fridge and freezer respectively.

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)

9.16 LED lighting

Already applied and so not reviewed.

9.17 Liquid line solenoid valve

Most modern professional 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 and the availability of small sized valves and also the lower refrigerant charge this allows, which is important when using flammable refrigerants.

Capillary tubes require optimisation during the design stage to achieve ideal evaporating temperatures. The capillary tube is optimised for a particular ambient temperature and maybe less efficient away from this condition.

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 before it reaches the compressor, it could damage it. One option to prevent this occurring is to add a liquid line solenoid that prevents back flow from the high to the low pressure side when the compressor is off. If a valve is applied, it is also necessary to use a high back starting pressure compressor and so some level of redesign maybe 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 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, Palm and Nordenberg (2010) state that most of the refrigerant is contained in the evaporator and compressor in the off cycle. Björk and Palm (2006) found losses due to on/off cycling. Compressor cycling was estimated to reduce the efficiency by 9% and the capacity by 11%. 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 26 shows the effect of including a liquid line solenoid in the refrigeration circuit of a chilled professional service cabinet under different operation 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.

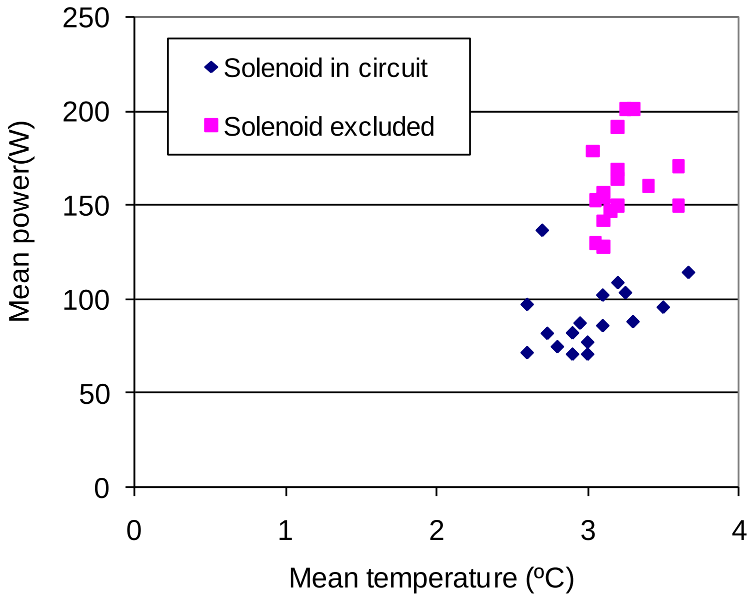


Figure 26. Effect of including a liquid line solenoid in a refrigeration circuit.

Janssen et al (1992) investigated the impact of off-cycle losses on energy efficiency. They found that continuously running refrigeration systems were 10-18% more efficient than cycling systems.

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)	10-30%
Quality of scope 2 emissions information	High
TRL level	9
Maintainability issues	None identified
Legislative concerns	None identified
Payback time (years)	No information available but solenoid valves (without any scale discount) are between €15-20. In the above example (Figure 26) where ~50W of saving was achieved the payback would be ~4-5 months

9.18 Magnetic refrigeration system

Technologies such as magnetic cooling have potential advantages such as no harmful 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 magnetized and cool when demagnetized. 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 potential for 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, this was 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 (backed by Cambridge University) 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 rare earth magnets used for the technology are produced in China which may limit availability. 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	No refrigerant applied
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)	Not known

9.19 Maintenance and servicing

Degradation in performance of professional 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.

Mudie et al (2016) found that poor maintenance in kitchens was a major contributor to excessive electricity usage. They found potential savings of 70 and 45% respectively for particular pieces of equipment that could be operated and maintained better.

Issues such as cleanliness of condenser can significantly reduce air flow though the condenser and increase energy use. Companies such as Foster provide ‘stayclear’ condensers on some of their products at no additional cost. These are claimed to achieve a 16% reduction in airflow (and 36% less energy) compared to a conventional condenser with a 94% reduction in airflow.

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 27). Modelling indicated that the average energy increase over 16 years was 27%.

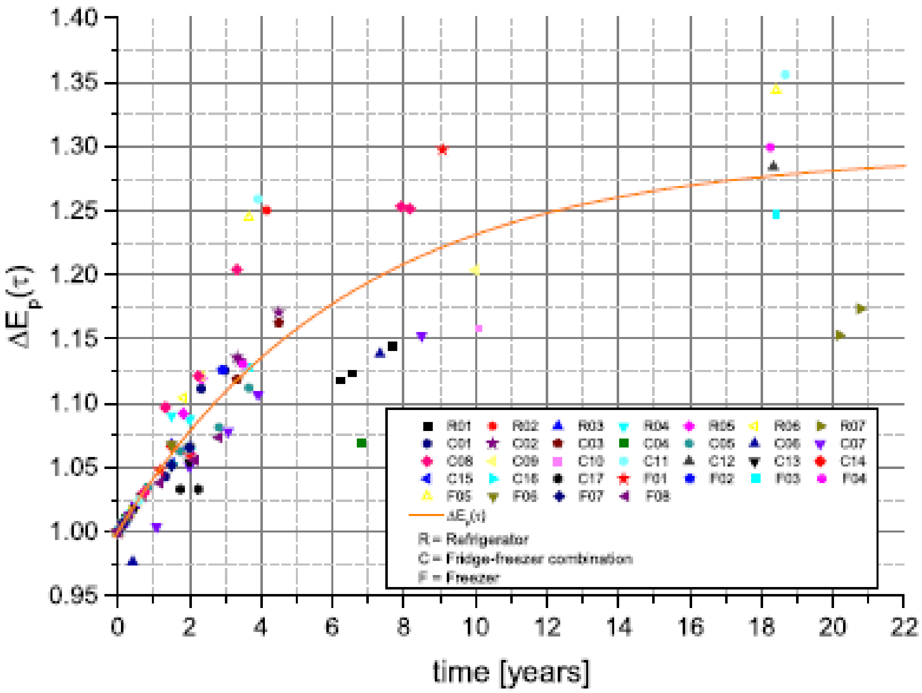


Figure 27. Corrected energy consumption and consolidated aging function ΔEp(τ) (line).

Leakage of refrigerant from integral; system 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. The impact of any refrigerant leakage is relatively low as most cabinets in Europe operate using R600a or R290).

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	None
Scope 2 emissions savings (% or another quantifiable metric)	Potentially 45%
Quality of scope 2 emissions information	High
TRL level	8-9
Maintainability issues	Non known
Legislative concerns	None known
Payback time (years)	Non known

9.20 Nanoparticles

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 of above size (Eastman et al, 1996). Theoretically, 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 (USA) 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 polyolester 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.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	None
Scope 2 emissions savings (% or another quantifiable metric)	Potentially some savings based on enhanced heat transfer. Very limited information in small integral systems.
Quality of scope 2 emissions information	Low
TRL level	3
Maintainability issues	Unknown
Legislative concerns	None
Payback time (years)	Not known

9.21 Phase change materials (PCMs)

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 Food Refrigeration Innovations for Safety, consumers' Benefit, Environmental impact and Energy optimisation along the cold chain in Europe (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-cycles 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)	n/a
Quality of scope 1 emissions information	n/a
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

9.22 Refrigerants

The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016. Its goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-century.

To control emissions from fluorinated greenhouse gases (F-gases), including hydrofluorocarbons (HFCs), the European Union has adopted the F-gas Regulation. The current F-gas regulation, which applies since 1 January 2015, replaces the original F-gas adopted in 2006.

The current Regulation strengthened the previous measures and introduced far-reaching changes by:

- Limiting the total amount of the most important F-gases that can be sold in the EU from 2015 onwards and phasing them down in steps to one-fifth of 2014 sales in 2030. This will be the main driver of the move towards more climate-friendly technologies;
- Banning the use of F-gases in many new types of equipment where less harmful alternatives are widely available;
- Preventing emissions of F-gases from existing equipment by requiring checks, proper servicing and recovery of the gases at the end of the equipment's life**.**

In 2020 HFCs with global warming potentials of more than 2,500 were banned in all refrigeration systems. This mainly covered R404A which has a GWP of 3922. A service ban also came into force which meant that equipment with a charge in CO_2 equivalent greater than 40 tonnes will no longer be able to be refilled or serviced with virgin HFCs with a GWP > 2,500. For an R404A system, this covers any system with a charge of more than 10.2 kg. Recycled or reclaimed gases with a GWP > 2,500 can still be used for servicing and maintenance until 2030, if labelled correctly.

Although possible, the use of HFCs with a high GWP will become increasingly expensive, so in the long term it will make financial sense to opt for equipment containing refrigerants with a low GWP.

From 2022 all F-gases with global warming potentials of more than 150 will be banned as the refrigerant or foam blowing agent in any hermetically sealed system. This mainly affects the use of HFC 134a (GWP of 1430) and most non-flammable “drop-in” refrigerants.

Typical interim drop-in replacements for R404A are R407A/F/H, R448A, R449A, R452A. These refrigerants are non-toxic and non-flammable but have a GWPs between 1300 and 2200. For longer term alternatives, refrigerants R455A and R455C have a GWP of 148 but are flammable (Class A2L) and therefore not “drop-in” refrigerants. Natural refrigerant such as hydrocarbons (HCs), CO_2 and ammonia offer very low GWP (<10) but in the case of HCs are also flammable, CO_2 is technically more difficult, and ammonia is toxic, therefore, it is difficult to be applied directly in public space, i.e. requires indirect systems.

HFC taxes are used in some European countries, for example in 2014 Norway had a tax of € 55 per kg of R134a (Maratou, Skacanova, and Chasserot 2014), in 2023, the tax rate is 0,952 NOK[37] per kilo of the GWP value.

9.22.1 Hydrocarbons

In most food service outlets, the smaller refrigerated cabinets are hermetically sealed integrals and almost all have moved to using hydrocarbon (HC) refrigerants. These refrigerants are naturally occurring (although require processing to ensure purity), low toxicity refrigerants that have no ozone depleting properties and negligible global warming potential. There are 2 common HCs used in refrigeration. These are R290 (propane) and R600a (isobutane).

Tecumseh (2019) state an increase in COP of between 8 to 31% from changing from their R404A compressors to replacement R290 compressors at -35°C evaporating temperature and 40°C condensing temperature. They also state an increase in COP of between -2 (decrease) to 28% from changing from their R134A compressors to replacement R290 compressors at -10°C evaporating temperature and 50°C condensing temperature.

[37] https://www.skatteetaten.no/en/business-and-organisation/vat-and-duties/excise-duties/about-the-excise-duties/hfc-and-pfc/

HC refrigerants have an A3 safety classification. Due to the flammability of HC refrigerants, the quantity of refrigerant which can be used in a refrigeration system is limited. Most systems can operate using less than 150 g of refrigerant.

9.22.2 Refrigerant - HFO refrigerants and blends

The small cold stores in food service outlets are most likely to operate using an HFC refrigerant. Such systems come under clause 12 of the F-gas regulations that states that from 1 January 2020 refrigerants with a GWP of above 2,500 will be banned from stationary refrigeration equipment (except equipment intended for application designed to cool products to temperatures below -50°C). Although most small cold stores will be able to continue operating on relatively high GWP refrigerants there is likely to be further phase down in the future and so when installing systems, it is advisable to consider lower GWP alternatives.

Hydrofluoroolefin (HFO) refrigerants are considered “fourth and last generation” refrigerants. They are unsaturated organic compounds composed of hydrogen, fluorine and carbon. The main benefit of these refrigerants is that they have 0.1% of the GWP of HFCs, however, their decomposition products, especially TFA and PFAS, are significantly reducing the applications which are allowed to apply these kind of synthetic working fluids. For refrigeration applications the two HFOs are R1234yf, R1234ze and R1234zd.

Blends

There are many refrigerant blends containing HFOs (Table 12).

Table 12. List of HFO based refrigerants suitable for professional refrigeration.

R-number	Composition	GWP	Replacement	Safety class
444A	R32/152a/1234ze	93	134a	A2L
445A	R744/134a/1234ze	120	134a	A2L
448A	R32/ 125/1234yf/134a/1234ze	1387	404A	A1
449A	R32/ 125/ 1234yf/ 134a	1397	404A	A1
450A	R134a/ 1234ze	605	134a	A1
451A	R1234yf/ 134a	133	134a	A2L
451B	R1234yf/ 134a	146	134a	A2L
452A	R32/ 125/1234yf	2140	404A	A1
454A	R1234yf/R32	239	404A	A2L
454C	R1234yf/R32	148	404A	A2L
455A	R32/ 1234yf/744	148	404A	A2L
513A	R1234yf/ 134a	631	134a	A1
513B	R1234yf/134a	596	134a	A1
515B	R1234yf/134a	293	134a	A1

Citarella et al.(2022) carried out a thermo-economic study food refrigeration system working with low environmental impact refrigerants. They found that R449A is the refrigerant with the lowest set-up costs, and its COP in the optimal configuration is similar than those of R452A and R404A, representing a good compromise as mid-term R404A replacement. Among the refrigerants with a GWP below 150, R454C had the lowest set-up costs and the second highest value of COP (Table 13).

Table 13. Capacity and COP of HFO blends at different conditions compared to R404A as well as GWP and ASHRAE class.

Refrigerant	Capacity	COP	Reference	Evaporating temperature
R448A	Similar	+4 to +9%	Sethi et al, (2016)	Low
R448A	-15 to -12%	+13 to 21%	Mota-Babiloni et al, (2014).	Low
R448A	-6 to -1%	+6 to +15%	Mota-Babii et al, (2014)	Medium
R449A	-9 to +2%	+2 to +15%	Tecumseh, (2016)	Low
R449A	-9 to -3%	+2 to +9%	Tecumseh, (2016)	Medium
R452A	-1 to +1%	+5 to +10%	Tecumseh, (2016)	Low
R452A	-4 to -2%	+1 to +2%	Tecumseh, (2016)	Medium
R454A	+8%	+8%	Hughes (2018)	Low
R454A	+6%	+4%	Hughes (2018)	Medium
R454C	-22 to -16%	+1 to +3%	Tecumseh (2020)	Medium
R454C	-30 to -20%	-6 to -2%	Tecumseh (2020)	Low
R455A	-2 to -13%	+6 to +8%	Tecumseh (2020)	Medium
R455A	-2 to -22%	-2 to +5%	Tecumseh (2020)	Low

9.22.3 Carbon dioxide

Carbon dioxide (R744) is an alternative refrigerant that could be applied to cold stores. It could be applied to refrigerated cabinets, but any developments have been overtaken by the use of HCs which predominantly in the smaller cabinet market.

The major benefit of R744 over currently used HFCs is that it has a GWP of 1. The major benefit over HCs, (the other alternative to HFCs) is that it is non-flammable. However, R744 is hazardous to health at reasonably low concentrations, so this also needs to be taken into account if the concentration of CO_2 can build up in confined spaces due to a leak. It also has a low critical temperature and so tends to be less efficient in trans critical operation. Mitigating measures can be applied to over come this issue (see retail road map for more detail) but currently the additional expense would be difficult to justify for smaller cabinets of small cold stores. R744 has been widely applied in supermarkets but less so in smaller systems such as small cold stores.

Scope 1 emissions savings (% or another quantifiable metric)	GWP of refrigerant can be reduced to as low as1 (but probably not practical for small cabinets)
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Variable depending on location and exact system adaptations

Quality of scope 2 emissions information	High. A number of peer reviewed publications agreeing and several case studies.
TRL level	TRL8-9
Maintainability issues	Training of staff for lower GWP refrigerants
Legislative concerns	None.
Payback time (years)	Variable depending on application, but can be as low as 1 year

9.23 Stirling coolers

Stirling coolers can operate down to cryogenic temperatures. Stirling coolers are closed-cycle regenerative thermal machines which compress and expand a gas. Free piston machines use a moving magnet or linear machine unit 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 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)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	No quantified information
Quality of scope 2 emissions information	Low
TRL level	4
Maintainability issues	None identified

Legislative concerns	None identified
Payback time (years)	No quantified information

9.24 System optimisation

Pedersen et al (2018) assessed how an under counter professional cabinet could be improved. Through a series of optimisation, they were able to save 50% of the energy. Most of this came though selection of the most efficient compressor for the appliance (37.3%). However, additional optimisation was achieved though air flow distribution, use of a more efficient condenser fan, removing cold bridges, increasing insulation thickness and use of R290.

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)	Up to 50%
Quality of scope 2 emissions information	Low
TRL level	8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Probably minimal as conventional components were just optimised

9.25 Thermoelectric refrigeration

Thermoelectric (or Peltier) refrigeration systems create cooling when a voltage is applied across joined conductors to create an electric current. When current flows, heat is at one junction and cooling occurs with heat being deposited at the other junction. The advantage of these type of coolers is that they have no moving parts and no noise.

Thermoelectric generators require a large DC and an AC/DC converter which makes the costly. They 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.

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
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Not able to quantify

9.26 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 that side gets colder. Potentially such a 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) propose 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)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	Potentially equivalent to vapour compression systems
Quality of scope 2 emissions information	Low
TRL level	3
Maintainability issues	Non known
Legislative concerns	Non known
Payback time (years)	Non known

9.27 Two-stage system

Two-stage systems are generally applied to industrial refrigeration plant. Generally speaking, this system has one condenser, two evaporators, two compressors and at least one 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 does less work. 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. With the application of variable speed compressor technology it seems unlikely that this technology would be suitable or applied to smaller professional systems.

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)	48.6%, but for older systems
Quality of scope 2 emissions information	Low
TRL level	8
Maintainability issues	None identified (however, a second compressor may add to maintenance)
Legislative concerns	None
Payback time (years)	No information identified

9.28 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 28). 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.

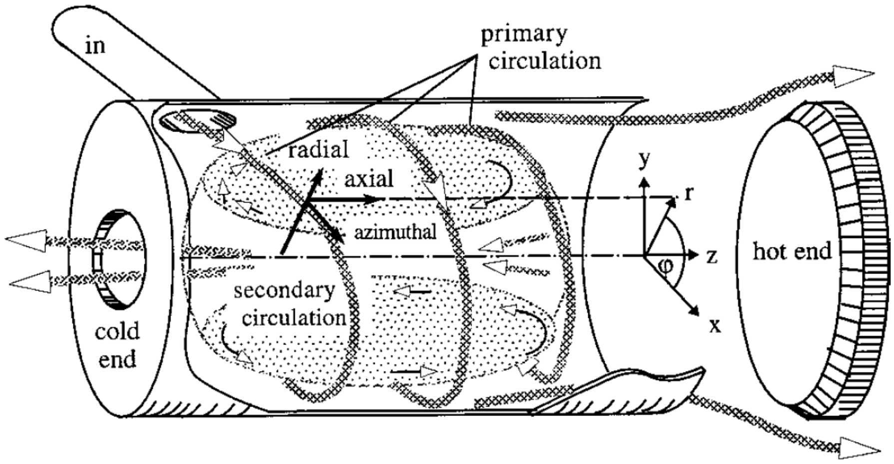


Figure 28. Vortex tube taken from (Ahlborn et al. 2000]).

A vortex tube was used by Choi et al (2018) to generate 3 different evaporating temperatures to provide cooling for 3 separate compartments (Figure 29). Such a system is claimed to have higher efficiency and is more adjustable than conventional direct expansion systems. Simulations indicated that R290 and R717 has better performance than R600a, R22 and R134a when used as the working fluid. 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.

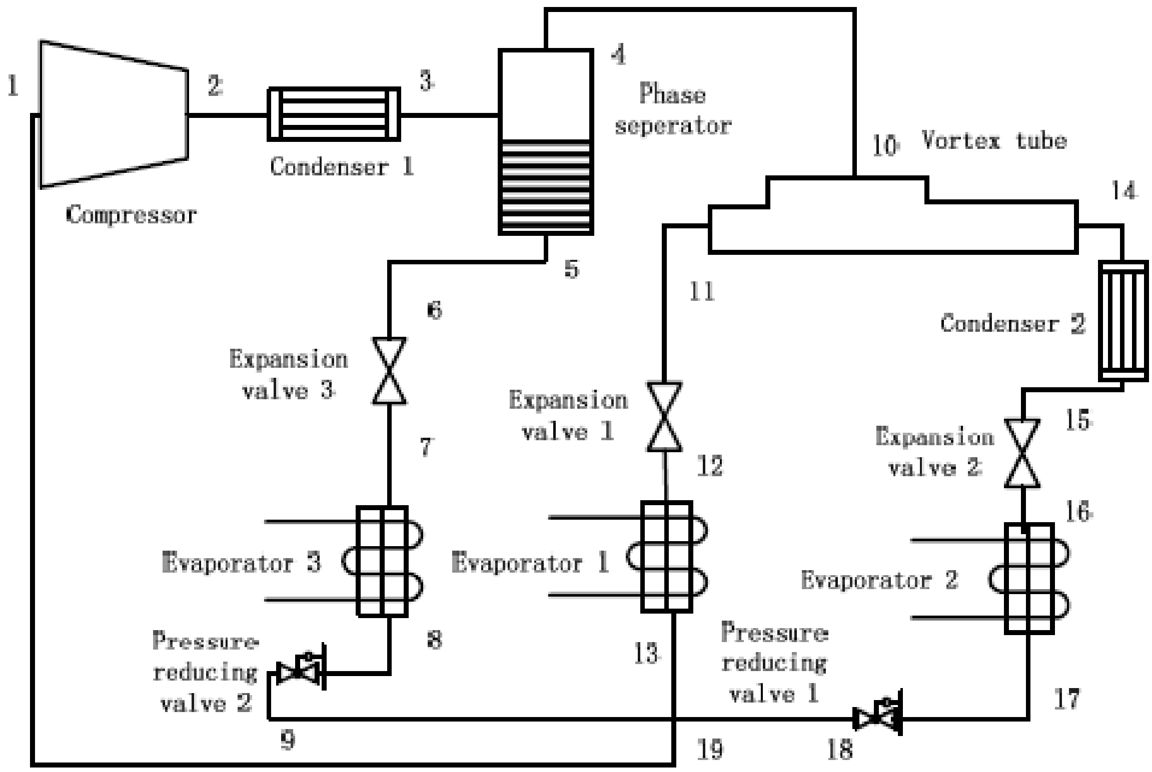


Figure 29. Novel cycle with a vortex tube.

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 quantified evidence of energy savings
Quality of scope 2 emissions information	Low
TRL level	2
Maintainability issues	Not known
Legislative concerns	None
Payback time (years)	Not known

9.29 Wide glide refrigerants

Most refrigerants used in professional 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 multi-temperature refrigerators. This is partly because some professional 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 air cooling or 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 30). 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 45K 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.

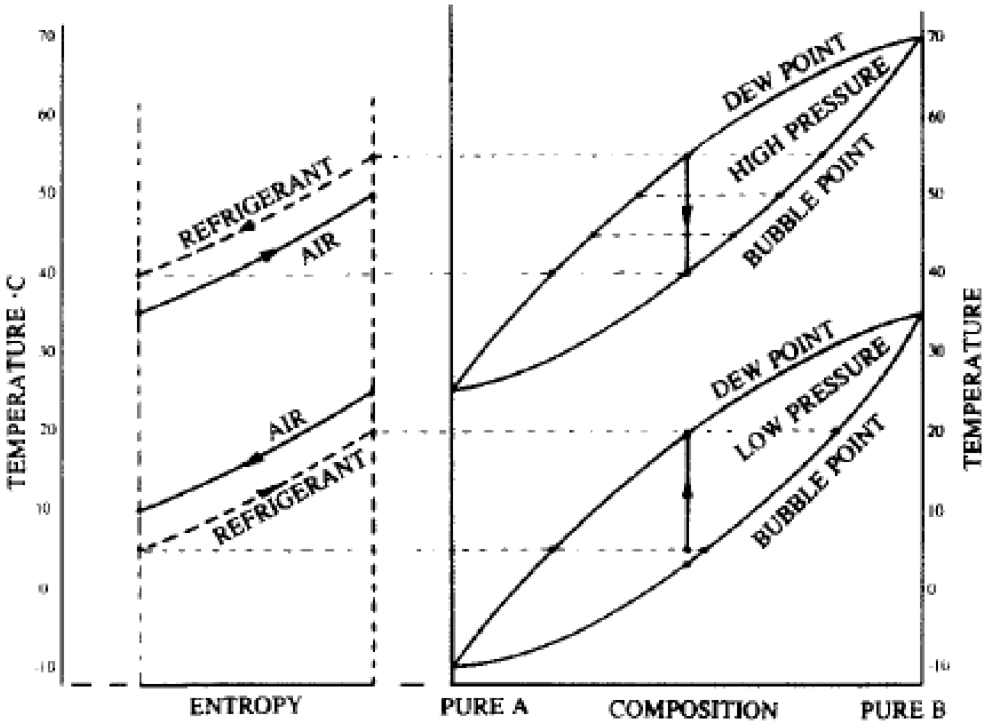


Figure 30. Temperature-entropy and temperature-composition diagrams illustrating the mixed refrigerant system. Upper pair of lines are for condenser and lower pair for evaporator (from Bensafi, and Haselden, 1994).

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 (2012) 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, but unlikely
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	9-20% for 2 compartments
Quality of scope 2 emissions information	Low
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, there may be additional cost heat exchangers but if energy savings of 10% could be achieved the paybacks should be <1 year

10 OVENS

10.1 Air impingement

Forced convection heat transfer by circulating heated air in ovens is widely used in units for cooking and baking (Cappelli et al., 2021). A special form of forced convection is *impingement*, which directs jets of hot gas perpendicularly towards the surface of the baking food at high speed, with the aim to reduce baking times and reduce the setpoint of the hot air temperature. The jets of heated fluid are addressed at high velocities (up to 50 m/s, but more commonly below 10 m/s) onto the surfaces of the food (Kerry, 2011). The impinging jets result in high convective heat transfer rates at the food surface. (Li & Walker, 1996) measured heat transfer coefficients during baking in conventional commercial conveyor ovens in comparison to impingement and reported average values of apparent convective heat transfer coefficients ranging from 22.8–84.8 W/m^2 K for the top and 17.4–110.9 W/m^2 K for the bottom of the oven, for the two types. Values over 200 W/m^2 K were reported for the convection heat transfer coefficient using air impingement systems (Gadiraju et al., presented 2003 IFT Annual Meeting-Chicago, 2003 as cited by (Marcotte & Grabowski, 2008)) compared to only about 10–20 W/m^2 K, in a conventional baking oven.

Impingement ovens use a variety of small nozzles, short tubes, perforated plates, or narrow slits to achieve impingement jets, therefore it has been found mainly beneficial for thin products such has pizza where the internal heat transfer resistance is small compared to that at the surface (Chhanwal et al., 2019; Walker, 2016). Impingement found its application in restaurants and food service on a wider scale than pizza only, and is used for casseroles, steaks, small bread loaves, cakes, pies and more. From the original application in small ovens, impingement now is also more and more used in large continuous ovens. These large-scale tunnel ovens use the principle of high-velocity air impingement from slots or nozzles for baking different types of products. High heat transfer rates also means high moisture removal rates by the impinging air, therefore the impingement will also increase water loss rates from the surface of the product, affecting e.g. the crust formation. Still, this may be balanced by the residence time in the oven that is reduced so much that products actually lose less moisture. The effects of changing to impingement cooking on food quality scale with the temperature adjustment as many transformation (such as leavening release, fat melting, sugar dissolution, protein denaturation, and starch gelatinization) rates leading to quality changes are temperature dependent.

According to Walker (2016), “any savings in baking times, lower temperatures, and reduction in energy use vary with the nature of the product (thickness, water content, etc.) and with the nozzle design and locations, but most importantly with the air velocity.” It is claimed that “the product of ‘time’ and ‘driving temperature’ (as an energy saving parameter) can be reduced to about one-half, where ‘driving temperature’ = ‘oven temperature’ − ‘product initial temperature.” (Walker, 2016). Still, there is no quantitative evidence to support this. For thicker products, the expected savings are claimed to be rather 1/3 instead of 1/2. (Wählby et al., 2000) reported, in an experimental oven intended for the domestic market using yeast buns (representing category bread) and pork cutlets (representing meats), that a jet impingement oven required 25 °C lower air temperature than a reference oven for baking buns in the same time, and a reduction of the cooking time of the meat by up to 50% at similar air temperature as recommended. (Banooni et al., 2008) studied experimentally application of impingement for baking of very thin breads (such as the Iranian breads) in ranges of temperature (150°C-250°C) and jet velocity (1 m/s-10 m/s). The sample baking time in a conventional oven with 200°C air temperature was about 10 min, which was about two times the baking time in the impingement oven at the same temperature with similar bread quality.

The above studies seem to agree that impingement may lead to up to 50% energy savings, although an integral analysis is missing that also accounts for the additional energy requirement for the air impingement system to operate (fan power) and assesses overall system performances. Using data and a parameterized reduced order model for a French bread baking commercial oven the potential energy savings of a newly designed impingement system with an array of circular jets were calculated (Alamir et al., 2013). The analysis indicated that air impingement could lead up to 17.9% energy savings. (Li et al., 2013) used a mechanistic heat exchange model in another optimization calculation and determined that almost 12% energy can be saved using jet impingement. An early review of the energy efficiency of ovens (Moreth, 1993, Morris, 1994 as cited by (Geedipalli et al., 2008) claims that jet impingement ovens are 65% efficient while standard gas fired ovens have only a 35% fuel efficiency.

Design features have a large impact on impingement heat transfer and will also affect the energy efficiency of the system. The rate of energy dissipation is largely dependent upon the shape of the nozzle, exit velocity of impinging fluid, length of nozzle and sharpness at nozzle exit, and adjustment of the plenum height (and tube distance from the product surface) clearly impacts on impingement efficiency (Kerry, 2011). The slot shape and length (i.e., '*short*', orifice type, or '*long*', finger type), and the layout of the arrays (i.e. uniform or staggered tube patterns), employed in various cooking systems clearly impact on the air velocity distribution and must be calculated during the design stages to ensure optimal heat transfer as a function of cooking time (Kerry, 2011). (Shevade et al., 2019) performed a computational fluid dynamics study of plenum and nozzle design parameters on the heat transfer rates to the surface of pizza type food product, for baking in a commercial conveyor oven. They only considered the turbulent airflow and heat transfer expressed by the surface heat transfer rates and air leakage. They suggested that with an optimal selection of the nozzle and plenum design features 20% energy savings could be achieved, but a comprehensive energy balance analysis of the complete system was again lacking.

Gains can also be expected when combining air impingement with other heating modes. (Mastrascusa et al., 2021) analysed, for continuous pizza baking, the CO_2 emissions and relative emission reduction of air impingement (AI) in combination with microwaves (MW), infrared heating (IR), superheated steam injection (SHS) and induction heating (IH). This was an experimental study performed in the laboratory by combining different apparatuses where needed. Energy consumption was computed as the sum of by power by run time of each technology. Emissions were calculated using data from the Mexican national electrical system, the value reported for the year 2019 was 0.505 kg CO_2 eq/kWh. Quality attributes were also assessed. The use of IR with AI presented the most significant reduction in cooking time (50%) and a reduction in energy consumption per pizza (27%) compared to the standard AI oven. The second higher reduction in energy and emissions is the combination which used MW and AI but failed on quality (insufficient browning). The relative savings of the successful AI and IR combination was calculated to be 27.1%.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	Air impingement compared to conventional heating: Baking time reduced by 30-50% (at same operational temperature and with similar baking quality) Energy savings 12-17.9% (from computational analysis in 2 studies) Increased energy efficiency: 65% compared to 35% (90's work) Multimode heating with infrared (experimental work): 50% reduction of cooking time 27% energy reduction 27.1% reduction in CO_2 emissions
Quality of scope 1/2 emissions information	Data from different peer reviewed journal papers on different applications, partly based on computational analysis using mechanistic and reduced order models. Few data on actual measurements.
TRL level	5-7 (hybrid) -8-9 (air impingement ovens for pizza)
Maintainability issues	Proper cleaning
Legislative concerns	-
Payback time (years)	Not available

10.2 Automatic shutdown

Stojceska et al. (2021) studied the effect of switching off equipment between productions for an entire production plant involving different pieces of equipment, including mixers, conveyers, cutters, feeders, ovens and coolers. While ovens had the largest share in the energy consumption (30-43%), the shutdown was only implemented for equipment with short start-up times, which excluded the ovens in this case. As a result, equipment switch off savings were between 0.4 and 0.5% of the total energy budget of the entire process. Practical guidelines towards energy savings in (food service) ovens (Pacific Gas and Electric Company, 1999) also state that preheat times are often half an hour, and it is not always recommended to turn it off between productions, unless for at least 2 hours. Switching off ovens directly after operational hours is also advised, instead of during later planned cleaning activities, for example, with potential large savings. Ovens with digital timers have an automatic shut-down function that turns the oven off after 12h of continuous operation, mainly for safety reasons (*Wall Ovens & Ranges - 12 Hour Automatic Oven Shut Off*, n.d.). It does not appear that easy and common to enforce intermediate automatic shutdowns during operation hours as it may often not be easily estimated if the shutdown period will be long enough to save energy with respect to the additional preheating time needed, which typically has the highest power demand of the whole heating process. It will rather require careful planning of the heating operations and clear instructions to operators. Smaller ovens with short preheating time and short process times that are not used continuously, such as toasters, have automatic shutdown already installed with timers. Apart from the use of timers, sensor technologies have been considered for inline baking quality assessment which could also aid the determination of the end of the heating process, which consequently could be used to switch off the oven. Among others, (Abdanan Mehdizadeh, 2022; Paquet-Durand et al., 2012; Yüksel, 2014) explored computer vision technology combined with machine learning. Online measurement of water content using a microwave sensor was suggested (Woodhead et al., 2014).

(Takacs et al., 2020) used mid-infrared imaging. Hyperspectral imaging was tested in different studies as well (Andresen et al., 2013; Polak et al., 2019). A more complete review of inline sensor technologies for baking is provided by (Jerome et al., 2019). As far as could be assessed in this review, none of these technologies have been explored for energy savings studies or practical use with respect to automatic oven shutdown.

Energy savings in batch ovens are expected equal to [(avoided overrun time) × (steady state oven power)] – [(preheating time) × (max. oven power)]. The typical average steady state oven power will be only a fraction of the max. oven power depending on the magnitude of the heat losses of the oven, or the efficiency of the heat process. With a steady state heating power that is 25% of the max. oven power, and a typical preheating time of 30 min, the automatic shutdown savings will be substantial starting from 2 h non-operation. For an oven with a shorter preheating time of 15 min, the shutdown saves energy starting from 1 h intervals. For a 1h baking process, the expected energy savings are about 20% for each additional overrun hour that can be saved. For a more efficient oven to keep the steady state temperature, say consuming only 10% of the max. power, the savings are beneficial starting from 10 times the preheating time, with less than 10% energy savings for each additional hour saved.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	10-20% of energy use for each non-useful heating hour saved. Reduced losses due to overheating: no data available.
Quality of scope 1/2 emissions information	Rough estimate, not verified.
TRL level	Timers: 8-9 Use of sensing technology: 1-4
Maintainability issues	-
Legislative concerns	-
Payback time (years)	Use of timer: 0 Use of sensing technology: not available

10.3 Control of exhaust hood

Demand Control Kitchen Ventilation (DCKV) systems have been suggested for commercial food service facilities (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. 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

Reduced run time of fan motors of the exhaust unit and balancing air supply unit(s) (makeup airflow/HVAC)

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 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)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	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 2 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 to updates of the US national codes (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). HVAC energy reduction, no average values reported. One particular case claims 29% savings (see below). Reported in (US Department of Energy, 2015)
TRL level	8-9
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.

10.4 Doors instead of open front/back

Hot holding cabinets are temperature maintenance units similar to refrigeration equipment. And though they are heated, this equipment is not for cooking. The equipment has a top- or bottom-mounted heat system, which consists of a heating element and potentially also air movement inside the cabinet, as well as humidity controls. Heating systems include convected air with fan-driven circulation or radiant heat with no mechanical air movement with thermostatically controlled air temperatures (Food Service Equipment and Supplies, n.d.). Mostly electricity powers hot food holding units. Single cabinets require 1200 to 1500 watts of electrical power, while double cabinets may use 1800 to 2000 Watts.

In the USA and Canada, ENERGY STAR (Energy Star, n.d.) certified hot food holding cabinets often incorporate better insulation which reduces heat loss, offer better temperature uniformity within the cabinet from top to bottom, and keeps the external cabinet cooler. In addition, many certified holding cabinets may include energy saving devices such as magnetic door gaskets, auto-door closures, or dutch doors. The measures together result in a list of certified appliances that are claimed 70% more efficient than standard models, saving 3000 kWh annually. An example given by (Pacific Energy Center, n.d.) states a non-insulated model used 1.35 kW and the insulated model used 0.43 kW, for a 0.9 kW savings. This was also verified in an experimental campaign by (Ruan et al., 2021).

The cost savings of ENERGY STAR certified holding cabinets were evaluated to be about € 1000 over a 12-year lifetime of the equipment (U.S. Department of Energy. Office of Energy Efficiency and Renewable Energy, n.d.), thus equipment priced no more than €1000 higher also save money.

On another aspect, (Ruan et al., 2021) investigated potential energy savings in food holding equipment on sites in California including heat lamps, heat strips, and heated shelves in addition to cabinets. Heat strips used a lot of energy because of their long hours of operation and steady input rate throughout the day. Heat strips must heat food from a distance. Their inherent inefficiency is that the heat source is directed downward at the food without any enclosure to contain the heat, which rises naturally.

Heat lamps operate under a similar concept but cover a smaller area and thus have a lower input rate. Heated shelves exhibited the same inefficiency with heat coming from the bottom instead of the top. The authors saw low potential for energy savings for heat lamps and heated shelves. Heat strips are energy intensive appliances that operate at a constant and relatively high input rate without any thermostatic feedback. Heat strips are frequently forgotten by staff and not powered off since it is difficult to tell if they are on or off. With a simple, automatic timer or sensing technology, there is potential to save a sizeable amount of energy on the magnitude of 10 kWh/day (equivalent to 12 hours off). Though sensing technology for heat strips is not currently available on the market, another solution could be to switch to halogen heat strips, which allow for temperature adjustment to match the required levels of heating demand. This type of replacement was claimed to theoretically save up to 81.4 percent of the operating energy, comparing the baseline resistance and halogen heat strip results.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	70% of annual energy consumption.
Quality of scope 1/2 emissions information	Annual energy use calculated using ASTM Standard F2140-11. Annual Energy Cost calculated based on an assumed electricity price of $0.09/kWh, which is the average electricity price at federal facilities throughout the United States. Lifetime Energy Cost is the sum of the discounted value of annual energy cost and an assumed hot food holding cabinet life of 12 years. Future electricity price trends and a 3% discount rate are from Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis–2021: Annual Supplement to NIST Handbook 135 (NISTIR 85-3273-36).
TRL level	8-9
Maintainability issues	-
Legislative concerns	-
Payback time (years)	12 years (lifetime of equipment)

10.5 Efficient/improved oven design

Improving energy efficiency of ovens has been suggested by means of design improvements. In most studies, computer simulation approaches such as computational fluid dynamics (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). Simplified quality kinetics indices are used to benchmark effects of changes on baking quality. The major variables affecting the baking process are the baking time and temperature, moisture content, and distribution of heat flux in the oven.

The model based analysis of (Paton et al., 2013) predicted that 19% of the energy used in an industrial oven is baseload, i.e. the energy that escapes via the oven walls, roof and flue gas losses. Their analysis estimated that a **10% baking time reduction** would mean an energy reduction of 19% × 10% = 2% per food item (in this case, bread). Building further on this model, (Khatir et al., 2013) found that increasing convective heat transfer coefficients (CHTC) from the hot air to the food in a bread baking oven from 10 W/(m^2 K) in a conventional oven to 35 W/(m^2 K) in an improved design of the airflow rates and distribution, could save energy by a reduction of baking time and thereby reduced heat losses through the oven walls (44.7 kJ/kg), although additional energy is required for running the fans (2.9 kJ/kg). Increasing the CHTC beyond 35 W/(m^2 K) was not found useful in terms of energy savings because of the limited gain in baking time and the exponential increase in fan energy. The energy required for baking the bread was assessed to be 800 kJ/kg, thus an **energy saving of 5.2%** (41.8/800) could be achieved on a specific food unit (kg) base. No experimental verification was presented. The potential energy savings for the UK were estimated to be around 25 GWh/year in the UK based on the bread total production, leading to a reduction in carbon emissions of 4484 tonnes CO2e. For France, this was estimated to be 11.22 GWh/year, or 2019 tonnes CO2e; For Sweden it was 70 tonnes CO2e. An estimate for Europe as whole was 43466 CO2e (Khatir et al., 2013).

Díaz-Ovalle et al. (2017) proposed geometric changes in an oven to reduce the preheating time and maintain temperature uniformity using CFD simulation. The authors showed that the baffle plate geometry exerted an important hydrodynamic influence in the reduction of pre-heating time, but it was less obvious from the study what the actual expected savings are. An air-forced convection rotary bread-baking oven with a 60 kW natural gas burner and 2 fans was modelled with CFD but implications of design on energy use were again not shared (Pinelli & Suman, 2017).

Shevade et al. (2019) performed a CFD study of plenum and nozzle design parameters of a pizza air impingement oven on the heat transfer rates to the surface of pizza type food product, for baking in a commercial conveyor oven. They only considered the turbulent airflow and heat transfer expressed by the surface heat transfer rates and air leakage. They suggested that with an optimal selection of the nozzle and plenum design features **20% energy savings** could be achieved, but a comprehensive energy balance analysis of the complete system was also here lacking.

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	1-4
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.

10.6 Improve combustion efficiency (gas/oil)

Gas burners are typically 85–95% efficient (Therkelsen et al., 2014). Still, the energy efficiency of an average wafer baking machine is reported to be only 35%, with the rest of the total energy lost to "atmospheric discharge" (Sovacool et al., 2021). It has also been reported that electric ovens are more energy efficient than direct-fired natural gas ovens, which generate large amounts of heat from the exhaust gases. So, with respect burner efficiency, it is mainly important to regularly check the efficiency and take appropriate measures to assure efficiency. It has been claimed that 5-25% or more savings in heat generation can be achieved by proper combustion efficiency in industrial applications such as steel production (Oakes and Bratcher, 2011).

Measures for oven combustion control have been adequately described by (Therkelsen et al., 2014). These authors state that oven burners are a critical component of oven energy efficiency. To optimize the efficiency, flue gas and temperature analysis can be used to determine burner operation and efficiency. For example, burners are typically running with excess O_2 greater than 4% in the flue gas, to avoid CO development and soot deposits (Oakes and Bratcher, 2011). But there could be margins to reduce and save fuel. As part of installation and commissioning, burners should be adjusted for efficient operation, which is an action with a five-to-ten-month payback period. After completing burner commissioning, a reference flue gas and temperature sample should be taken. This reference measurement can be used to determine if burners are operating efficiently or not. When variations in flue gas and temperature are observed, the most common corrective action will be to adjust the burner air/fuel ratio. Potential fuel savings can be determined from published charts (Oakes & Bratcher, 2011). These authors also provide some examples with fuel saving costs of more than 20% in industrial furnaces. An oxygen trim control may be appropriate to manage combustion inefficiencies in a more continuous way. The oxygen trim system uses a sensor to measure the excess oxygen in the flue gas and will change the fuel or air flow to correct this level to match a pre-set level. Oxygen trim controllers cost between €6000 and €10,000 to install but will reduce the time required to assess efficiency and maintain oven efficiency in the future. An example is explained by (Anonymous, 2007). Return on investment depends on the savings expected. In some instances, a burner will be damaged and need to be repaired or replaced. Burner repair commonly has a payback period of 1.5 years and can be performed during periods of routine maintenance.

Therkelsen et al. (2014) also discusses flue gas monitors that can be used to maintain flame temperatures within optimal limits while monitoring carbon monoxide (CO), oxygen, and smoke levels, with respect to use in combustion boilers: "Oxygen measured in exhaust gas is a combination of deliberately added excess air and unintentional air infiltration. By combining an oxygen monitor with an intake airflow monitor, it is possible to detect even small levels of unwanted air infiltration. Elevated CO or smoke exhaust signals that either air/fuel ratios need to be adjusted or combustion burners need to be maintained or replaced. Using a combination of CO and oxygen readings, efficiency can be maximised, and air pollutant emissions reduced through optimization of fuel/air mixture level. Case studies indicate an average payback period of 1.7 years for this measure and show that it is typically financially attractive only for large boilers."

Furthermore, a portion of oven exhaust gas can be re-circulated in the oven or mixed with incoming combustion air to reduce fuel consumption (Therkelsen et al., 2014). See the respective review on this topic. Mukherjee et al. (2019) also states that measures to reduce secondary leak air flow by 30-35%, significantly reduce the dilution of hot products of combustion inside the oven and yields an overall fuel savings of 8.5%.

An interesting alternative to gas recirculation in ovens where the consumption temperature is much higher than the required temperature for baking has been suggested by (Corina, 2017). It was shown that the technology of an integrated cogeneration engine (ICE) in (indirect heating) ovens is relevant from the energy efficiency point of view. The idea of ICE is to avoid the losses during recycling and mixing direct burner gasses with oven gasses, but rather use the surplus heat of the burner for other purposes. The energy efficiency of the process of obtaining gases in the combustion chamber of ICE was calculated to be 10,6% higher (92,6% instead of 82%) than the same process in the combustion chamber of the classic oven. Therefore, the integration of cogeneration in baking installations increases energy efficiency of the analysed process as a whole which also produces electricity and warm water of 70°C that are included as useful outputs. It was noted "that the proposed technology can be implemented in any enterprise equipped with natural gas oven, regardless of the type of products cooked/baked". In the particular case studied, the electricity produced by the ICE integrated with the bakery oven, will account for 38% of the total electricity demand for the analysed enterprise. To establish this efficiency, however, the total gas consumed increased by a factor 2.4 for the production of the same amount of oven heat. The return on investment was also not analysed.

The analysis made by the Carbon Trust in UK (Carbon Trust, 2016) for 89 bakery sites, showed that improved combustion efficiency leads that on average reduction of 196 tons of CO_2 per site with a payback time of 3 years, mainly for indirect-fired ovens. Actions include regular servicing of the burners and use of an oxygen trim, with estimated savings of 10%.

Scope 1 emissions savings (% or another quantifiable metric)	Maximal range 5-25% energy use savings, but likely between 5-10% (for indirect fired ovens). 196 tons CO2 per site (bakery sector).
Quality of scope 1 emissions information	Savings depends on the extent of deviation of the optimal efficiency of the combustion burning process, which can be assessed by measurement flue temperature and excess oxygen concentration. Too high O_2 will be less efficient. Established in many industrial combustion applications.
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	8-9
Maintainability issues	Routine maintenance: Regular measurement of flue gas concentrations and temperature to assure reference values are maintained. Repair/replace burner if needed.

	If full control system is preferred, additional installation (sensors, controller, actuators) and maintenance costs are expected for an oxygen trim controller
Legislative concerns	-
Payback time (years)	1.5 years for burner repair 3 years for oxygen trim

10.7 Improved oven control e.g. active exhaust control

Zareifard et al. (2006) improved heating uniformity in an infrared oven by better control of the heating power of different infrared heaters. Standard deviation of product heat fluxes among nine positions varied to over 250 W/m^2 K or 29%. The improved IR heating control was able to reduce the differences to less than 5%, improving uniformity and reducing total baking time by 10%.

Papasidero et al. (2016) presented an approach to optimize the total energy absorbed by the food product (bread), in a batch process with different energy sources (convection and radiation), at the level of adjusting the control. The optimization showed that the highest temperatures and the most important energy contribution are related to the initial dough heating part, while the final part is more related to achieve the targeted quality and require less energy. A 20% energy save with respect to the base case was achieved where levels of air temperature and IR temperature were allowed to vary across 4 periods of the total baking time. The study was not conclusive on the final solution as a different number of baking periods further changed the optimal temperature profiles.

Afkar et al. (2020) evaluated by modelling and experiments the effects of different dynamic heat flux profiles on the quality and the energy consumption of the baking of flat bread. The study revealed that the heat flux profile has a significant effect on the bread quality. The amount of energy required for baking the bread using an ascending or descending heat flux profile was 360 kJ per heating element, while the base case with a constant heat flux used 504 kJ. This would mean an energy saving of 28.6%. The bread quality assessments revealed that the bread baked using the ascending heat flux profile was of a better quality compared to the other profiles in terms of brightness and sensory quality characteristics.

The performance of a convection oven cavity can be improved by implementing more advanced control algorithms to the unit (Ryckaert et al., 1999). These authors showed that with experimental results that the dynamic behaviour of the oven cavity is modified significantly through the implementation of a model-based tuned P.I.D. controller, in comparison to a simple on-off control. The temperature inhomogeneity is much smaller with the P.I.D. controller, as compared to the classical on–off controller. Furthermore, the average temperature in the cavity, obtained with the P.I.D. controller, tracks the setpoint temperature much better. The performance of the P.I.D. controller for a setpoint of 70°C indicated that uniformity is improved and a reduction of required heating power by 75% was achieved during steady state temperature control of the cavity.

Stigter et al. (2001) applied classical control theory to a heat conduction model with convective boundary conditions to obtain optimal heating strategies. The methodology was applied to two case studies, namely, a cylindrically shaped geometry (with mashed potato) and a commercially available container geometry (with ready-made lasagne). The results indicate a ΔT type heating profile, including a final oscillating behaviour that fine-regulates the temperature to an almost uniform temperature of 100°C. Such improved uniformity will help in reducing losses (over- or under-heating) and may affect total heating time, thereby allowing energy savings. The energy impact was however not investigated.

Active control strategies for hybrid heating modes (e.g., microwave ad convection) have been for long subject of research (Sanchez et al., 2000). Oven temperature controllers should be designed by inverting a model of the process in order for them to be optimal, which may lead to complexities in the case of highly non-linear processes such as food baking. Still, simple control structures can be proposed to overcome these limitations without risking robustness and tracking efficiency. These use easily derived time varying linear models which are inverted to guarantee efficiency. Robustness is induced by continuously updating model parameters through recursive estimation from input–output data. Both characteristics were demonstrated via experiments performed under realistic conditions (Sanchez et al., 2000), but energy aspects were not addressed in this work.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	Optimized profiles of heating power can reduce energy consumption by 20-30%. Heating time reductions up to 10% Improved control leads to better uniformity, reducing losses.
Quality of scope 1/2 emissions information	Based on peer reviewed research articles.
TRL level	4-9
Maintainability issues	Regular calibration of sensors.
Legislative concerns	-
Payback time (years)	No information. Expected short due to low cost of components (electronics and sensors).

10.8 Keep oven loaded

The energy analysis of the bakery industry conducted in the UK sheds light on the specific energy consumption (SEC) of baking processes in (large) gas fired tunnel ovens (Carbon Trust, 2016). Measured throughput (kg/h) and energy use per time (kWh/h) were used to calculate the SEC for direct and indirect fired ovens. Low throughputs of less than 1000 kg/h had SEC above 1 kWh/kg, while high throughputs (> 2000 kg/h), resulted in SEC values below 0.5 kWh/kg. A high negative sensitivity of energy use per load mass was seen in this range. The direct fired ovens had much higher throughput (> 4000 kg/h), with SEC below 0.3 kWh/kg and much lower sensitivity to changes in loads. The reason is that for lower throughputs the total time to produce the same amount increases with consequently more heat losses (accounting for 90% of the total energy balance of the ovens considered but should on average be around 65% for gas fired ovens (Mukherjee et al., 2019); the reason may be the age of the oven considered (> 30 years old)), lowering. It can be reasonably argued that in (electric heated) batch ovens, that are claimed more energy efficient due to no losses caused by gas exhaust (Klemes et al., 2008) as cited by (Ladha-Sabur et al., 2019)), the effects of assuring high loads on energy consumption savings are less. As an example, compare 2 ovens with different efficiency, say oven 1 with 20% efficiency and oven 2 with 50% efficiency. Halving the load in the two ovens, will lead to a specific energy use increase by up to 80% for oven 1 and still 50% for oven 2. Therefore, for producing the same amount of product one should run ovens at full capacity as much as possible in all cases.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	Up to 50% energy savings per kg for doubling the throughput load on inefficient low throughput ovens (e.g., indirect fired tunnel ovens) Up to 33% energy savings per kg for doubling the throughput load on efficient high throughput ovens (e.g., direct fired tunnel ovens, or electric ovens)
Quality of scope 1/2 emissions information	Savings are dependent on overall oven efficiency and throughput. No data on batch ovens. Above are from measurements in case studies in larger UK study of the Carbon Trust.
TRL level	8-9
Maintainability issues	-
Legislative concerns	-
Payback time (years)	0

10.9 Motor efficiency (mixers, conveyors etc.)

Electrical motors run conveyors, combustion air fans and convection fans (Stojceska et al., 2021). Energy efficiency could be improved by use of the control systems in the ovens to lower the speed of the motor (Therkelsen et al., 2014). These authors discuss an innovative oven hood design that includes adjustable speed drives on its oven air supply and exhaust fan motors with a control system to run motors at a low speed with reduced energy consumption, until loaded. The claimed reduction of energy use by the oven hood controls were nearly 75% compared to standard designs.

Indirect fired ovens have additional fans to ensure heat transfer from the heat exchanger to the oven air and distributing the hot air to the food. In one study (Carbon Trust, 2016), an indirect fired oven had double the electric power (60 kW) of that of a direct fired oven (30 kW), contributing considerable to the lower efficiency of the indirect oven.

Another way of improving energy efficiency is to replace the existing electric motors with modern high efficiency motors (Stojceska et al., 2021). The electric motor that drives the metallic conveyor belt in the studied tunnel ovens had a reference efficiency of 70.6%. According to the authors, modern motors should obtain efficiencies of around 80% for the same size range. In the analysis of the application in this study, the motor efficiency increase could result in 11.8% energy use reduction for the considered load. This estimate could be on the high end, as conveyer belt motors are relatively low power (0.5 kW), according to (Carbon Trust, 2016): the contribution of electricity to specific energy consumption of baking ovens was 32 kWh/t (5.1% of total) for 590 kWh/t gas use in an indirect fired oven, and only 6 kWh/t (2.6% of total) for 221 kWh/t gas use in a direct fired oven. Therefore, a 10% increase in motor efficiency should have a limited impact on total energy consumption of this type of ovens, in the order of 0.2 to 0.5%. The 75% energy savings of properly used variable speed motors for exhaust control could lead to 2% to 4% overall energy savings.

Electric ovens should be more heat-source efficient (not having exhaust losses), so the relative impact could be slightly larger compared to gas fired ovens.

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)	More efficient motors: 0.2-0.5% energy savings in gas fired ovens 0.5-1.0% energy savings in electric oven Variable speed control motors (for fans): 2-4% energy savings
Quality of scope 2 emissions information	Re-estimated based on literature data of actual measurements.
TRL level	8-9
Maintainability issues	-
Legislative concerns	-
Payback time (years)	Not available.

10.10 Position away from chillers/freezers

Ovens require a well-ventilated space away from cooling/freezing equipment. Thereto, ovens can be thermally isolated by means of heat resistant curtains, and dedicated ventilation, or simply placed in another room than the heat sensitive equipment. The insulation of the oven and the other equipment will also improve system efficiency. Oven insulation typically has a payback period of about 1.5 years while insulation of other equipment have 0.5–1 year payback periods, based on assessments by the Industrial Assessment Center of the US Department of Energy that can be consulted on https://iac.university/searchAssessments (Therkelsen et al., 2014). Fisher et al., (2015) considered the positioning of heating equipment in a kitchen with respect to the exhaust hood. Hood exhaust rates could be reduced by 30% if side panels are installed. Similar savings can be made if gaps behind appliances are sealed. Heavy-duty equipment should be positioned in the middle of the cookline under a single hood. If not, incorporating a side panel or end wall is imperative. Also Demand Control Kitchen Ventilation (DCKV) is to be used (US Department of Energy, 2015), as explained in the review of exhaust control.

Thermal flows in cooking production areas can be simulated by means of computational fluid dynamics (Chen et al., 2020; Jiang et al., 2012), but these studies have been mostly directed to air quality aspects. It could be considered to perform CFD of production areas to assess thermal loads on heat sensitive equipment under different solutions such insulation panels and ventilation.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	Reduction of hood exhaust flow rate by 30%
Quality of scope 1/2 emissions information	Extensive studies in US.
TRL level	8-9
Maintainability issues	No
Legislative concerns	No
Payback time (years)	0.5-1.5

10.11 Recover exhaust heat

Exhaust heat from cooking/baking operations has been reported an important energy loss of food processing operations (Sovacool et al., 2021). For example, the energy efficiency of wafer baking machines has been reported to be only 35%, with the rest of the total energy lost through the exhaust (Mukherjee et al., 2019). These authors propose waste heat recovery as a very effective technique to offset these losses. In their review (Mukherjee et al., 2020) they state that most ovens in industry rely on the heat released from burning fossil fuels, mainly natural gas or propane and 'Less than half of this heat contributes to the actual processing of the product and the remaining is released to the surroundings as waste heat, primarily through exhaust gases at 150 to 250 °C. In the UK alone, the food and drink manufacturing sector releases circa 2.8 TWh of recoverable waste heat into the atmosphere, annually.' Their rough estimation of waste heat recovery from the UK Food and Drink sector alone amounts to 500,000 tonnes of CO_2 emissions, based on previous work by (Law et al., 2013).

The findings of Mukherjee et al.(2020) for a pilot scale and industrial scale wafer baking oven study indicate that utilising an oven's exhaust gases to preheat combustion air can deliver up to 33% fuel savings, provided a sufficiently large heat sink in the form of oven combustion air is available. The analysis was based on experiments on the pilot scale system, using only an electric preheater to simulate system performance, and computational analysis using energy analysis software for the industrial scale. The relatively simple technology was assessed to also offer a short payback period of only 1.57 years, with CO_2 savings of 71 to 356 tonnes per year from a single manufacturing site. The solution for preheating combustion air was compared to other ways of heat recovery, namely reheating of process water, a combination of preheating and reheating, and alternative heat recovery options such as Regenerative Organic Rankine Cycles (RORC) and Vapour Absorption Refrigeration (VAR), requiring somewhat more complex technical installations (Figure 31). This was done also by a computational analysis. The result shows that the effectiveness and oven productivity in kWh/kg wafer are most optimal for preheating, reheating and their combination. The effectiveness is for each technology a reflection of the rate of gas/electricity saved (in kW) per rate at which the recoverable heat is released (in kW). CO_2 savings of RORC and VAR options were limited to 28 and 41 tonnes per year, respectively.

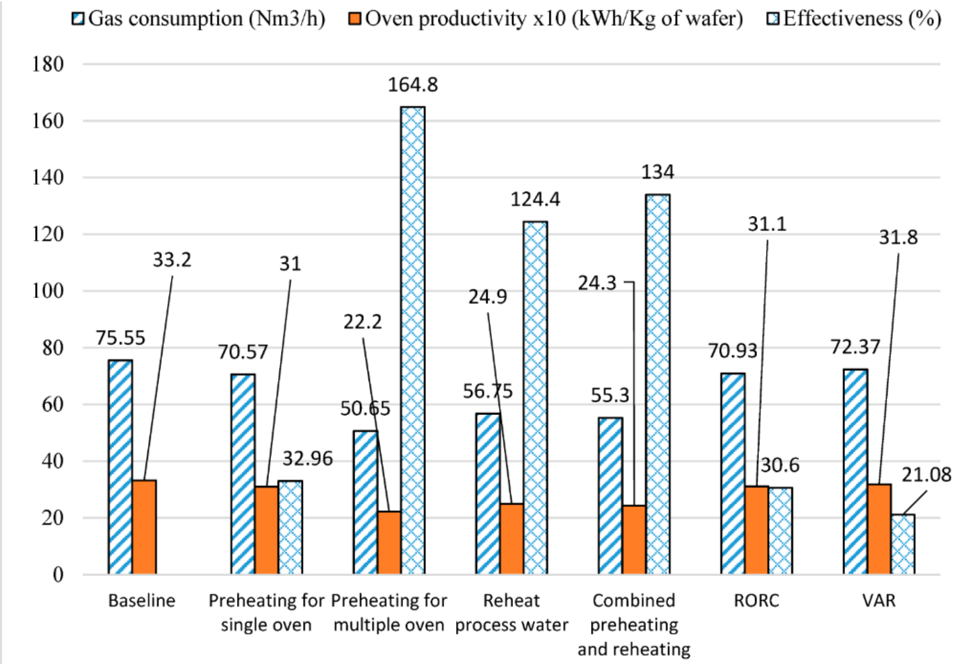


Figure 31. Comparison of heat recovery technologies based on oven's gas consumption, productivity and effectiveness. (taken from Mukherjee et al., 2020).

Detailed economic models for the different waste heat recovery options investigated were also developed to evaluate the return on investment. Payback periods were between 1.57 and 5.13 years for the preheating and reheating options, and 15.75 and 32.75 years for the RORC and VAR solutions. The authors then provided a route for electing the best fit technology, also requiring prior oven optimization and measurement of exhaust properties before starting any (computational) analysis. As far as understood from the reported studies of these researchers (Mukherjee et al., 2017, 2019, 2020), no actual experimental validation of the findings has yet been performed.

In kitchens heat recovery from the cooker hoods is theoretically feasible but heat is generally vented straight out of the building as the extract air contains grease and soot particles. These stick to surfaces and block heat exchangers. Recently a company called Enjay has started installing a counter current heat exchanger called Lepido which is designed with larger space between the fins and particle repellent geometry so that particles pass though the exchanger. This reduces build-up of particles. The company claim that heating bills can be reduced by 90% or 85,000 kWh/year for a typical restaurant. The company does have many case studies which appear to back up their claims (https://www.enjaysystems.com/our-product). Other systems such as the one produced by dext (https://dextheatrecovery.com/dexthermic-heat-exchanger/) also seem to provide similar systems. The DexThermic system is designed to directly reclaim heat to a hot water system.

Scope 1 emissions savings (% or another quantifiable metric)	Up to 33% fuel savings for a single manufacturing site with combing recovery heat for preheating multiple ovens (up to 5, 835 kW each), reheating process water or a combination of both. CO_2 emission savings: 28-356 tonnes per year for a single manufacturing site
Quality of scope 1 emissions information	Based on a parameterized computational study that was not verified with actual experimental data, for a very specific wafer baking system.

	Therefore, it may prove difficult to translate the impact of heat recovery to other types of ovens.
Scope 2 emissions savings (% or another quantifiable metric)	90% reduction in heating. Typical 58,000 kWh/year reduction in energy (Lepido)
Quality of scope 2 emissions information	Reasonable number of case studies that appear to justify claims for advanced heat exchangers (Lepido)
TRL level	8-9
Maintainability issues	Need to make sure that particles do not block heat exchanger (in kitchens)
Legislative concerns	-
Payback time (years)	1.57-5.13 years depending on the type of heat recovery, and for the specific oven that was studied 1-2 years for Lepido system

10.12 Reduce heating up time

Warm up of the oven is required to reach the desired baking temperature. Generally, the time should be minimized to save energy, and this is more important when the oven is more regularly shutdown between bakes. Usually, the heating up requires higher heating power levels due to the high temperature difference between the ambient and set point temperature to be overcome. Minimum oven heat-up time can be determined by recording how long after the oven is turned on temperature sensors indicate a desired baking temperature has been reached. According to (Therkelsen et al., 2014), one bakery reduced heat-up time by 20–25 min for cabinet ovens and by 40–50 min for tunnel ovens, without giving details about the particular measures taken.

These could include reducing thermal mass of the oven, optimized heat distribution (e.g., improved convection) from the burners/heating elements and a higher efficiency (less direct losses from the heat source) and improved control.

If the shorter heat-up time is due to using a higher initial set-point temperature and/or by installing a higher heating power, likely the energy savings with respect to the base case are negligible.

The preheating contribution to the total energy use depends on the number of successive bakes that are made after the initial preheat. Consider a 10 kW oven baking 7 kg of product in 1 h with a specific energy consumption of 1.5 kWh/kg (Ladha-Sabur et al., 2019), and a typical preheat time of 30 min. For a single bake, the contribution of the preheat will be 32% of the total, for 8 successive bakes it will reduce to 6%. A 10% reduction of the preheat time would reduce the contribution by 2% for 1 bake and 1% for 8 bakes, with respect to the total energy consumption per day for baking.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	1-2% energy savings for a 10% reduction in preheat time.
Quality of scope 1/2 emissions information	Rough estimate. No data available.

TRL level	8-9
Maintainability issues	Regular checking by recording temperature profiles during preheating will learn if preheat times increase due to aging of the system.
Legislative concerns	-
Payback time (years)	Depends on measures taken. No data available.

10.13 Reduce thermal mass of tins

As part of the energy efficiency analysis for the bakery sector (Carbon Trust, 2016), the heat absorbed by the tins to bake the foods in was assessed. In their analysis, a tin had a capacity to bake 4 800 g bread loaves and weighed 6kg; if a steel lid was used, the weight increased to 8.5 kg (a mass ratio of tins:bread of 2:1 was assumed). After heating, tins are cooled and used again. The mass of the steel tins consumes a certain amount of energy to bring the tin to the baking temperature of about 250°C, depending on its mass and specific heat. Reducing the energy consumed by the tins requires a lower mass and/or an alternative material with lower specific heat. According to the reported thermal analysis, tins make up 10 to 30% of the consumed natural gas in indirect and direct fired ovens, respectively, while the product baking only uses 12 to 35% of the gas, with direct fired ovens the more efficient. A 30% reduction in tin mass would lead to a gas use savings of 3.5% in the indirect oven, and thus about 10% in the direct fired oven. Alternative materials such as thermoplastics and other metals have been suggested to reduce heating requirements of the tins by 50% or a 6% reduction in gas consumption.

Paton et al. (2013) also considered tins in the energy analysis of a large direct gas fired oven. Tins and lids accounted for 6.5% of the total energy and the product energy taking 55% of the total; thus, representing a much more efficient baking process. In this case the % saving of a reduced tin mass would be considerably lower than in the case discussed above.

Scope 1/2 emissions (as relevant for electricity/gas) savings (% or another quantifiable metric)	3.5% gas consumption savings in ovens for a 30% reduction in tin mass 70-115 tons CO_2/year per site Expected smaller in more efficient ovens.
Quality of scope 1/2 emissions information	Carbon Trust funded analysis from 89 sites in the UK. Reported in the Industrial Energy Efficiency Accelerator Guide to the Industrial Bakery Sector. 2016.
TRL level	5-7
Maintainability issues	Need for adapted handling, cooling and cleaning systems for tins
Legislative concerns	-
Payback time (years)	Not available

10.14 Switch off conveyors when not in use

Ruan et al. (2021) investigated energy saving options for small conveyer ovens (toasters) used in restaurants. Conveyor toasters provide higher production capacity and ease of operation, compared to standard pop-up toasters, at a greater energy cost. The research team monitored conveyor toasters at 10 different sites. In 6 of the 10 sites, the toasters were replaced with appliances that had smart energy saving control: “Equipped with a sensor, these toasters would activate their energy save mode if there wasn’t any product placed into the toaster for a given period of time. The default manufacturer setting for this technology was 30 minutes. Once energy save mode was activated, the toaster would pause the conveyor and significantly lower the electrical input to the heating elements. Once new product was finally placed into the toaster again, the sensor would deactivate the energy save mode and reengage the toaster at full input, slightly extending the cook time of the first batch after resuming cooking operation to maintain the same toasting quality.” The authors found that the conveyers with automatic energy save modes reduced energy use by 21 percent. Payback periods ranged anywhere from instantaneous to six years at the very worst, with an average payback of around three years.

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)	21% energy use savings
Quality of scope 2 emissions information	Based on measurements in operational settings in 6 sites.
TRL level	8-9
Maintainability issues	-
Legislative concerns	-
Payback time (years)	3.1

11 HVAC

11.1 Air conditioning

Air conditioning, which includes cooling and dehumidification, is required in professional, commercial as well as industrial activities (Chua, et al., 2013). In food service outlets air conditioning is common to remove heat from the kitchen and ensure comfortable conditions for customers.

According to BSRIA (2009), air conditioner sales were anticipated to have exceeded USD 70 billion in 2008. Carbon and energy savings could be obtained by increasing the effectiveness of room air conditioner (RAC) and in light commercial application with best available technologies in market (Shah et al., 2021). Advanced low frequency compressor technologies, large heat exchangers with thermodynamically efficient materials and designs, highly efficient direct current fan motors, sophisticated metering devices, and intelligent sensors for temperature and humidity control are some of the = techniques utilized to obtain high efficiency in AC technology application (Shah et al., 2021). The importance of the inverter technology and the operation of AC at parts loads to obtain high COPs were strongly recommended by other studies as well (IEA, 2011, Kouropoulos, G.P., 2016).

Chua, et al., 2013 reviewed the most current advancements in cutting-edge cooling technologies and literary approaches that may help to enhance COP of the AC (shown in Figure 32). The key findings from the paper were that the utilization of innovative dehumidification could obtain energy efficiency improvement by 33%, while COP has been seen to improve by up to 20% through improved compression technology. In this regard the development of the scroll compressor in recent years might be viewed as a significant technological advance in the compressor industry. The efficiency of the scroll compressor is around 10% higher than that of the typical reciprocating compressor. Additionally, the development and application of intelligent air flow control systems can enhance Indoor Air Quality, support thermal comfort, and increase energy efficiency.

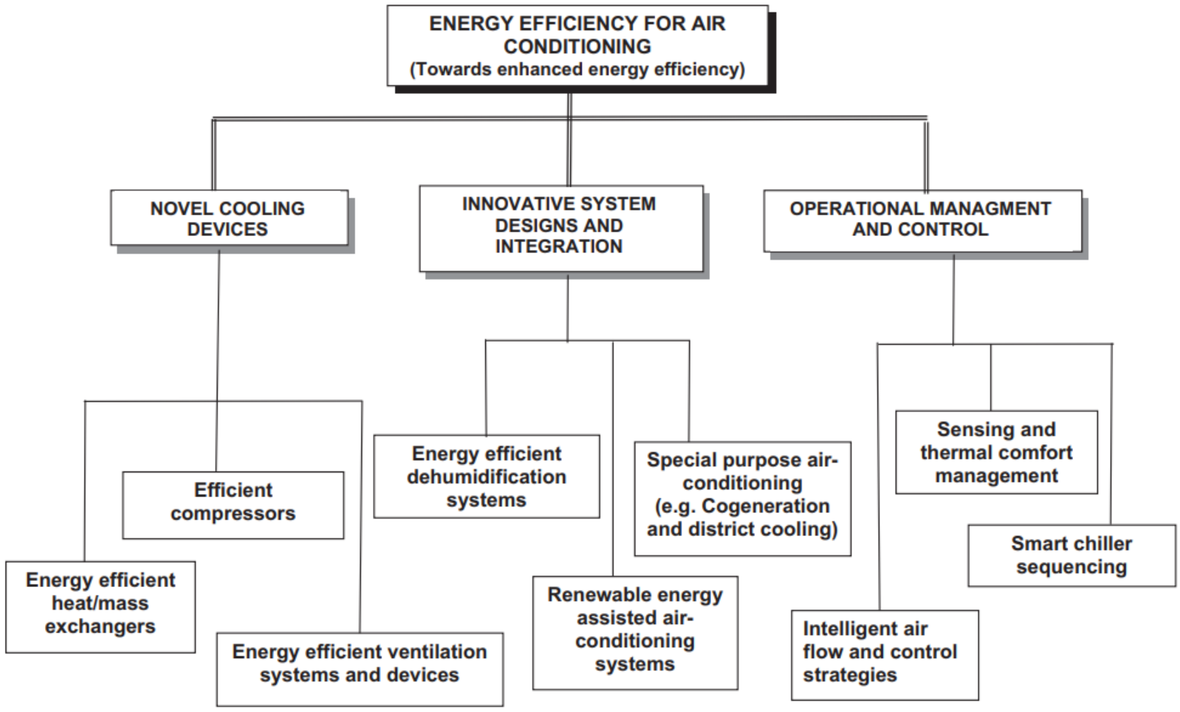


Figure 32. An outline of the technical review for energy efficiency in air conditioning.

The ACs coefficient of performance (COP) has been reported to be in the range of 6 to 7.23 when performing at its best (IEA, 2011). Performance gains during the period of 2001 to 2008 were made possible through advancements in individual parts and improved system integration. While developing technology road map and 2050 energy scenarios ultra-high efficiency air conditioners can obtain a COP of 9 with improved cooling and humidity control. In this case, air conditioners could reduce CO_2 emissions by 2 Gt by 2050 (IEA, 2011). Based on this information energy savings of 24.5% is assumed. However, the information is not specifically related to supermarket AC system but based on all type of AC applications in a different sector.

Scope 1 emissions savings (% or another quantifiable metric)	No information available
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	24.5% of energy savings and 2 Gt carbon emission savings by 2050 Based on the report of 2011.
Quality of scope 2 emissions information	Medium confidence

Availability barriers	Available
TRL level	8-9
Maintainability issues	Some problems
Legislative concerns	No impact
Payback time (years)	No information is available specifically for AC technology

11.2 Cold air retrieval

The air-air energy recovery process is the most common cold air retrieval for HVAC. Heat/cold between two airstreams at different temperatures are connected through a heat exchanger to recover heat/cold. Energy could be recovered either in its sensible (temperature only) or latent (moisture) form, or a combination of both (ASHRAE, 2016b). Devices used for sensible and latent heat exchange are known as energy recovery ventilators (ERV) and devices used for sensible heat exchange are known as sensible heat exchangers. Both types are available for commercial applications.

Cold air retrieval is especially suited for hot, humid climates where comfort air-conditioning is widespread. Consider an air-to-air cold retrieval exchanger operating in a hot, humid climate. For a heat exchanger that transfers heat but not moisture, the incoming air will be cooled down while bringing humidity into the building. The moisture brought into the building may increase the relative humidity in the conditioned space, resulting in an increased need for refrigeration and reheating to dehumidify the air to achieve the desired conditions. Alternatively, a heat exchanger that transfers heat and moisture will supply less humid air, requiring less energy for comfort conditioning.

Types of ERVs include fixed-plate heat exchangers, rotary wheels, heat pipes, runaround loops, thermosiphons, and twin-tower enthalpy recovery loops (ASHRAE, 2016b). The effectiveness of ERVs for ventilation is the ratio of actual energy or moisture recovered to the maximum possible energy that can be recovered.

Scope 1 emissions savings (% or another quantifiable metric)	Effectiveness defined as actual transfer of energy/maximum possible transfer between airstreams. 50-85%
Quality of scope 1 emissions information	These effectiveness values can be determined either from measured test data or using correlations that have been verified in the peer-reviewed engineering literature
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	8-9
Maintainability issues	No major maintainability issues. ASHRAE have listed up some technical considerations Air leakage, pressure drop, maintenance, corrosion, fouling, filtration, condensation and freeze-up.

Legislative concerns	None
Payback time (years)	Normally < 5 years, often < 3 years, not uncommon < 1 year.

11.3 Controls (advanced)

There are many forms to control HVAC systems. The simplest form of control is a manual on/off switch. On/off control is not an ideal solution in most cases because the maximum output of the cooling or heating system does not match the current demand for most days. Turning the system on half the time and off for the other half could meet the demand, but it will result in fluctuating temperatures around the desired temperature. The average temperature may be met, but the high and low temperatures will be uncomfortable for the people in the locale. Controlling the system with shorter time intervals will reduce the temperature fluctuations.

Time control

Time control allows systems and components to turn on and off at certain times and durations, which is useful for a system with a predictive schedule. The control system could be programmed to have a given temperature while the locale is open and another temperature when the locale is closed.

Temperature control

A temperature control system could be as simple as a thermostat and a motorized valve. The thermostat has a controller with a sensor measuring the temperature in the room. The controller will compare the measured temperature to the desired set point temperature and regulate the motorized valve to either increase or decrease the cooling/heating. Multiple thermostats and motorized valves are required for systems supplying heat/cold to multiple zones with a single heating or cooling source. This setup allows it to adjust the temperature for the specific rooms or zones independently.

Multiple control valves in the same heating/cooling system

Either a fixed speed pump or variable speed pump supplies the pressure in the cooling/heating system. For a system with a fixed speed pump, the pressure in the system will be influenced by regulating/closing one valve; thus, the other valves must adjust to keep the same flow as before. This method of operating the system wears the valve because they constantly need to adjust for the pressure. A better way to operate the system is with a variable speed pump and pressure sensor to keep the constant pressure in the system independent of the opening of the valves.

Programmable logic controller

A programmable logic controller (PLC) is a sophisticated way to regulate the temperature. For a given day, the PLC will check in the schedule if the locale will be open or not. And if so, at what time will the locale be open. If the answer to this is yes, it will be open between 11 am-11 pm. The PLC will check the current temperature in the locale in advance and the temperature outside and then calculate how long it takes to heat or cool the locale to the desired temperature. The PLC will then start the process of heating or cooling the locale, so it is ready for opening.

Data-driven control

The traditional rule-based and model-based strategies described above could be inefficient due to the complexity of buildings' thermal dynamics and environmental disturbances. Wei et al., (2017) developed a data-driven approach that leverages the deep reinforcement learning (DRL) technique to intelligently learn the effective strategy for operating the building HVAC system. One of their experiment results demonstrated that the proposed DRL-based algorithm could achieve up to 20-70% energy cost reduction compared to a rule-based baseline control strategy.

Oldewurtel et al., (2010) developed and analyzed a Stochastic Model Predictive Control (SMPC) strategy for building climate control that takes into account weather predictions to increase energy efficiency while respecting constraints resulting from desired occupant comfort. The SMPC approach was analyzed and shown to significantly outperform current control practice (rule-based) for selected cases.

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)	20-70% energy cost reduction compared to a rule-based baseline control strategy.
Quality of scope 2 emissions information	L
TRL level	8-9
Maintainability issues	None identified.
Legislative concerns	None
Payback time (years)	Variable.

11.4 Boilers with higher efficiency

A variety of technological advancements have been developed and integrated to support the effective energy management of future district heating and cooling sector. The main type of heating boiler on the market is condensing boilers, which recover a significant amount of thermal energy from the water steam contained in exhaust gases.

Demand flexibility may be facilitated by the integration of the electricity system with the heating and gas systems. Such integration offers an opportunity to increase the electricity consumption during hours of very high electricity production from variable electricity sources by producing heat (power-to-heat) or gas (power-to-gas). One option for increasing electricity system flexibility is to integrate the electricity system with the district heating systems via the use of power-to-heat technologies such as electric boilers. The power-to-heat technology is assumed to be electric boilers which are cheaper, but less efficient than heat pumps (Schweiger et al., 2017). The key feature of the smart grid is the two-way communication between supply and demand sectors which makes it possible to unlock power flexibility. In the industrial sector, technical data play a key role in operational scheduling and flexibility management. A data lake is required to store, manage and preprocess the raw data to be tailored for demand flexibility. In this way, data collecting, communicating, storing, and processing are still controversial issues (Golmohamadi, 2022).

Building space heat demand will change in the future and thereby the temperature requirements will change. For newly built buildings and future buildings, 50°C supply temperature to the SH system is enough, with floor heating or low-temperature radiators, and there is still the option to boost the supply temperature during the coldest periods. In fact, the district heating supply temperature can be even lower, but it needs supplementary heating system to heat up domestic hot water. Domestic hot water preparation requires certain temperature levels and thereby influence the substation layout and component sizes (Li and Nord, 2018).

Two practical approaches for reducing CO_2 emissions include fuel switching and increasing process efficiency. Transitioning energy systems from fossil fuels to decarbonized alternatives is more urgent than ever given the ongoing rise in global greenhouse gas (GHG) emissions and their escalating effects on the climate. With future increases in GHG emissions expected to cause additional warming of the planet, the immediate deployment of commercially available clean energy technologies is vital. The electrification of industrial process heating is one such solution to decarbonizing a sector heavily reliant on fossil fuels (Schoeneberger et al., 2022).

Two systems with conventional and hybrid renewable trigeneration technologies were analyzed for applications in residential buildings. The conventional system (Case 1) utilizes a boiler for space and domestic hot water heating and a chiller for space cooling. The renewable trigeneration system (Case 2) is equipped with an air-to-water heat pump which is integrated with a ground-to-air heat exchanger and building integrated PVT panels for preheating/precooling the incoming air and for electricity production. It is operated utilizing electricity only (from the PVTs and the grid), which leads to CO_2 free system electricity only (from the PVTs and the grid), which leads to CO_2 free system operation on site. The full year simulation of both systems results showed that the trigeneration system achieves lower primary energy consumption and CO_2 emission in comparison to the reference boiler-chiller system, mainly due to the introduction of significant renewable components. The annual primary energy saving is 42 - 45%. The CO_2eq emission reduction resulted from the renewable trigeneration system is also significant, standing at 43 - 82 % (Eun-Chul Kang et al., 2016). Dominkovic et al. (2015) modelled a system of biomass trigeneration combined with pit thermal energy storage in Matlab on hourly basis and hybrid optimization model was used to maximize the net present value, which was the objective function of the optimization. The results show that the pit thermal energy storage was an excellent option for storing energy and shaving peaks in energy demand.

Greenhouse gas emission reduction measures and potential GHG savings include energy efficiency improvements and other measures, such as replacement/upgrading burners (up to 6 %); tuning of process (up to 3 %); optimization (up to 4 %); instrumentation & controls (up to 4 %); air preheater (up to 1 %); insulation (up to 7 %); reduction of air leakages (up to 4 %); capture energy from boiler blowdown (up to 8 %); reduce slagging and fouling of heat transfer surfaces (up to 4 %); co-firing (20-30 % reduction with gas co-firing); fuel switching (20-35% reduction switching from coal to oil; 20-35% reduction switching from coal to natural gas) (EPA, 2010).

Improved efficiency of boilers used for heat applications by adding advanced technologies (such as advanced heat recovery, controls and burners) to the boiler system. These technology-based efficiency improvements can be achieved when retrofitting or replacing an existing boiler with new technology, when purchasing a natural gas boiler to meet new demand, and/or when switching from a fuel oil, coal or electricity based boiler to a natural gas boiler. Retrofit projects are defined as those that add technological components to an existing boiler unit to improve overall efficiency.

Wang et al. (2011) prepared a techno-economic analysis of a coal-fired CHP based combined heating system with gas-fired boilers for peak load compensation to identify the optimal basic heat load ratio that leads to acceptable economic performance. They discovered that it is of great importance from the energy policy perspective to seek economic harmony for successful penetration of gas into the heating market (Wang et al., 2011).

Traditionally it was observed that life cycle of boiler is nearly 15 - 20 years and it has to be replaced after that. A study on the boilers reveals that boiler categorization can be done under different heads together with discussion of the role of different mountings and accessories. Different research approaches have been discussed related to the materials of boiler and its components, regarding various hazards possible in the boilers and suitable measures have been proposed to avoid them. A maintenance schedule has also been prepared so as to optimize different maintenance actions. The usage of different fuels has been observed including the related problems in fuel and their solutions along with biomass as an alternative of the conventional fuel. As boiler is an integral and critical component of the system so all the discussed factors would lead to reduction in the boiler hazards and would ultimately enhance the system's reliability (Agarwal and Suhane, 2017).

Barma et al. (2017) described the amount of energy used in boilers, ways employed to evaluate their energy efficiency, losses occurred and their causes, ways of waste heat recovery and minimizing heat loss using technologies, role of maintenance activities, and technical education to make people aware of the energy usage. A small improvement on the boiler efficiency will help to save a large amount of fossil fuels and to reduce CO_2 emission. The efficiency of the boiler can be improved by doing scheduled maintenance work, which helps to run a boiler at its highest efficiency (Barma et al., 2017).

As the hot flue gas transfers heat to water by convection heat transfer, a major portion of heat is lost through the outgoing flue gas. As the temperature of the flue gas leaving a boiler typically ranges from 150 to 250 °C, about 10–30% of the heat energy is lost through the process and is the highest source of heat loss in the boiler system (Figure 33). Boiler efficiency could be improved by recovering part of the total heat content of flue gas. This heat can be used to preheat combustion air, boiler feed water within the boiler, or as driving heat source for other purposes such as absorption chiller (Barma et al., 2017).

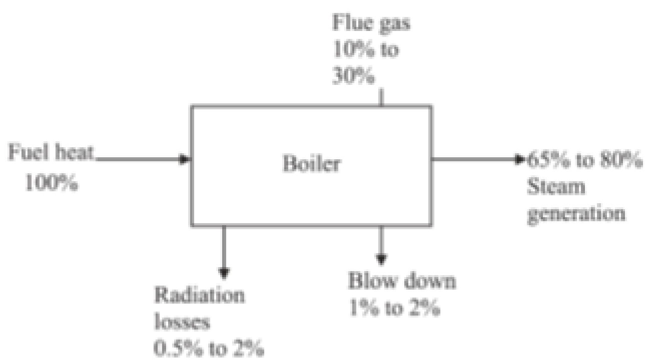


Figure 33. Typical heat balance of a boiler (Barma et al., 2017)

In all central heating systems, heat is provided by either an oil- or gas-fired boiler or a biomass boiler. Boilers nowadays, exhibit efficiencies of more than 90%. In low temperature wet systems, the use of condensing boilers increases the efficiency to 100% (Martinopoulos et al., 2018).

A piping network is needed to be employed for recovering condensate from different heating facilities, which involves a financial investment. But the substantial savings in energy and chemicals costs makes building a return piping system attractive. It has been found that 2% of the boiler population can achieve a 10% energy savings with a payback period of 1.1 years (Barma et al., 2017).

Heat pumps are able to create a temperature lift of a heat source which makes the heat source useable at higher temperature and in case of waste heat recovery from low temperature exhaust; this technology can lift the temperature for using the recovered heat at higher temperature. It is potential to create temperature lift of boiler exhaust economically in excess of 40 °C, but the overall efficiency is reduced due to energy requirement of the heat pump. Application of heat pump is common all over Europe but fewer in UK. A survey regarding public attitude on waste heat recovery revealed a major portion of the food industry in UK considers heat pumps as a 'risky' or 'unsure' even though the payback period varies from 2 to 5 years in some case studies in UK (Barma et al., 2017).

Cogeneration has been considered worldwide as the major alternative to traditional systems in terms of significant energy saving and environmental conservation as well as GHG emission. Heat should be produced in combination with power, as this increases energy efficiency significantly which is an extremely important to energy sustainability. The most promising target in the application of CHP lies in energy production for buildings, where small-scale and microscale CHP is usually installed. Currently, micro-scale and small-scale CHP systems are undergoing rapid development, and are emerging on the market with promising prospects for the near future. Combination of cogeneration technologies to various thermally fed systems such as absorption or engine-driven chillers allow for setting up a so-called trigeneration system. In addition, high efficiency electro-energetic technologies such as electric heat pumps well fit into the existing energy systems to enhance the overall performance (Barma et al., 2017).

Biomass boilers are generally characterised by difficulties when requested to be operated during rapid transients for load following: a longer time period to ignite the fuel and reach rated output respect to gas or oil boilers, lower performances and higher emissions at part load. The energy demand profile of a supermarket has been used to size the thermal energy storage (TES), the biomass boiler and to select the operating conditions of the plant. Based on the results of the thermodynamic simulations and upfront and operational costs estimate, the investment profitability is evaluated, for each configuration. The main conclusions are: (i) coupling the biomass boiler with a TES allows the boiler to work at higher part load conditions and at a higher global energy efficiency, with a lower biomass consumption and reduced emission; (ii) the hypothesis to supply heat to the store only by means of cogenerated heat from the organic Rankine cycle unit, and operate this generation system in heating load following mode, is not profitable in comparison to baseload operation to maximize electricity generation (and discharge excess heat) (Sorrentino et al., 2018).

Electric heaters convert electric current to heat. Various types of electric heating devices are available. Storage heaters take advantage of cheaper, off-peak electricity tariffs during low demand periods such as afternoon and night. A storage heater stores heat in clay bricks and then releases it during the day when required. A room thermostat monitors room air temperature and regulates heat delivery as needed. Electric panel heaters supply heat through a combination of radiation and natural convection. About 90% of the heat comes from convection, while only 10% is radiated from the front of the panel. A thermostat is controlling the operation and the heat release. Radiant electric heaters heat surfaces, objects and occupants via infrared radiation emitted by the heater. They do not heat the air within the room directly, namely only surfaces in a direct line of sight to the element are heated. The room air starts to be heated, as long as the temperature of the surrounding surfaces will rise above the air temperature. Radiant heaters can be useful for heating briefly and intermittently occupied spaces or large-size spaces where they provide heat locally to the occupants, for example, in production halls focusing on the working places. Their effectiveness decreases drastically in noninsulated rooms, especially if there is high moisture content in the air. There are also various other types of electric heaters like portable infrared heaters, convection oil-filled heaters, electric fireplaces and under floor heating. The efficiency of all electric heating devices, from the consumer's point of view, is considered 100% since almost all purchased energy is converted to heat (Martinopoulos et al., 2018). An electric boiler or an electrically driven heat pump can be also installed as main heat source in central systems. In areas that enjoy a mild climate, air-to air heat pumps reach a seasonal performance factor of more than 3. Geothermal heat pumps, which exhibit seasonal performance factors that can range between 3.5 and 4.5, are a more efficient solution for areas with colder climate. Heat pump systems can operate either autonomously or in a hybrid mode (boiler and heat pump). In a hybrid heating system, a boiler is combined with a heat pump which can be either an air source heat pump or ground source heat pump. These systems merge the high-efficiency of a heat pump and the high-efficiency of a condensing boiler to improve overall system efficiency even in very harsh climatic conditions (Martinopoulos et al., 2018).

Acha et al. (2020) investigated the viability of fuel cells (FC) as combined heat and power (CHP) prime movers in commercial buildings with a specific focus on supermarkets. Up-to-date technical data from a FC manufacturing company was obtained and applied to evaluate their viability in an existing food-retail building. A detailed optimisation model for enhancing distributed energy system management to optimise the techno-economic performance of FC-CHP systems. The optimisations employ comprehensive techno-economic datasets that reflect current market trends. Outputs highlight the key factors influencing the economics of FC-CHP projects. Furthermore, a comparative analysis against a competing internal combustion engine (ICE) CHP system is performed to understand the relative techno-economic characteristics of each system. Results indicate that FCs are becoming financially competitive although ICEs are still a more attractive option. For supermarkets, the payback period for installing a FC system is 4.7-5.9 years vs. 4.0-5.6 years for ICEs when policies are considered. If incentives are removed, FC-CHP systems have paybacks in the range 6-10 years vs. 5-8.5 years for ICE-based systems (Acha et al., 2020).

Scope 1 emissions savings (% or another quantifiable metric)	Up to 8 % depending on technical solution.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	20 – 35 % using fuel switching.
Quality of scope 2 emissions information	Verified in the peer-reviewed environmental engineering and technical literature
TRL level	8-9
Maintainability issues	None identified
Legislative concerns	None identified
Payback time (years)	Dependent on solution, heat prices and geographical location. Typically 4-10 years, in some cases 1.1 year.

11.5 Door air curtain

HVAC air curtain systems are most commonly placed above doors in the entrance but could also be used in loading bays. The air curtain creates a barrier between the outside and the inside air. The air curtain is created by a fan using air from the inside to blow from above the door to limit the influx of outside air. The reduction of outside air coming inside reduce heating/cooling cost depending on the outside temperature and ease the control of the relative humidity in the store. The air curtain system could be equipped with a heat exchanger or an electrical heating element. A system with a heat exchanger uses a refrigerant to heat or cool the air depending on the season, which is usually integrated into the main refrigeration system of the locale. The effectiveness of air curtains is defined by the prevented energy loss from an open door divided by the amount of energy that would have been lost without an air curtain (ASHRAE, 2016a). There are two different types of construction of air curtains. The first is a non-circulating system, where the air is drawn directly from the surroundings. And the second is recirculating, which collects and returns the air back to the air handling unit for the air curtain. The recirculating type is to a lesser degree used for supermarkets, but more widespread for cold stores. The effectiveness of non-circulating systems is in the range of 60-80%, while the recirculating systems have an effectiveness of 80-90%. Installing a non-circulating air curtain is easy and could easily be retrofitted to existing openings, while a recirculating system requires planning and will impact the opening.

Air curtains have been studied for over 50 years. Hayes, (1968) developed theoretical models to describe airflow and jet of vertically downwards blowing air curtains under steady-state conditions. More recently, advanced infiltration characteristics models have been developed, taking into account pressure differences and weather conditions (Wang and Zhong, 2014). These models have been experimentally validated (Goubran et al., 2016).

Gil-Lopez et al., (2013) studied the effects of the thermal loads and hygrothermal conditions of a store with high pedestrian traffic under three air conditioning situations: without climatic separation, with a conventional air curtain, and with a high-efficiency air curtain. The store is 200 m^2 and located in Javea, east of Spain, close to the Mediterranean Sea. The electric consumption of the cooling system was reduced almost by 33% for the most efficient air curtains compared to the case without air curtains due to the effectiveness of the climate separation and lower power consumption.

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 33% reduction in electric consumption of the cooling system
Quality of scope 2 emissions information	Verified in the peer-reviewed engineering literature
Availability barriers	None
TRL level	8-9
Maintainability issues	None Annual periodic maintenance
Legislative concerns	None
Payback time (years)	2-5 years (Airtècnics, 2022)

11.6 Fan motors with higher efficiency

The thermal comfort of the customers and staff members in supermarkets are strongly depended on the temperature and quality of the air. To deliver the desired air quality and temperature, three interconnected systems including the heating and cooling systems as well as the ventilation system are used. The goal of a building's HVAC system is to give its occupants total thermal comfort. However, due to its high cost, energy conservation in this system is one of the most crucial issues (Soyguder and Alli; 2009).

Air handling units (AHUs) are designed to match peak conditions. As building load fluctuates, the fans do not require to run at this condition all the time. Mechanical throttling devices are historically used to reduce airflow, but this is an inefficient mechanism. Variable frequency drives (VFDs) to modulate the airflow is a more efficient mechanism to cope with variable loads. Changing a fan's speed enables it to more precisely match changing load requirements, and as fan power draw is related to the cube of its speed, lowering speed can significantly reduce energy consumption (Saidur, et al., 2012). Instead of running continuously at maximum speed, variable speed drives enable the fan motor speed to change in response to the actual operating circumstances. For instance, lowering a fan's speed by 20% can save almost 50% of the amount of energy and with annual energy savings of $543 for a 5 Hp motor (Saidur, et al., 2012).

VFDs can be retrofitted to existing AHUs. Emerson showed a 52% reduction in energy consumption by doing this in 78 food retail stores (Emerson, 2022). Schibuola (2018) showed energy savings of 38.9% in the electric consumption of pump and fans by applying VSDs to HVAC systems serving a library. ABB (2012) suggest that paybacks can be as low as 1 year in retail environments.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	39-52% in fan energy
Quality of scope 2 emissions information	M
TRL level	TRL7-9
Maintainability issues	None known
Legislative concerns	None
Payback time (years)	Potentially <1 year

11.7 Heat pumps, heat reclaim and radiant heat

Using highly efficient heating systems and waste heat recovery (heat reclaim) is one of the main aspects to reduce the primary energy consumption. This is also reflected by the Directive 2012/27/EU (EU, 2012) of the European Parliament and of the Council on energy efficiency which indicates to install highly efficient heating and cooling systems in buildings and to recover waste heat. Since heat reclaim, heat pumps and radiant heat are mostly playing together, they are considered in one technology review.

1 Ventilation system

Heat recovery in ventilation systems is most efficient in commercial kitchens when used to supplement water heating, rather than simply the tempering of incoming supply air. In the UK, most specifications call for the temperature of incoming fresh air entering the kitchen to be no less than 10 °C. This being based on health and welfare considerations for the kitchen staff working adjacent to the air entry points. (CIBSE, 2021)

With reference to CIBSE (2021), there are two main methods (air-to-air or air-to-water) for heat recovery in ventilation systems, these are shown schematically in Figure 34. For more detailed information, the technical memorandum “Energy efficiency in commercial kitchens” (CIBSE, 2021) can be consulted.

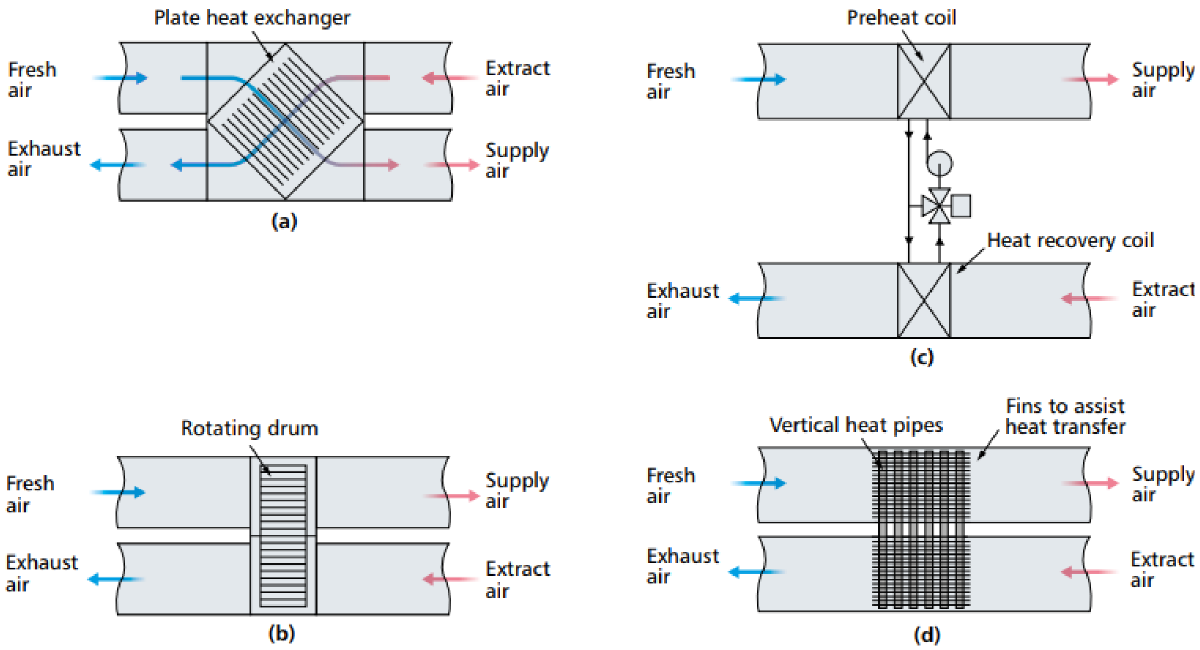


Figure 34: Ventilation heat recovery devices; (a) plate heat exchanger, (b) heatwheel, (c) runaround coil, (d) heat pipes (CIBSE, 2021)

In addition to the measures in the ventilation system described by CIBSE (2021), night ventilation can reduce the cooling demand in the morning hours, according to HKI (2019).

2 Refrigeration system

Heat recovery in refrigeration systems usually takes the waste heat generated by large refrigeration systems and uses it to supplement the hot water supply to the kitchen via a heat exchanger. This is known as a secondary system, and usually uses water, glycol or brine as the heat transfer medium. Another benefit from refrigeration heat recovery is that it can help to reduce the heat gain in the area where the refrigeration equipment is installed, which helps the equipment to run more efficiently and reduces the demand on ventilation. (CIBSE, 2021)

Sawalha (2013) lists the possible integration concepts, explained in the following sections. Figure 34 and Figure 35 show a simple scheme of the integration of a heat recovery system in a refrigeration system via an intermediate circuit. Within this heat recovery solution, the refrigeration system operates at a floating condensation pressure. If heat is required by e.g. a heating, ventilation and air conditioning (HVAC) system, the condensation pressure is increased to provide a suitable temperature level.

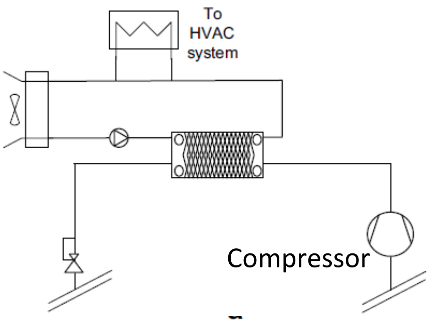


Figure 35: Simple scheme of a direct heat recovery solution via an intermediate circuit and a floating condensation pressure (Sawalha, 2013)

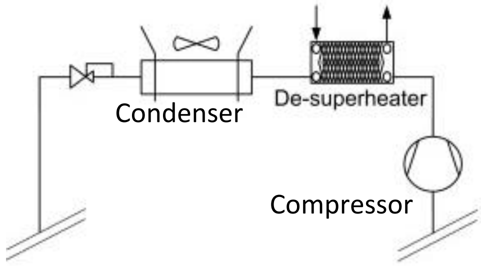


Figure 36: Simple scheme of a direct heat recovery solution via a desuperheater (Sawalha, 2013)

Heat recovery via a desuperheater prior to the air-cooled condenser enables reaching supply temperatures higher than the condensing temperature utilizing only a part of the waste heat. **Error! Reference source not found.** shows a simple scheme of a heat recovery via a desuperheater. According to Sawalha (2013), this heat recovery solution is viable in systems operating with refrigerants that have a relatively high discharge temperature, i.e., CO_2, NH_3.

If the temperature level of the rejected heat from the refrigeration system is too low to be directly used for heating applications, a heat pump can be used to lift the temperature to a suitable level. **Error! Reference source not found.** shows a simple scheme to integrate a heat pump, basically resulting in a cascade system. In this solution, the heat pump extracts the heat from an intermediate circuit, which is used to cool the condenser. If the heat rejected from the refrigeration system is used by the heat pump the refrigeration system can operate at a lower condensation temperature, which increases the efficiency of the refrigeration system. If the rejected heat from the condenser is not completely used by the heat pump, the excess heat can e.g., be rejected in an air cooler which potentially increases the condensation temperature (and thus pressure) of the refrigeration system depending on the operating conditions. This will lead to a reduced efficiency of the refrigeration system but increased efficiency when the heat pump is in operation. In case the heat pump is integrated after the condenser in the refrigeration system, further sub-cooling of the refrigerant in the refrigeration system can be provided, which improves the efficiency of the refrigeration system. Figure 37 and Figure 38 show a simplified schema of the integration of a heat pump after an air-cooled condenser.

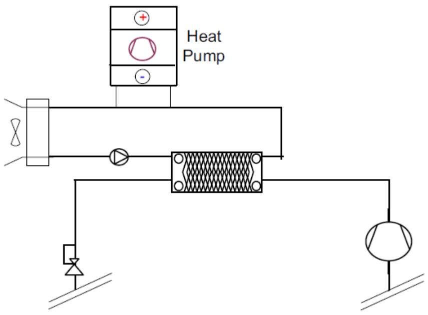


Figure 37: Simplified schema of a heat recovery with a cascade system (Sawalha, 2013)

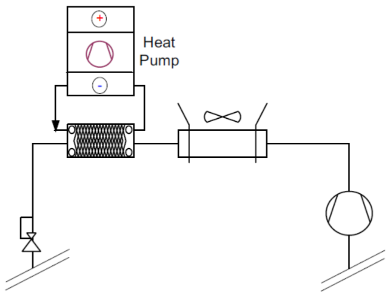


Figure 38: Simplified schema of a heat recovery by means of a heat pump integrated after the aircooler (Sawalha, 2013)

2.1 *Additional applications of heat pumps in commercial kitchens*

For hygienic reasons, parts of the kitchen is extract air must be removed from the system as exhaust air. Due to the position of the air suction ducts above the cooking zones, this extract air is warm, humid and loaded with grease. This energy-rich exhaust air can be used to heat water for the high water demand. With heat pumps using e.g., R744 as refrigerant, a high temperature level for the domestic hot water can be achieved. Figure 39 shows a scheme of a possible implementation. One problem to be solved is the grease separator to protect the other components; this will have to be integrated as an additional object in the kitchen's maintenance plan.

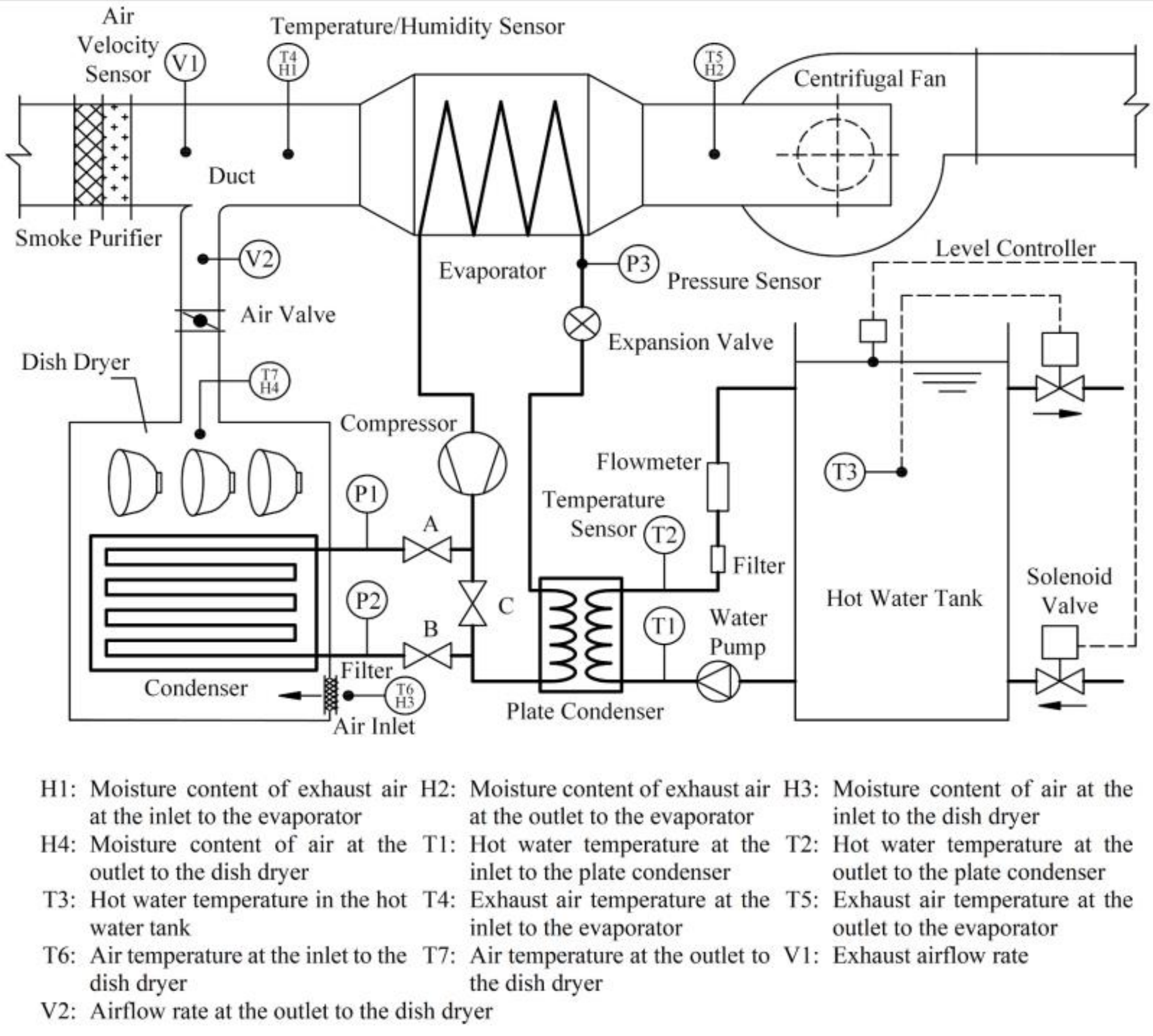


Figure 39: Example of aa HEAT-Recovery System shown by Yuan Wang, (2020)

In Figure 6, a setup for heat recovery from the exhaust air using an R744 heat pump is illustrated. In this configuration, extract air is utilized as the heat source, and the heat is transferred to the domestic hot water through a plate condenser or to the dish dryer. The dish dryer has been integrated into the refrigeration circuit for this application but could also be operated with water.

Figure 40 shows that the water demand follows the energy demand with a certain time delay. With increased energy demand, the exhaust air is also more energy-rich and is thus available as a heat source for the domestic hot water boiler. This means that the load profiles are suitable for the use of waste heat as a heat source for the domestic hot water.

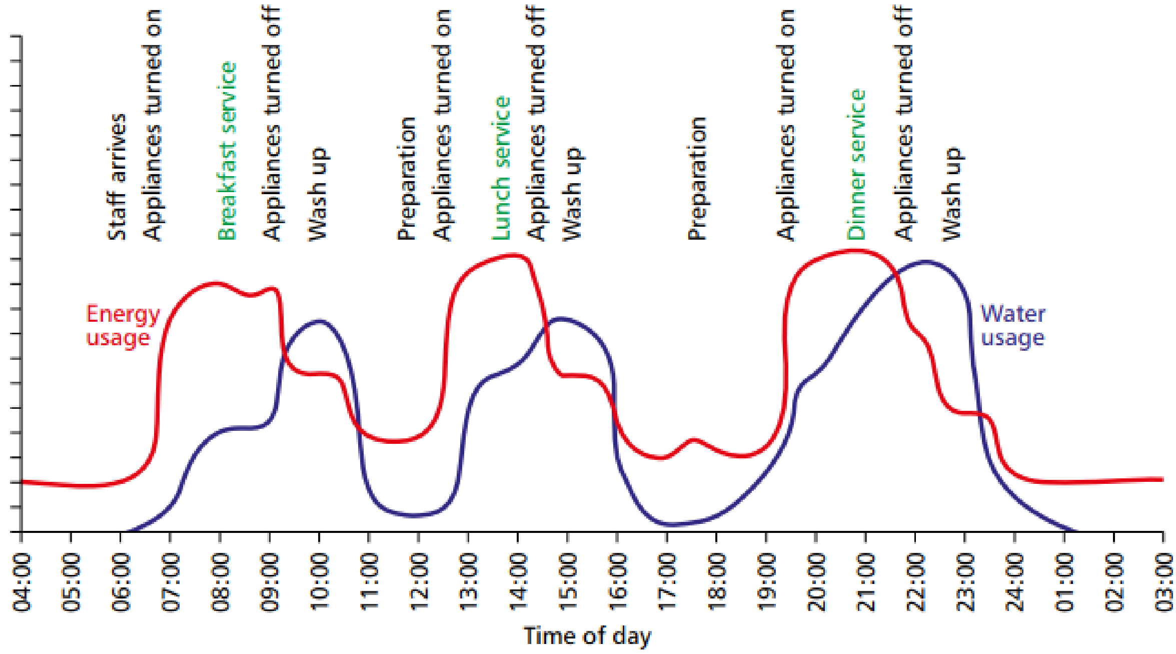


Figure 40: Example of energy and water usage in a three-service kitchen (CIBSE, 2021)

3 Radiant heating and cooling

According to CIBSE (2021), it is essential that the source of room heating for the kitchen is not solely the cooking equipment, but that the kitchen has its own independently controlled heating system.

Radiant heating heats a building mostly through heat radiation, rather than convection used by conventional methods. According to ASHRAE (2008), a technology is designated as radiant heating or cooling, if the amount of energy exchanged by radiation is more than 50 % of the total heat transferred.

There are many subcategories of radiant heating and cooling according to EN ISO 11855-1:2022 including: radiant ceiling panels, embedded surface systems, thermally active building systems and infrared heaters.

In order to provide acceptable thermal conditions, the air temperature and the mean radiant temperature, should be considered. The combined influence of these two temperatures is expressed as the operative temperature. Compared with a convective heating and cooling system, a radiant heating system can achieve the same level of operative temperature at a lower air temperature and a radiant cooling system at a higher air temperature. Especially in well insulated buildings with largely sized radiant surfaces the room temperature can be slightly reduced. Caritte (2015) analysed the influence of the temperature set point on the total heating demand and found out that, a reduction of the room temperature set point of 1 K (during the heating period) could save 25 % of the total heat demand throughout the year. This leads to the conclusion that by using a radiant heating system, the room temperature can be decreased and therefore the energy consumption can be reduced without significantly effecting the thermal comfort.

Environmental and operational carbon dioxide usage benchmarks per meal served (CIBSE, 2021)
Table extracted from CIBSE (2021)

Facility	Standard	Environmental ($kgCO_2$/meal)	Operational ($kgCO_2$/meal)	Combined ($kgCO_2$/meal)
Coffee shop	Good practice	0.16	0.24	0.40
	Typical	0.18	0.27	0.45
Fast food outlet	Good practice	0.19	0.29	0.48
	Typical	0.22	0.34	0.56
Restaurant:				
— fine dining	Good practice	0.93	1.40	2.33
	Typical	1.05	1.58	2.63
— staff	Good practice	0.43	0.65	1.08
	Typical	0.49	0.73	1.22
— themed	Good practice	0.36	0.54	0.90
	Typical	0.41	0.61	1.02
— traditional (full service)	Good practice	0.46	0.69	1.15
	Typical	0.52	0.78	1.33
Hotel:				
— business/holiday	Good practice	0.73	1.10	1.83
	Typical	1.21	1.81	3.02
— luxury	Good practice	0.81	1.21	2.02
	Typical	1.29	1.93	3.22
— small	Good practice	0.65	0.98	1.63
	Typical	1.06	1.58	2.64
School:				
— primary	Good practice	0.07	0.11	0.18
	Typical	0.11	0.16	0.27
— secondary	Good practice	0.07	0.11	0.18
	Typical	0.10	0.15	0.25
Hospital	Good practice	0.30	0.94	1.24
Ministry of Defence:				
— officers' mess	Good practice	0.76	1.13	1.89
— senior ranks' mess	Good practice	0.67	1.00	1.67
— junior ranks' mess	Good practice	0.43	0.64	1.07

Quality emissions information	The CIBSE Energy Benchmarking Tool (CIBSE, 2021) is maintained and successively expanded for the UK by the Chartered Institution of Building Services Engineers CIBSE and Universety Collage London and thus represents a good data basis for the UK.

Environmental and operational energy usage benchmarks per meal served (CIBSE, 2021)

Table extracted from CIBSE (2021)

Facility	Standard	Environment (kW·h/meal)			Operational (kW·h/meal)			Combined (kW·h/meal)		
		Fossil fuel	Elec.	Total	Fossil fuel	Elec.	Total	Fossil fuel	Elec.	Total
Coffee shop	Good practice	0.36	0.21	0.57	0.54	0.32	0.86	0.90	0.53	1.43
	Typical	0.41	0.24	0.65	0.62	0.36	0.98	1.03	0.60	1.63
Fast food outlet	Good practice	0.21	0.36	0.57	0.32	0.54	0.86	0.53	0.90	1.43
	Typical	0.30	0.39	0.69	0.44	0.59	1.03	0.74	0.98	1.72
Restaurant:										
— fine dining	Good practice	2.12	1.26	3.38	3.19	1.88	5.07	5.31	3.14	8.45
	Typical	2.41	1.41	3.82	3.62	2.11	5.73	6.03	3.52	9.55
— staff	Good practice	0.99	0.58	1.57	1.48	0.88	2.36	2.47	1.46	3.93
	Typical	1.12	0.66	1.78	1.69	0.98	2.67	2.81	1.64	4.45
— themed	Good practice	0.83	0.49	1.32	1.24	0.73	1.97	2.07	1.22	3.29
	Typical	0.94	0.55	1.49	1.41	0.82	2.23	2.35	1.37	3.72
— traditional (full service)	Good practice	1.04	0.62	1.66	1.57	0.92	2.49	2.16	1.54	4.15
	Typical	1.19	0.69	1.88	1.78	1.04	2.82	2.97	1.73	4.70
Hotel:										
— business/holiday	Good practice	1.69	0.97	2.66	2.54	1.46	3.00	4.23	2.43	6.66
	Typical	3.38	1.36	4.74	5.08	2.03	7.11	8.46	3.39	11.85
— luxury	Good practice	2.12	0.97	3.09	3.17	1.46	4.63	5.29	2.43	7.72
	Typical	3.81	1.36	5.17	5.72	2.03	7.75	9.53	3.39	12.92
— small	Good practice	1.27	0.97	2.24	1.91	1.46	3.37	3.18	2.43	5.61
	Typical	2.54	1.36	3.90	3.81	2.03	5.84	6.35	3.39	9.74
School:										
— primary	Good practice	0.27	0.05	0.32	0.41	0.08	0.49	0.68	0.13	0.81
	Typical	0.39	0.08	0.47	0.59	0.11	0.70	0.98	0.19	1.17
— secondary	Good practice	0.26	0.06	0.32	0.39	0.09	0.48	0.65	0.15	0.80
	Typical	0.34	0.08	0.42	0.52	0.12	0.64	0.86	0.20	1.06
Hospital	Good practice	0.2	0.6	0.8	0.3	0.09	1.20	0.5	1.5	2.0
Ministry of Defence:										
— officers' mess	Good practice	1.76	1	2.76	2.64	1.5	4.14	4.40	2.50	6.90
— senior ranks' mess	Good practice	1.56	0.88	2.44	2.34	1.32	3.66	3.90	2.20	6.10
— junior ranks' mess	Good practice	1	0.56	1.56	1.5	0.84	2.34	2.50	1.40	3.90

Quality of scope 2 emissions information	The CIBSE Energy Benchmarking Tool (CIBSE, 2021) is maintained and successively expanded for the UK by the Chartered Institution of Building Services Engineers CIBSE and Universety Collage London and thus represents a good data basis for the UK.
TRL level	TRL 7 HEAT-Recovery System from Exhaust Air TRL8-9 (for all other technologies)
Maintainability issues	the grease separator
Legislative concerns	No legislative concerns about the implementation of these technologies The general framework for the installation of highly efficient heating and cooling systems is given in Directive 2012/27/EU of the European Parliament and of the Council

Payback time (years)	n.a.

11.8 Variable frequency drives

Variable frequency drivers are systems that can control or alter the speed of electrical motors. There are many terminologies for this kind of technology. The most common are AC drive, frequency converter (FC), variable speed drive (VSD), adjustable speed drive (ASD), adjustable frequency drive (AFD), and variable frequency drive (VFD) (Danfoss, 2019). VSD and ASD refer to speed control in general, while AFD, VFD and FC are directly connected to adjusting the feeding frequency of a motor. Since VFD can control or alter the speed of electrical motors, it will impact all components with an electrical motor, for example, all types of compressors, pumps, and fans. (Sturm et al., 2013).

The operating characteristic of centrifugal fans and pumps makes them suitable for VFD. According to the fan and pump affinity laws, the fan or pump power has a cubic relationship with the motor speed. Therefore, significant power savings could be achieved by better motor speed control (Li, 2015).

Variable speed compressors

There are several types of compressors in the HVAC segment, and the most significant are reciprocation, screw, scroll, and centrifugal. Refrigerant compressors are typically used in air conditioners, air-handling units (AHU), or chillers in residential and commercial buildings.

Using VFD compressors in the HVAC system gives better control to closely match the cooling and heat demand. Traditionally, the system would use a fixed-speed compressor, which only turns on and off. On/off operation would lead to poor control and inefficient systems. Other advantages of variable speed drivers are energy savings and increased efficiency of systems, matching the speed of the drive to the process requirements, matching torque or power of a drive to the process requirements, reducing mechanical stress on machines, and lower noise levels.

Lim et al., (2019) experimentally verified the energy savings of a VFD compressor in an air conditioner system. They compared it to the constant-speed air conditioner for Korean and Saudi Arabia climates throughout the year. The energy savings of the VFD air conditioner largely depended on the temperature and cooling load changes for a day or season. It was observed the inverter energy savings were 18.3–47.1% and 36.3–51.7% during the Riyadh's (March–November) and Seoul's (June–September) cooling months. The authors estimate the payback time to be around 2.5 years.

Variable speed fans

Fans are used for many purposes in HVAC systems, and two of the most common use cases are free discharge fans and ducted fans.

Free discharge fans discharge to the atmosphere or an open environment and do not have any fixed pressure component. Traditionally, large discharge fans used constant-speed motors with on/off control or two-speed motors. Due to the no fixed pressure components to the fan, it is well suited for the energy savings potential given by VFDs. Some examples are cooling tower fans and small fans inside thermal units, such as fan coils, water-source heat pumps, and variable refrigerant flow terminals.

Fans in ducted systems are more complicated than free discharge fans. The purpose of a fan in a ducted system is to generate pressure and airflow. Variable airflow volumes (VAV) systems regulate the airflow to the zones in the building depending on the operation. Thus, the load on the fan makes it suitable for VFDs.

Braun et al. (2016) investigated VFDs on the supply fans for two air handler units that regulate airflow throughout the client's office building located on a brewing facility campus. The supply fans operate at full capacity, regardless of occupancy in the building. The authors used industry simulation and estimating software to develop a VFD schedule to determine the capacity for operational cost savings for these air handler units, based on occupancy of the building. The analysis results show that implementing VFDs on these two air handling units can reduce operational HVAC costs by 18%.

Variable speed pumps

Pumps are used to increase the pressure to make working fluids (for example, water) flow through HVAC components. Previously, multiple pumps of decreasing sizes were manifolded. With lower loads on the system, the controller turned another smaller pump on and the larger pump off. Manifolding multiple, constant-speed pumps was complex and challenging to control. Introducing a VSD creates a continuously working range. Some possibilities to control the speed pump are constant pressure control at the pump or the end of the system or critical valve reset.

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)	Highly dependent on operation and load profiles
Quality of scope 2 emissions information	M
TRL level	8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	<1 year to 5 years, highly dependent on the operation

12 OTHER/ANCILLARIES

12.1 Building fabric optimisation

The building is enclosed between the internal and exterior environments by the building envelope, which is made up of the walls, windows, and foundation (Cheekatamarla, et al., 2022). Energy utilization in buildings is heavily influenced by energy losses through building envelopes. Building energy efficiency standards, establish minimal standards for newly constructed and refurbished buildings. Depending on the building applications and regions, different minimum efficiency standards apply. These regulations also demand that buildings be airtight, which goes along with the requirements to reduce energy losses caused by the heat transmission via building envelopes. In The UK, current non-domestic new builds have a maximum wall insulation U-value of 0.26 W/m^2K.

Thermal insulation is used to minimise heat through the walls of a building. Due to the larger surface area, walls tend to lose more energy than any other part of the building exterior. Thermal insulation materials are used in building envelopes and can be added to walls to retrofit existing buildings. The thermal performance of insulation can be defined by its R-value (RSI value in SI units) which is the resistance to heat transfer (larger value more thermal resistance, better insulation) or U-value which is the opposite (U-value = 1/R). According to UK Building regulations (Revised 2022 Part L Target Thermal U-Values), new commercial wall fabric shall have a U-value of no more than 0.26 W/m^2K (RSI value of 3.85).

Hill (2016) modelled heat transfer in a supermarket. He showed that current design practice does not consider the cooling effect of the refrigeration. Recognition of the cooling impact of refrigeration cabinets on the retail floor, and modelling, accordingly, have shown that, contrary to current design practice, there is a significant energy saving advantage to be gained from increased levels of insulation. When the refrigeration is modelled as a cold source, as it will be for "remote" refrigeration. The dominant factor in this is the demand for heating in the store, which rises as the insulation level falls (and therefore as the U value rises). Other elements of energy demand are not seen to change significantly. A reduction in U value from 0.25 to 0.125 W/m^2 K would deliver a saving of 3% in the energy demand of the retail floor.

To meet the demands of the upcoming zero energy and zero emission buildings, thicker building envelopes are needed when applying standard thermal insulation materials. In Europe, targeting to an average U-value close to 0.2 $W/m^2{\cdot}K$ is optimal (Adl-Zarrabi, 2020). Using traditional insulation materials this means an insulation thickness of about 20 cm. There is a need to develop high performance thermal insulation because very thick building envelopes are not desirable (Jelle, et al., 2014).

The following is a discussion of several high-performance thermal insulation materials, dynamic insulation materials, novel building envelope designs to redirect thermal energy, and high thermal mass building envelopes.

a) Vacuum insulation panels

Typically, vacuum insulation panels (VIPs) are made of a laminated metalized polymer laminate film covering an open porous core of fumed silica or fibrous material. Non-aged centre-of-panel thermal conductivity value for a VIP can be as low as 2 to 4 mW/m·K depending on the core material (Adl-Zarrabi, 2020). Commercially available products (Kingspan OPTIM-R) quote an aged design value thermal conductivity of 0.007 W/m·K.

According to Simões (2021) to achieve a U-value (takes into account thermal bridging) of 0.24 W/m^2K would require an encapsulated VIP of thickness 40 mm and to achieve a U value of 0.12 W/m^2K would require 75 mm. The equivalent thickness of Expanded Polystyrene (EPS) thickness would be 127 and 272 mm respectively. The insulation cost of VIP is 3000 €/m^3, with an installation cost of 62.5 Euro per m^2 and a service life of 25 years. Compared to 120 €/m^3, 50 €/m^2, and 25 years respectively for EPS.

b) Aerogel

Aerogel is a synthetic, porous, extremely light substance. Without the gel's structure significantly collapsing, the liquid component is replaced with gas. This results in a solid with an incredibly low density and thermal conductivity (Berardi, 2019). Aerogels have a large specific surface area, a very low apparent density (Meliță et al., 2019). Thermal conductivities of the aerogel board was reported as 15-17 mW/(m·K) (Adl-Zarrabi, 2020).

Aerogel-based blankets, where aerogel is coupled with a fibrous matrix, have been used in buildings for both internal and external insulation of the walls since the early 2000s (Adl-Zarrabi, 2020). Case studies showed that aerogel blankets are possible to install in up to five layers (50 mm) without too much difficulty.

When used as a retrofit solution 35 mm of aerogel has the same insulating effect as 82 mm of polyurethane. The cost of retrofitting aerogel is 45% higher than the average of other types of insulation (Orsini, 2020).

c) *Active and thermally anisotropic insulation*

The capabilities of the building envelope can be increased by controllable active insulation systems (AISs), which allow the thermal resistance of the insulation material to be dynamically regulated within a defined range. With AISs, the building envelope may be used to manage heat transfer rather than acting as a passive barrier between indoors and outside. Additionally, AISs can function as thermal batteries that can be loaded and discharged on demand when paired with the thermal mass in the envelope system (Antretter, et al., 2019). Cooling during peak load hours in Los Angeles could be reduced by more than 80% without a negative impact on thermal comfort conditions.

Kisilewicz (2019) present results from a thermal barrier or active thermal insulation system of pipes placed inside the structure of an external building envelope in which a heating and cooling medium circulates, supplied with low temperature energy from the ground. The effective operation of active thermal insulation is possible due to the energy from the building partitions that is stored in the ground. During the summer, thermal energy received from the partitions is stored in the ground, and during the heating season, it is then returned to the interior of the partitions, creating a layer of elevated temperature, or a 'thermal barrier'. In the analysed periods, the reduction of the total amount of heat loss through external walls was from 53% in February to 81% in November.

Biswas, et al (019) carried out numerical simulations of thermally anisotropic building envelope (TABE). These add thin conductive layers between the insulation (shown in Figure 41). The conductive layers are linked to a thermal loop that sends thermal energy (heat or coolness) to a system for energy storage or other applications. The indoor environment is then heated or cooled using the stored energy. Sensors and controllers are used to maximize energy savings or peak load reductions.

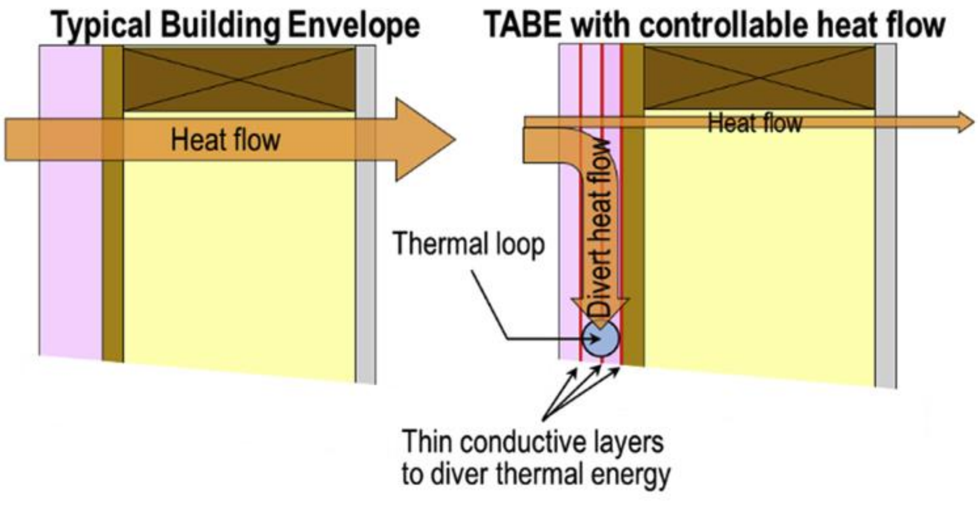


Figure 41. Thermally anisotropic building envelope.

Combined FEA and EnergyPlus^{TM} simulations of a typical two-story, single-family residential building, predicted annual savings of 19-26% in cooling energy use and 13-26% in heating energy use under Phoenix and Baltimore weather conditions.

e) *Phase change materials*

Phase change materials (PCMs) can be integrated into building envelopes. PCMs react to temperature changes by passively charging and discharging. They can move peak cooling or heating to off-peak hours depending on the PCM formulation, but they cannot regulate the timing of charging or discharging (Harris, C., 2019).

Konstantinidou (2019) carried out life cycle cost implications of integrated phase change materials in office buildings. They found that the energy saving achieved (18%) during the use stage cannot compensate the high cost of construction (80% higher). Based on the results, a price reduction of 30% in PCM would be required to bring their use up to parity with conventional materials.

Scope 1 emissions savings (% or another quantifiable metric)	No information available
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	A reduction in U value from 0.25 (similar to current maximum value allowed) to 0.125 W/(m^2 K) would deliver a saving of 3% in the energy demand of the retail floor If thickness of insulation was the limiting factor, then advanced building insulation would save emissions. However, it is more likely that the buildings are constructed to building codes and minimal cost. In which case advanced insulation is more expensive for equivalent insulation effectiveness
Quality of scope 2 emissions information	High
TRL level	TRL7-9 for increasing U-value by conventional means
Maintainability issues	No issue
Legislative concerns	No concern
Payback time (years)	Payback is generally negative

12.2 Building glazing optimisation

Glazing allows for entry of daylight and as such reduces the need (and energy use) for artificial lighting. However, glazing is also one of the weakest thermal points on a building and contributes significantly toward heat losses (or undesired heat gain). As much as 10 to 20% of a buildings heat loss can be attributed to glazing (Pacheco et al., 2012a). Therefore, improved glazing systems may play a vital role in the strive towards low-to-zero carbon food service facilities.

The thermal properties of a window is described by the key parameters U-value and G-value. U-value, or total heat transfer coefficient, is a measure of how effective an insulator a material is. For materials typically used in buildings, Cuce & Riffat (2015) reports that average U-values are 0.25, 0.16, 0.30 and 2.00 W/m^2K for floor, roof, external walls and windows respectively. If a building is to attain the requirements of the Passivhaus Standard, in which the space heating/cooling should be less than 15 kWh/m^2/year, it requires that glazed elements should have a U-value below 0.85 W/m^2K. The G-value, or Solar Heat Gain Coefficient (SHGC), is the transmittance of energy as a result of solar radiation and is represented as a ratio between 0 to 1 where 1 is the maximum amount of solar heat allowed through a window, and 0 is the least. Typical values range between 0.2 and 0.7 (Aguilar-Santana et al., 2020).

A number of reviews on glazing technologies have been identified in scientific literature (Aguilar-Santana et al., 2020; Cuce and Riffat, 2015; Jelle et al., 2012; Pacheco et al., 2012b). The reviews cover a large list of glazing technologies, ranging from uncoated single glass static configuration to active technologies (integrating movable/switchable devices) for shading and energy harvesting purposes. In terms of energy efficiency, most of the literature is focused on the U- and G-values attainable by the different technologies, but also the VT-value (visible transmittance) which is an optical parameter describing the allowance of visible light through windows: high VT means more daylight and therefore a reduction in electric lightning and heating loads.

Multipane glazing effectively introduces an air gap between two (or more, seldom more than 3) panes which acts as a thermal insulation layer, thus reducing heat transfer through the window. Compared to single-glazing, heat losses may be reduced by 50% (Aguilar-Santana et al., 2020). Replacing air with other gases, e.g., noble gases such as Argon, Krypton or Xenon, may improve the insulative properties even further due to their lower thermal conductivities (Cuce and Riffat, 2015). Double and triple glazed multipaned glazing constitutes the majority of existing high-performance technologies since they are cost-effective, but vacuum glazing and aerogel glazing are expected to increase the market share going forward due to remarkably lower U-values (around 0.3 W/m^2K). Low emissivity (low-e) coatings can be applied to the internal glass surface to reduce heat loss by reflecting interior long wave infrared, while still allowing visible light and short infrared to pass through and is thus beneficial for colder climate regions. Electrochromic is an example of a dynamic glazing technology, also referred to as "smart windows", where the VT and G-value can be adjusted by applying small amounts of voltage. Compared to the low-e coatings that are designed for certain conditions, this technology allows a more dynamic control over transmittance properties which can improve energy savings. Another novel technology is utilizing phase change materials (PCM) in windows, enabling storing and releasing of heat and thus able to reduce heat losses during winter and heat gains during summer.

Energy saving in buildings is an important area in which emission reductions can be achieved. By optimizing a building envelop, and in particular the glazing, is a viable route to achieve such savings. However, a balance must be struck between allowing transmittance of natural daylight which generates savings on energy use for artificial lightning (and gives biological benefits for humans) and energy savings due to reduced heat loss or gain. Thus, the type of building and climate region plays a vital part in the design and choice of glazing technology. As for emission savings, they are directly linked to the potential savings of energy use, which implies that the energy sources carbon factor also needs to be considered for quantification. For examples of energy efficiency improvements, the reader is referred to (Hee et al., 2015).

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)	n/a
Quality of scope 2 emissions information	n/a
Availability barriers	None
TRL level	8-9
Maintainability issues	Dependent on solution

Legislative concerns	None
Payback time (years)	Dependent on solution

12.3 Building lighting efficiency

Improving energy-efficiency in buildings has been major focus area for retailers over time, as one of the cheapest ways of reducing both costs and carbon emissions (European Parliament, 2010).

Ferreira et al. (2020) studied the policy, strategy and building practice of the best EI and CI (energy and carbon intensity) performing retailers in comparison with the worst performing ones, this study set out to identify the measures that contribute most to the retailers' enhanced environmental performance like energy and carbon. As for building practice, LED and photovoltaic technology are amongst the most popular high performance sustainable solutions. LED lighting systems can reduce energy consumption by 50% when compared with fluorescent T8 lighting (Schönberger et al. 2013). Despite this the greatest difference between best and worst performing food retailers was found regarding natural refrigerants (p = 0.001).

The efficacy of LED products has steadily improved since their introduction as a source for general illumination. This trend is expected to continue, thanks to new materials, better manufacturing processes, and new configurations. However, the variability in LED products is greater than for the more mature technologies and the products are changing rapidly. Importantly, efficacy should not be the only factor when comparing products. Other performance characteristics, such as colour quality, luminous intensity distribution, and dimmability must be included in a holistic decision. Although high efficacy is an important attribute for energy savings, it is imperceivable to the users of a space. https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/led_energy_efficiency.pdf

Generally other energy saving light systems are daylight harvesting, motion sensor lighting (light on demand) and dimmable lighting (Ferreira et al., 2019).

Lighting energy can generally be reduced by 40–80% by installing more efficient lighting fixtures, improved lighting controls and taking advantage of daylight where available (Fedrizzi & Rogers, 2002).

Richman and Simpson (2016) further reported that choices of rotating fixtures 45-degrees and hanging them closer to the floor can reduce costs whereas light levels were not impacted. Occupancy sensors in offices and warehouse spaces didn't have any impact.

Case study

Meijer operates more than 240 super centres and grocery stores across Michigan, Ohio, Indiana, Illinois, Kentucky and Wisconsin. With the conversion to LED, Meijer said it expects to cut the electrical power use of its store lighting by as much as 50% annually. The LEDs — supplied by GE lighting, Cooper and Phillips — will replace all in-store interior lighting, including ceiling and spotlight illumination. https://www.dbusiness.com/daily-news/grand-rapids-meijer-to-transition-to-led-lighting-by-2021/

Smart (wireless) lighting

https://www.gecurrent.com: A connected lighting system with advanced sensors and controls can communicate with networked devices throughout a store to enable exciting outcomes—from helpful wayfinding to high accuracy indoor positioning, to heat mapping analytics that help drive conversions. For example, occupancy and heat mapping data enabled by intelligent light fixtures can determine which aisles are the most trafficked, or when extra staffing is needed in checkout ahead of the long lines. This enables retailers to improve operational efficiencies and the shopper experience. Smart light fixtures can identify repeat customers by their smartphone and provide incredible insights on shopping decisions, dwell time and the path to purchase. As automated checkout, personalized discounts and smart shelves become the norm, smart lighting can support a variety of IoT use cases and countless applications yet to come.

New cloud-based, remote access, wireless control, monitoring and management systems for indoor lighting are now meeting the demand of retailers. Such systems give users the freedom to commission, configure and control lighting with multi-site control from a single hub. Usage patterns can be managed to enable the most effective energy strategy to be implemented. Luminaires can be switched or dimmed collectively, or individually, and scheduled to activate lighting when needed. Information on testing for audit tracking and energy hotspots can also be accessed. The bottom line is that wireless lighting control systems open up significant opportunities for stores to save energy.

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)	LED lighting systems saving energy by 50%
Quality of scope 2 emissions information	Verified in the peer-reviewed engineering literature
TRL level	8-9
Maintainability issues	None anticipated.
Legislative concerns	Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings
Payback time (years)	Variable.

12.4 Maintenance and operational practices

Several authors have reported that maintenance and operational practices can significantly reduce energy used in kitchens. For example, Paillat (2011) found that replacing two hot plate range tops by a solid top and an induction range top enabled 38% energy savings. Moreover, training of personnel reduced total energy used by cooking appliances by 7%. In the study it was often found that cookers were not switched off when not in use.

Mudie et al (2016) also found that fitting simple and inexpensive time clocks or motion sensors to heat-lamp gantries could yield substantial savings with relatively short payback times. In their work they pointed out that such advice had been provided by Batty et al (1988) over 3 decades ago but had not been implemented. The authors considered that this was a reflection on the lack of investment in energy saving within the industry.

Mudie et al (2016) highlighted that behavioural factors and poor maintenance were identified as major contributors to excessive electricity usage with potential savings of 70 and 45%, respectively. They stated that Initiatives are needed to influence operator behaviour such as strict protocols, better feedback and behaviour change campaigns. They also suggested that more appropriate sizing of equipment may also have significant benefits.

Food waste is an area where operational practices can have significant savings. In a study in 6 countries for WRAP and WRI Clowes et al (2018) found that by measuring waste, engaging staff and general better management that the average benefit-cost ratio for food waste reduction was more than 6:1 over a 3-year time frame. They also found that investment was recouped within 1 year for 64% of sites and within 2 years for 80% of the sites examined. Most of the investment was between $10-15k and consisted of purchasing smart scales or similar measurement technology and training of staff.

Scope 1 emissions savings (% or another quantifiable metric)	No metrics in terms of carbon saved through food waste reduction but food waste can be reduced by up to 21%
Quality of scope 1 emissions information	Significant saving in waste from better operation, training and management.
Scope 2 emissions savings (% or another quantifiable metric)	45-70% of energy used by individual equipment
Quality of scope 2 emissions information	Medium
TRL level	TRL8-9
Maintainability issues	No issue
Legislative concerns	No concern
Payback time (years)	Can be short, depends on exact application

12.5 Renewable energy (solar electricity)

The overall push for renewable resources will drag the whole food sector towards a higher share of renewable use through, for instance, the use of more renewable electricity, an increased use of renewable heat or biofuels in machinery operations and transport (Monforti-Ferrario et al., 2015). EU solar energy has a significant potential to rapidly become a mainstream part of power and heat systems and a main lever to achieve the European Green Deal objectives. As part of the REPowerEU plan, the strategy aims to bring online over 320 GW of solar photovoltaic by 2025 (more than doubling compared to 2020) and almost 600 GW by 2030 as declared in EU Solar Energy Strategy (COM, 2022). Large-scale deployment of PVs will reduce the reliance on natural gas used to produce power. Solar energy in the form of electricity, heat or hydrogen can replace natural gas consumption in industrial processes.

The electrical energy supply technologies chosen to reduce environmental impacts and to obtain the zero energy and near zero climate change impact DC network were new solar panels installed on the building rooftop and available electricity from new wind turbines at the nearby locations (Burek and Nutter, 2019). Flat roofs are ideal for solar panels, but available space is less than the total building roof. Thus, the total roof area available for installation of solar panels was assumed to be 75% of building area. In addition, building’s flat roof will typically contain mechanical equipment, such as HVAC, refrigeration, and more (Burek and Nutter, 2019). Adding onsite solar PV system can achieve net-zero energy design for the retail building (Syed and Hachem, 2019). Burek and Nutter (2019) concluded, that in an effort to identify reduction opportunities from electric grid dependency of buildings, this study analysed the replacement of fossil fuel derived electricity with an optimal combination of wind and solar energy. Renewable energy sources were shown to be beneficial in building sustainability in certain locations. However, a solution that worked for one location did not work for other locations in terms of wind-to-solar energy ratio and their cost-effectiveness. Solar energy production for internal uses was identified as a major opportunity for sustainable agriculture-based social structures and it remains a promising and developing sector, also thanks to the recent massive decrease of PV panel costs (Monforti-Ferrario et al., 2015).

According to Jiang and Tovey (2009), to achieve low carbon sustainability in large commercial buildings five aspects should be considered: awareness raising, energy management system, energy saving technologies, deployment of renewable energy and offsetting methods as a last resort.

Energy efficiency is the consensual priority amongst retailers when introducing sustainable high-performance solutions in their stores. This is largely because of the potential high cost savings and because energy efficiency contributes to the reduction of GHG emissions. Reducing energy demand ultimately means an increase in efficiency through a reduction in waste. The most common energy efficiency solutions used by retailers are economically driven: photovoltaic energy produced on site, green energy offsetting, LED lighting and energy management are the most popular measures cited by retailers. In fact, building commissioning can account for 16% energy savings for existing buildings and 13% for new construction (Ferreira et al., 2018). At the food retail and distribution level, grocery stores and supermarkets can adopt many of the same energy-efficiency practices and technologies as industry—including those for refrigeration and lighting (Sovacool et al., 2021). Cold storage and refrigeration are needed at each stage of the food chain to increase shelf life, cut losses, and maintain the quality of products made from crops, livestock and fisheries. Cooling is an energy-intensive process presenting both a challenge and an opportunity. The cold chain, including industrial and domestic refrigeration, already accounts for 5% of global GHG food-system emissions and its importance in total emissions is likely to increase (Tubiello et al., 2021). If the increase in future cold storage capacity were to come from fossil fuels–based systems, the resulting increase in GHG emissions would further exacerbate climate change. However, advances in renewables-based and efficient cooling systems present an opportunity to expand cold storage capacity in a way that is environmentally sustainable and more accessible, particularly in rural areas (IRENA and FAO, 2021). While the emission amount of the PV panel given to the environment for 17 years is 201.4 kg CO_2, the emission amount released to the environment to generate the same amount of electricity is determined as 1918 kg CO_2 in the natural gas power plant. Thus, it is understood how environmentally friendly the PV panels compared to other energy sources. PV panel provides savings in the amount of 1.72 tons CO_2 emission compared to the thermal power plant (Yıldız et al., 2020). PV electricity contributes 96% to 98% less greenhouse gases than electricity generated from 100% coal and 92% to 96% less greenhouse gases than the European electricity mix.

Ferreira et al. (2018) investigated carbon (CI) and energy intensities (EI) of food and non-food retailers resulting in “best practice” and “conventional practice” benchmarks for the two groups. Concerning EI, food retailers' “conventional practice” ranged from 346 to 700 kWh/m^2/y, with “best practice” located below a 346 kWh/m^2/y threshold. Non-food retailers' “conventional practice” ranged from 146 to 293 kWh/m^2/y, with “best practice” located below a 146 kWh/m^2/y threshold. Hence, the best “conventional practice” mark of the non-food retailers is approximately half that of the food retailers. Variability in food retailers was almost double that of non-food retailers. This can be explained by refrigeration systems which in retail stores can account for up to 50% of energy consumption. Concerning CI, food retailers' “conventional practice” ranged from 115 to 420 kg CO_2eq/m^2/y, with “best practice” threshold found below 115 kWh/m^2/y. Non-food retailers' “conventional practice” ranged from 70 to 177 kg CO_2eq/m^2/y, with “best practice” threshold found below 70 kWh/m^2/y. Electricity can be responsible for up to 60% of the carbon emissions in food retailers (Ferreira et al., 2018).

A study on the profitability of commercial self-consumption solar installations in the supermarkets sector led in three German supermarkets showed the profitability of these kind of systems if the costs of the PV systems decrease between EUR 200/kWh and EUR 600/kWh. Since energy consumption is largely due to refrigeration, energy uses are more relevant during the summer season. Two different stores, typical of Italian territory, were used for testing the methodology proposed: a quite large store and the typical local store. The first has a total surface of about 20,000 m^2 while the second has a total surface of 4830 m^2. In the first case the size of the PV plant can range from a minimum value of less than 500 up to 2100 kW, while in the local store, the PV plant size ranges from 80 to 320 kW. In both the cases, the share of the energy produced with the PV plant moved from about 20 up to 70%, if a storage system of relevant size was used. The energy storage could be interesting both to use the energy in excess produced during the day and it can also help with the fluctuating energy supply and demand. In all the cases considered it was possible to use the roof surface of the store for installation of the PV plant. In general, it appears to be quite easy to define a PV plant that could be able to produce energy for the seasonal peak and covering an amount of the energy required for the whole year in the range between 40 and 60% of the total yearly energy required (Franco and Cillari, 2021). Sovacool et al. (2021) estimated energy savings, carbon savings, and payback periods for the food and beverage industries of Austria, France, Germany, Poland, Spain, and the United Kingdom and find out, that solar PV installation payback period is 13.7 years.

Concerning on-site generation by PV panels, bioenergy CHP engines, solar thermal panels in small stores, biomass boilers in medium sized stores and ground source heat pumps technologies, during their gradual deployment across the estate UK would enable the supermarket chain to generate 17% of its energy requirement on site by 2030 (Caritte et al., 2015).

The use of renewable energy sources at retailers is widespread throughout Europe. Many stores are installing PV-panels on roofs, with electricity generation values varying from 5 to 80 kWh/m^2 yr (sales area). Nevertheless, retailers rarely install renewable energy facilities in an integrative manner, i.e. combined with measures to reduce the energy demand and increase the efficiency of current systems. Although almost all retailers in Europe have invested in zero energy or carbon stores applied in one or two stores as lighthouse projects, the systematic implementation of integrative concepts to achieve zero energy building as standard practice is still some way off. Then, the production of renewable energy on site is not considered as a best environmental management practice per se: it should be combined in an integrative approach (Galvez-Martos et al., 2013). Main barriers for the adoption of the described practices can be summarized as follows (Galvez-Martos et al., 2013):

– the relatively low importance of energy costs within the total operational costs of retailers reduces the economic attractiveness of energy saving measures. The most effective measures have the best performance in the long-term. Then, payback time policy (e.g., only to implement projects with payback times shorter than 3 years) can make them unaffordable. As well, subsidies received for the implementation and use of renewable energy sources can make some measures, such as the installation of PV panels on roof, much more economically attractive than other measures reducing the overall energy demand of the building. This effectively leads to the offsetting of excess primary energy consumption, rather than the optimum two step approach of (i) reducing demand by increasing efficiency; (ii) increasing the share of cleaner energy sources.

–building characteristics are only partially under the control of retailers. Several chains in Europe have a high percentage of rented stores and they are limited in the changes to the building envelope and installations by lease agreements.

–for some techniques, like natural refrigerants, two barriers are relevant: first, the lack of suppliers seriously constrains the uptake of novel technologies in some European regions; and second, the demand for technical skills and training associated with innovative applications can reduce the rate of uptake of techniques.

Consumer demand is a major driver of the adoption of corporate environmental sustainability (CES) strategies. Incentives such as tax rebates for recycling waste, constructing energy-efficient buildings, and adopting greener alternatives (e.g., solar panels, fuel-efficient vehicles), can also be more coercive for CES adoption. There is some evidence to suggest that CES will progressively become a strategic management issue for retailers rather than a cost saving and marketing incentive, as companies better understand the multiple value creation options it can bring. However, there is currently very little literature to substantiate or find ways to catalyse such phenomena (Naidoo and Gasparatos, 2018).

Presently, the RES use for on-site power generation, especially through solar photovoltaic systems, appears to have gained more ground than RES-powered thermally driven refrigeration systems, as far as large refrigerated warehouses are concerned. There is significant progress in roof mounted photovoltaic systems powering conventional vapour compression refrigerating units (Fikiin et al., 2017).

Installing large amounts of solar PV to drive heating, ventilation, air conditioning and refrigeration (HVAC&R) processes, however, is not an optimal solution. Foremost, HVAC&R processes often require 24/7 operation with solar providing only intermittent power during daylight hours (ARENA Project, 2022).

Results for the reference case in north-eastern Italy show that PV installation with a min cost optimization can lead to both reduced yearly total cost (-1.3%) and energy savings withdrawal from the grid (-16.4%), thus embracing the economic and environmental dimensions of sustainability. The introduction of PV generation in storage facilities leads to both economic and energy saving benefits, while providing more flexibility on designing and controlling the whole cold chain. Results obtained by the proposed optimization model highlight that a cost-efficient integration of photovoltaics with automated storage facilities is achievable. The obtained 16.4% energy demand reduction with PV installation for a typical automated warehouse within the cold chain can effectively contribute to achieve the 5–10% energy intensity reduction expected by the SE4All goals. Furthermore, combining the integrated PV with various demand-response strategies, smart-grid and intermediate energy storage systems can lead to further energy savings, thus representing a promising future research field to be investigated (Meneghetti et al., 2018).

The design of PV plants to support the operation of energy systems for the food store, with different objectives is proposed. In general, it appears to be quite easy to define a PV plant that could be able to produce energy for the seasonal peak and covering an amount of the energy required for the whole year in the range between 40 and 60%. The smooth trend of energy demand, with peaks in the middle part of the day, reflects how these kinds of building perfectly suits for a deep integration of RES electrical systems. A full self-consumption (98-99%) can be reached by sizing the PV plant according to the minimum daily consumption and considering the summer solar irradiation condition. Moving to other reference for sizing, as the weekdays average hourly base or a share (70%) of the total annual energy demand, including this time the local average solar irradiation, a reduction of 20% of the self-consumption occurs, but the self-sufficiency increases around 100%. Results show that a high percentage of self-consumption can be achieved, and that a battery storage set at a mean daily PV potential production level (4 kWh/kW in the case) perfectly suits to reach a self-sufficiency between 50-70%. Retail and food stores have proven to be a perfect promoter for PV diffusion either in a high self consumption configuration, or turning them into energy hub for mobility to building or energy sharing policies (Franco et al., 2021).

The use of both on site and offsite solar PV to power stores is increasingly common. Solar PV is well suited to the higher daytime loads that food and grocery stores are subject to. There are opportunities to take advantage of existing thermal mass and store energy via refrigeration in cold storage. This can be further added to using phase-change materials (PCM including ice). PCM thermal energy storage together with a refrigeration system can be used to store substantial renewable energy generated by solar PV. There is also likely to be an increase in the integration of electric batteries into refrigeration systems, as the economics of batteries steadily improves (Xia et al., 2016).

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)	PV electricity contributes 92% to 96% less greenhouse gases than the European electricity mix.
Quality of scope 2 emissions information	Verified in the peer-reviewed environmental engineering literature
TRL level	8-9
Maintainability issues	Low
Legislative concerns	COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. EU Solar Energy Strategy. {SWD (2022) 148 final}. Brussels, 18.5.2022. COM (2022) 221 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN
Payback time (years)	Dependent on technological solution and electricity prices. Typically (without financial support instruments) 13.7 years.

12.6 Renewable energy (solar thermal)

Solar heat and solar power combined with heat pumps can replace natural gas boilers for heating in residential or commercial spaces. Solar energy in the form of electricity, heat or hydrogen can replace natural gas consumption in industrial processes. Solar energy systems have long been a low-cost and reliable solution for heating in many European countries but overall solar heat accounts for just around 1.5% of heating needs. To reach the EU 2030 targets, energy demand covered by solar heat and geothermal should at least triple (COM, 2022). Solar energy can also provide industrial heat, which accounts for 70% of industrial energy demand. Based on solar collectors or concentrated solar, solar heat can deliver heat for industrial processes from 100 to over 500°C. Nevertheless, the potential of solar heat for industrial processes is still largely untapped. Two of the main obstacles it faces are administrative hurdles and the gap between the payback times of these investments and the financial requirements of most industrial actors (COM, 2022).

To decrease GHG direct emissions, namely stationary combustion for comfort heating, food retailers can recover waste heat from the refrigeration cycle, hence suppressing the need for additional store heating. To address fugitive emissions resulting from unintentional release of GHG from refrigerant systems, retailers can invest in gas leakage detection and improved maintenance in HVAC and refrigeration systems. The later can minimize food retailers' carbon footprint by up to 30%. Gas transfer to CO_2 in refrigeration systems also ranks high for European food retailers, because of its impact on the company's overall carbon footprint. In addition, to decrease GHG indirect emissions from the consumption of purchased electricity, retailers can invest in on-site production of renewable energy, in the purchase of green energy or in offsetting methods. Energy efficiency solutions minimising energy consumption are the first step to decrease emissions from the electrification process (Ferreira et al., 2018).

Mekhilef et al. (2011) have reviewed the possible uses of solar energy in industry, showing its special suitability when a constant flow of moderate heat (80-120 °C) is needed.

Sovacool et al. (2021) estimated energy savings, carbon savings, and payback periods for the food and beverage industries of Austria, France, Germany, Poland, Spain, and the United Kingdom and find out, that energy generation from solar heat payback period is 14.9–45.9 years.

Spain's National Confederation of Installers has published a technical paper about the potential of solar-powered heat pumps in the Spanish energy market. A residential PV system deployed without a heat pump in Spain has a payback period ranging from 6 to 10 years but coupling the array with a heat pump means it can be repaid in less than 5 years. In addition, if the heat pump produces hot water for a household, works efficiently for low-temperature systems such as radiant floors, and also produces cooling during the summer, the payback time could range between 2 and 3 years (CNI, 2022).

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)	30%
Quality of scope 2 emissions information	Verified in the peer-reviewed environmental engineering literature
Availability barriers	High capital costs. Administrative hurdles. High payback time.
TRL level	8-9
Maintainability issues	Many technological processes are required.
Legislative concerns	COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. EU Solar Energy Strategy. {SWD(2022) 148 final}. Brussels, 18.5.2022. COM(2022) 221 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN
Payback time (years)	Dependent on solution, heat prices and geographical location. 2-4 up to 46 years.

12.7 Packaging – low carbon options

Directive 94/62/EC on packaging and packaging waste (PPWD) with amendment (Directive EU/2018/852) sets out the EU’s rules on managing packaging and packaging waste. Aim is at least 65 weight percent of all packaging waste is recycled (by December 31st 2025) and at least 70 weight percent of all packaging waste is recycled (by December 31st 2030°.

Recyclable means that packaging materials can be separated from waste flows and can be reused (circular economy).

A recent study (Qin and Horvath, 2022) showed that in the farm food production packaging contributes 11-31 % to the total GHG emissions. These are the results of a model to estimate the GHG emissions from the entire food cycle (production, packaging, transportation, refrigeration, and waste management).

Packaging's carbon footprint is calculated by measuring GHG emission generated during production processes. Paper and cardboard as raw materials have a smaller environmental impact compared to plastic. Plastics can be fossil based (raw material is oil) or biobased (raw material is starch (potato or corn) or sugar from vegetables.

Other processes that have an impact on GHG emission are transport (raw materials to factory, to storage facility and to end consumer) and useful life (reusable, possibility for recycling or composting (biodegradable)). Some fossil-based plastics are not compostable (LDPE, MDPE, HDPE, PP, …) but recyclable; other fossil based (bio polyester, PBAT) are compostable.

Some biobased plastics with corn, sugar, starch, sewage sludge, (PLA, PHA) are compostable. Other biobased plastics (Polyethylene, natural rubber, nylon types) from corn, sugar, starch is not compostable but often recyclable.

Avoiding overpacking is the most important measure in reducing the GHG emission. Innovative and new technologies for sustainable materials and for expanding the range of biodegradable materials resulting in a circular economy are necessary. Aim is to extend packaging life and avoiding problem plastics that in combination with other materials and types non-recyclable material cannot be reused.

Innovative technologies and practical applications

Papkot ™ (France) (www.papkot.com) offers a 100 % paper salad bag. This paper bag is plastic free coated and is biodegradable and home compostable.

FunCell (Functionalization for Cellulosic materials) (https://funcell.fr) is extracting from biomass a polymer that is used as additive for cellulosic materials (paper, cardboard, ...). Paper coated with this biosourced additive can replace plastic offering water barrier, grease barrier.

Biotec (https://www.biotic-labs.com) uses macroalgae to create fully biobased, fully biodegradable PHBV polymers. It realizes a transition from fossil-fuel plastics to a fully biological process with zero waste and a circular economy approach.

Traceless (www.traceless.eu) uses natural biopolymers in agricultural industry residues for the production of bio-circular and plastic free materials.

Recup (www.recup.earth) produces paper cups coated with EarthCoating® an innovative barrier coating that replaces 51 % of the plastic with minerals. So the cup can be recycled as paper.

Smurfit Kappa (www.smurfitkappa.com) developed a water-resistant paper developed: AquaStop™.This paper can be recycled as paper and offers a sustainable alternative to single-use plastic.

Circleback (https://en.circleback.works) is a company that offers a closed-loop system for packaging through a deposit system. It gives brands access to high-quality recycled plastic made from their own packaging.

Shellworks (www.theshellworks.com) produces biopolymers extracted from seafood waste (film applications) and after use can be dissolved in hot water.

Woola (www.woola.io) makes packaging of leftover sheep wool. It offers an alternative to the plastic bubble wrap. Bubble wool is a sustainable way for packaging fragile objects also wool envelopes or bottle sleeves are possible.

Alpla (www.alpla.com) reinvigorates paper bottle mission with new fibre screw caps partnership.

Frugalpac™ (https://frugalpac.com) is a sustainable packaging company that creates and supplies recycled paper-based bottles and cups for food and drinks industry. (for example gin in Frugal paper bottles).

Schubert group launches 'mission blue' : a sustainability initiative for packaging systems to achieve a circular economy.(https://www.schubert.group).

Sorma Group (https://sormagroup.com) produces Sorma Papervertbag, a plastic free traditional net packaging for fruit and vegetables by using fsc paper and cellulose.

KX Pack (http://kxpack.eu) introduces compostable packaging based on bagasse fiber from sugar cane waste.

PerfoN (www.perfon.nl) part of Oerlemans Packaging BV produces plastic films with laser perforations built from mono materials and 100 % recyclable.

REV Packaging Solutions (www.revsrl.com) offer monomaterial plastics for packaging (wrappings, clingfilm and packages of different art). These packages are totally recyclable.

Fonkels (https://fonkels.com) offers cardboard boxes of 100 % recycled cardboard an alternative for the plastic boxes.(for soft fruit).

Magical Mushroom Company® (https://magicalmushroom.com) (MMC) uses agricultural waste and mushroom mycelium resulting in mushroom packaging, an alternative to polymer-based plastic.

Scope 1 emissions savings (% or another quantifiable metric)	When avoiding packaging up to 100 % savings. Reusing and recycling, depending on the technology, up to 50 %
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	Directive 94/62/EC Directive EU/2018/852
Payback time (years)	Unknown

12.8 Waste technologies and impact of changes (landfill, AD, incineration etc)

Anaerobic digestion

Due to the rapid growth of the world economy and population, the amount of food loss and waste has increased significantly in the last decade. According to the Food and Agriculture Organization of the United Nations (FAO) (2019) report, about 33% of human food, totalling about 1.3 billion tonnes annually, is wasted worldwide, which has a production value of $750 billion (Pramanik et al. 2019; Mirmohamadsadeghi et al. 2019; FAO, 2019). The food loss per capita in Central and West Asia and North Africa is 6–11 kg per year, while it is 95–115 kg per year in North America and Europe (Mirmohamadsadeghi et al., 2019). Food waste (FW) occurs at all stages of the food supply chain, including agricultural processing, sorting, storage, transport, distribution, sale, preparation and serving (Xu et al., 2018). In the EU, approximately 53% of FW is generated in households, 12% in the food service sector and 5% (an average waste of 9.4 kg per capita per year) in retail (Stenmarck ir kt., 2016). Analyzing only the retail trade chain, the causes of food waste are related to the fact that many food products have a limited shelf life, constantly changing demand and quality standards of buyers. Storage conditions, packaging quality and handling practices also influence the amount of food waste generated (Monforti-Ferrario et al., 2015; FAO, 2019).

FW has a detrimental effect on the environment, so the proper management of FW has become a major goal in many countries around the world. Food waste contains high levels of moisture, volatile solids and salts, and is therefore considered as a major source of GHG emissions, odour, pest attraction and groundwater pollution. In addition, activities related to food production, such as agriculture (including land conversion), processing, manufacturing, transportation, storage, refrigeration and retailing, generate significant GHG emissions (Mirmohamadsadeghi et al., 2019; Pramanik et al., 2019). Slorach et al. (2019) reported that globally, food waste accounts for 6.7% of all anthropogenic GHG emissions annually.

Food waste can be managed in a number of ways, but anaerobic processing is one of the best alternatives to food waste management in terms of greenhouse gas emissions. One reason for this is that food waste is rich in readily available nutrients for methane-producing anaerobic bacteria. Another reason is that the main product, methane, can replace fossil fuels and the waste produced during the biogas production process (digestate) can be used as a substitute for mineral fertilizers (Chew et al., 2021; Eriksson et al., 2015; Mirmohamadsadeghi et al., 2019; Mondello et al., 2017; Moult et al., 2018; Pramanik et al., 2019).

As a renewable biofuel, biogas can play a very important role in alleviating concerns related to the rapidly increasing energy demand and the instability of the energy resource market (Mirmohamadsadeghi et al., 2019). Biogas can be used in various ways: for the production of electricity and heat by combustion biogas in cogeneration plants, supplied to natural gas networks or used as fuel in transport vehicles (Chew et al., 2021). Given the unique advantage of this renewable energy source, there has been renewed grow interest worldwide in biogas production from various organic wastes, including food waste (Mirmohamadsadeghi et al. 2019).

In the scientific literature, anaerobic fermentation is widely recognized as an economically and environmentally friendly process for the utilization of any biological waste. Studies have analysed data from store databases, delivery records, and store sales data provided by retailers. Some studies have also included onsite waste audits to measure the quantity of food waste, whilst others have conducted interviews with retail staff to obtain estimates for food waste. Based on LCA studies, it has been shown that biogas can have positive environmental impacts, including volatile GHG emissions, eutrophication, acidification, and the generation of photochemical oxidants (Albizzati et al., 2021, 2019; Chew et al., 2021; Eriksson et al., 2015; Maroušek et al., 2020; Mondello et al., 2017; Moult et al., 2018; Vandermeersch et al., 2014).

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)	Dependent on solution: from -65 to -314 kg CO_2 eq./t FW.
Quality of scope 2 emissions information	Verified in the peer-reviewed environmental engineering literature (LCA, case study).
TRL level	8-9
Maintainability issues	Control of certain process key parameters (e.g. C/N, pH, temperature, feed rate, alkalinity) is required.
Legislative concerns	Under the Regulation (EU) 2019/1009 and Regulation (EC) No 1069/2009 for animal by-products and derived products not intended for human consumption
Payback time (years)	Dependent on solution. e.g., 1 MW plant pawer payback time is 3.2–4.8 years.

(Albizzati et al., 2019; Benato and Macor, 2019; De Clercq et al., 2017; Goodman-Smith et al., 2020; Mirmohamadsadeghi et al., 2019; Mondello et al., 2017; Moult et al., 2018; Pramanik et al., 2019)

Composting

Composting of organic food waste is a natural process of decomposition of food waste under aerobic conditions, where microorganisms break down food waste into its simplest components. Composting reduces the volume of accumulated waste over time and creates a stable product with a high content of nutrients, resulting from the microbial transformation of raw organic materials (Palaniveloo et al., 2020; Rastogi et al., 2020). This organic-rich product is used as a natural fertilizer in the agricultural sector because it has a positive effect on the soil and the environment, thanks to its high fiber content and inorganic nutrients (Mondal and Palit, 2019; Palaniveloo et al., 2020).

In line with the Sustainable Development Goal 12 (SDGs) of Responsible Consumption and Production to substantially reduce food waste generation through prevention, reduction, recycling and reuse by 2030, composting is seen as a solution to properly manage waste to promote good health and well being through sustainable practices (Palaniveloo et al. 2020). Composting of organic food waste reduces the impact on many sectors. For example, reducing methane and nitrous oxide emissions from landfills directly reduces the greenhouse effect, and application of compost reduces the need for pesticides and synthetic fertilizer (Risse and Faucette, 2009; Palaniveloo et al. 2020). Composting provides carbon sequestration. Odours and volatile compounds are eliminated using compost. Also compost application on soil improvement helps prevent erosion, runoff near streams, lakes, and rivers, and turf loss on hillsides, roadsides, parks, golf courses, and sport fields. Compost is used to restore forests, wetlands, and degraded soils (Favoino and Hogg, 2008; Palaniveloo et al., 2020).

In the scientific literature, food waste composting is widely recognized as an economically and environmentally friendly process for the utilization of any biological waste. Studies have analysed data from store databases, delivery records, and store sales data provided by retailers. Some studies have also included onsite waste audits to measure the quantity of food waste, whilst others have conducted interviews with retail staff to obtain estimates for food waste.

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)	Dependent on solution: from -31 to -63 kg CO_2 eq./t FW.
Quality of scope 2 emissions information	Verified in the peer-reviewed environmental engineering literature (LCA, case study).
TRL level	TRL 8-9
Maintainability issues	Control of certain key parameters (oxygen concentration, mixing, moisture content).
Legislative concerns	Under the Regulation (EU) 2019/1009 and Regulation (EC) No 1069/2009 for animal by-products and derived products not intended for human consumption
Payback time (years)	Dependent on solution: from 11 to 14 years. Due to a too long payback period, a financial subsidy is a necessity for organic fertilizers to replace traditional mineral fertilizers.

(Albizzati et al., 2021; Chen, 2016; Moult et al., 2018)

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14 ENERGYPLUS™ MODELLING

14.1 Modelling methodology

Using the data collected from a UK quick service restaurant (QSR), a first case study was simulated. The aim was to assess the impact of various opportunities to reduce carbon emissions from a QSR in 6 different European countries and to determine how close to carbon neutrality it could achieve by 2050. The work presents results from an EnergyPlus™ building model (US Department of Energy, 2022) that examines the impact of external and internal environmental conditions on energy consumption and carbon emissions from a QSR when new carbon saving technologies were applied. The environmental impact was characterized by the total equivalent warming impact (TEWI).

14.2 Software and interfaces

The total energy consumption for the modelled scenarios was calculated using EnergyPlus™ V22.2.0. SketchUp Pro (Trimble Inc.) 2023 was employed for drawing and creating the model geometry, while OpenStudio V1.5.0 (by NREL, ANL, LBNL, ORNL, and PNNL) was used to incorporate and adjust various properties such as weather files, construction, materials, occupancy, internal loads, schedules, water systems, HVAC, and refrigeration systems. The workflow of the software used in this study is presented in Figure 42.

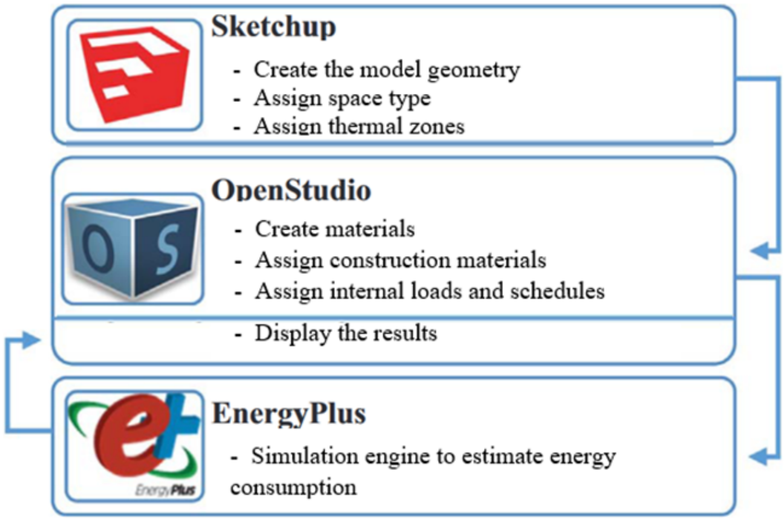

Figure 42. Workflow for modelling and simulating a building

14.3 Case study modelling

Figure 43 shows a detailed modelling methodology adopted in all the work.

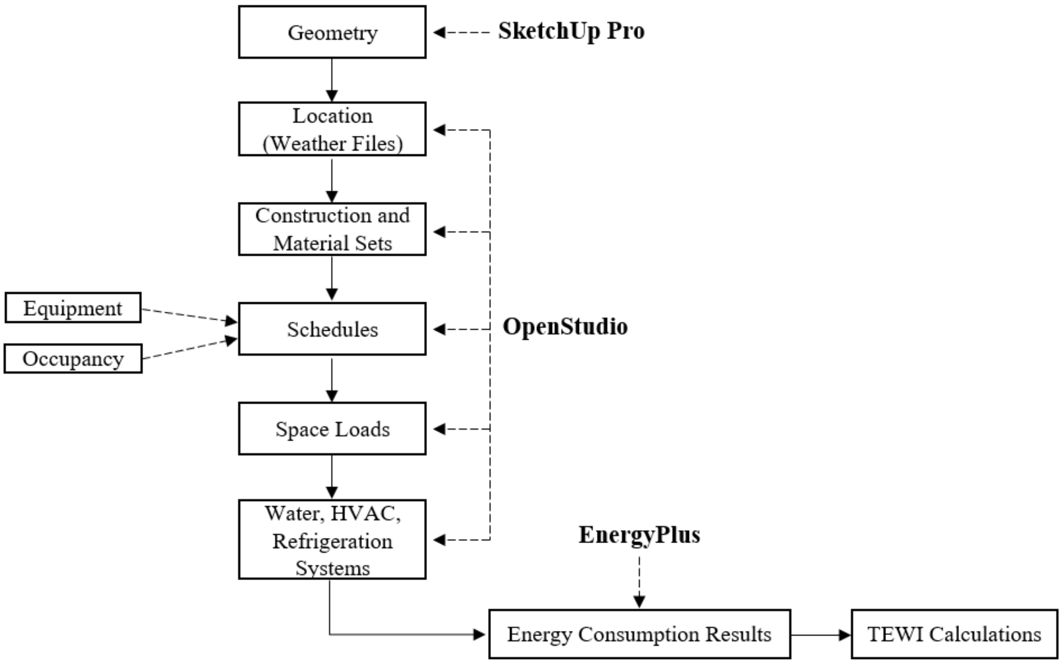

Figure 43. Methodology of work for modelling and simulating the case studies

14.3.1 Building envelope

This geometry was derived from the QSR study in the UK (London), using architectural plans containing all the required dimensions. The QSR had a floor area of 431 m^2 and was divided into 10 zones. The height of the QSR was 4.5 m. The geometry was created on SketchUp. The name of the space types and their corresponding floor area is shown in Table 14 below.

Table 14. Table showing the space type names with their corresponding floor area

Space type	Floor area (m^2)
Chiller	16
Corridor	25
Dining room	179
Drive thru	10
Freezer	18
Kitchen	88
Office	9
Staff room	25
Store	21
WC	40

Figure 44 shows the geometry of the QSR adopted in the simulation.

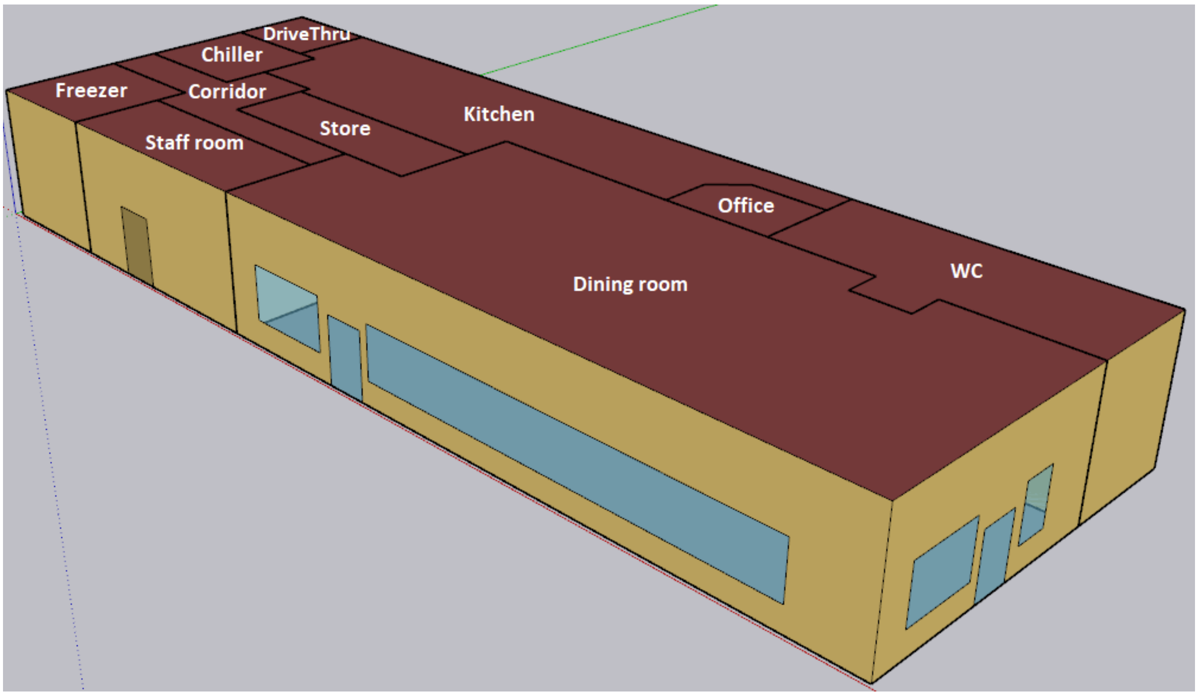

Figure 44. Geometry of the QSR with its space types

14.3.2 Schedules

The individual loads in spaces are a strong function of the schedules, which usually varies with the time of day and day of the week. The OpenStudio scheduling tab encompassed various factors such as the QSR's operational hours, occupancy, lighting, equipment usage, etc.

14.3.3 Constructions and materials

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 fast-food restaurant, a recent standard construction set from the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) within the library was employed (90.1-2019 – ASHRAE 169-2013), using materials from OpenStudio's built-in libraries. These default materials included concrete, gypsum, typical Insulated wood, etc.

14.3.4 Load definitions

Space load definitions fall into several categories including people, lighting, electric, gas, and other equipment uses. All electrical devices were added in OpenStudio as electrical input loads.

14.3.5 Hot water systems

Parameters like the maximum target temperature for heating were specified. The hot water system included a pump, a service water loop comprising a resistive water heater on the supply side, and area connections for water use on the demand side (Figure 45). The daily water consumption was taken from the actual establishment, and an assumption was made for the inlet water temperature based on the average ambient temperature of London.

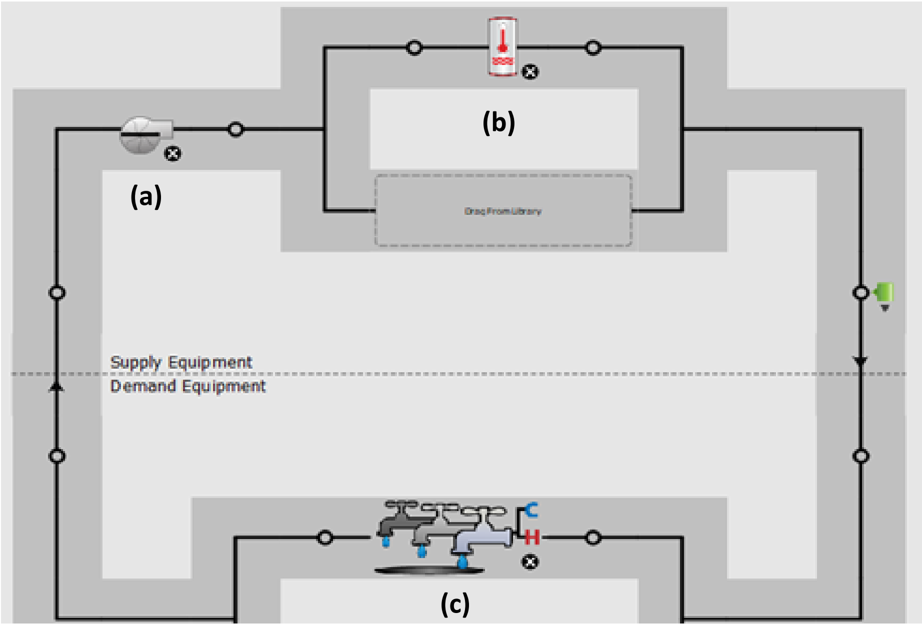

Figure 45. Adding a hot water loop for the QSR: (a) Pump, (b) Electrical Heater, (c) Water Use Connection

14.3.6 HVAC systems

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^{TM} 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. Heating was from heat pumps. The supply side of these HVAC systems had a cooling coil, a heat pump and a supply fan (see Figure 46). On the demand side, the kitchen and the dining rooms were connected using zone air terminal units. Each of the remaining areas was regulated by a packaged terminal heat pump unit (PTHP), which is a ductless, through-the-wall heating and cooling system.

The COP of the heat pump was calculated based on the outside dry-bulb temperature using a cubic equation from default values in EnergyPlus^{TM}:

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

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.

The COP of the cooling coil was calculated based on the outside dry-bulb and wet-bulb temperatures using a biquadratic equation from default values in EnergyPlus^{TM}:

$$COP_{T,\ cooling} = \frac{COP_{rated,cooling}}{0.3424+3.488\mathrm{e}{-2}\ T_w-6.237\mathrm{e}{-4}\ T_w^{\ 2}+4.977\mathrm{e}{-3}\ T_d+4.379\mathrm{e}{-4}\ T_d^{\ 2}-7.280\mathrm{e}{-4}\ T_w T_d} \qquad \text{Eq. (2)}$$

where $COP_{T,\ cooling}$ is the COP at different temperatures, $COP_{rated,cooling}$ is the COP at rated conditions (air entering the cooling coil at 19.4°C wet-bulb temperature and air entering the outdoor condenser coil at 35°C dry-bulb temperature), T_w is the wet-bulb temperature and T_d the dry-bulb temperature in °C.

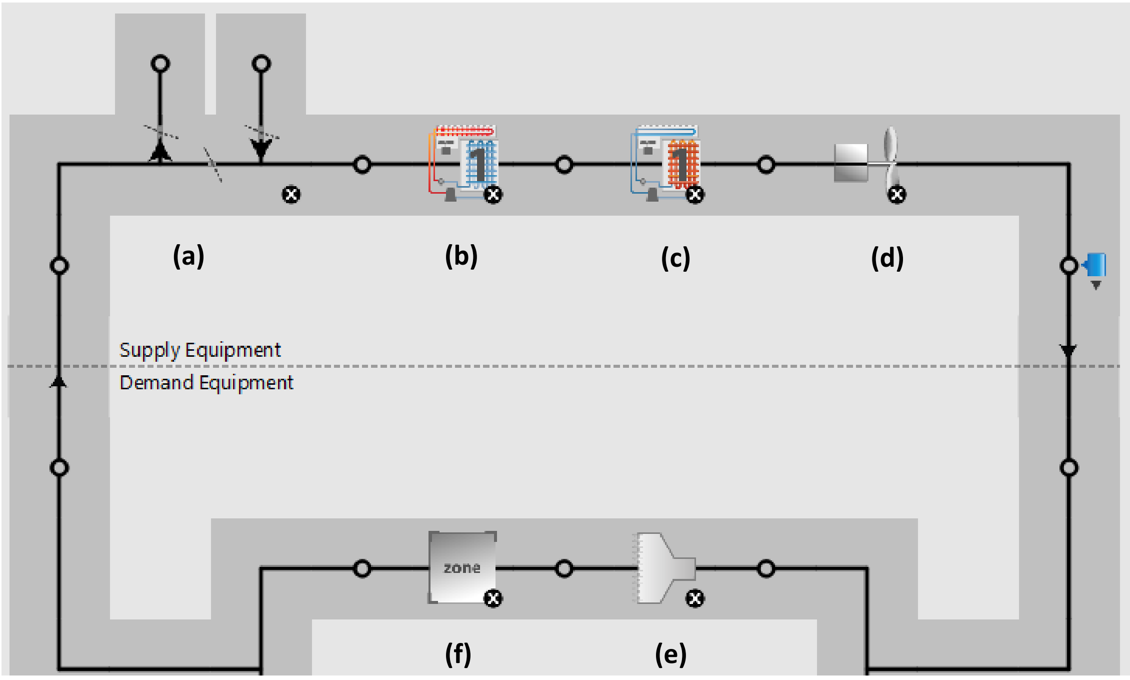

Figure 46. Adding a PRHP unit for the QSR: (a) Outside Air System, (b) Cooling Coil, (c) Heat pump, (d) Fan, (e) Zone Terminal Units, (f) Zone

14.3.7 Cold stores

EnergyPlus™ can model a wide variety of systems and components found in commercial and industrial applications.

The QSR had two cold stores: a chiller, and a freezer operating on R448A direct expansion (DX) systems. The refrigeration system was divided into two racks. One rack served the low temperature (LT) needs for the freezer, while the other served the medium temperature (MT) requirements for the chiller. Each system was equipped with an air-cooled condenser with a variable speed condenser fan and one compressor. The sizing of the condenser was determined by considering a temperature difference of 10 K between the condensing temperature and the ambient temperature. The maximum rated fan power was assumed to be 3% of the heat rejection based on Foster et al. (2018).

Figure 47 shows the refrigeration systems of the chilled and freezer cold stores.

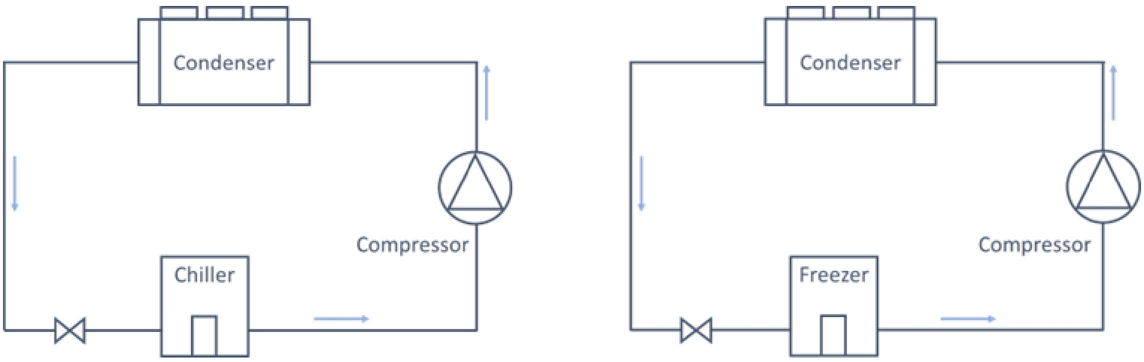

Figure 47. Adding two refrigeration systems for the chilled and freezer cold stores of the QSR

14.3.8 Model inputs

Details of the model inputs are presented in Table 15.

Table 15. Model inputs for the QSR

Opening hours	From 6 am – 10 pm (Monday-Sunday)			QSR data
Internal heat loads		Lighting load consumption (kWh/year)	Electric load consumption (kWh/year)	
	Corridor	436	194	EnergyPlus™ default
	Dining room	7,189	30,066	EnergyPlus™ default
	Drive Thru	233	350	EnergyPlus™ default
	Kitchen	5,494	134,753 343,783	EnergyPlus™ default After calibration with QSR data (section 2.3)
	Office	206	308	EnergyPlus™ default
	Staffroom	561	844	EnergyPlus™ default
	Store	558	372	EnergyPlus™ default
	WC	930	133	EnergyPlus™ default
Heating thermostat	21°C (kitchen) 20°C (all the other areas)			QSR data
Cooling thermostat	23°C (all the areas)			QSR data
HVAC system	Cooling DX Rated COP	3		EnergyPlus™ default
	Heating DX Rated COP	2.75		Expert advice
	Fan total efficiency	0.7		EnergyPlus™ default
	Controlled thermal zones	All areas		QSR data
	Heating design supply T	40°C		EnergyPlus™ default
	Cooling design supply T	15°C		EnergyPlus™ default
Hot water system	Water consumption: 2,200 L/day Specific heat capacity of water = 4.185 $J.K^{-1}.kg^{-1}$ Inlet T: 11.15°C Target T: 60°C			QSR data At average $T_{35.6°C}$ Mean ambient T EnergyPlus™ default
Refrigeration system (R448A)	Compressors	Copeland-DISCUS-LOW_2DB3-060E-TFD Copeland-DISCUS-MEDIUM_3DF3-120E-TFD		EnergyPlus™ default

	Evaporating T	Chilled/Frozen: -8°C/-33°C[38]	Footnote 1
	Minimum condensing T	21°C[39]	Footnote 2
	Refrigerant charge (kg)	3.2[40]	Footnote 3
	Refrigerant leakage for cold stores (/year)	10%[41]	Footnote 4
Cold stores (Chiller and freezer)	Total area	Chiller/Freezer: 16 m^2/18 m^2	QSR data
	Operating T	Chiller/Freezer: 3°C/-18°C	QSR data
	Height of doors	2 m	EnergyPlus default
	Cooling coil capacity	4690 W	EnergyPlus™ default
	Fan	735 W	EnergyPlus™ default
	Light	120 W	EnergyPlus™ default
	Defrost	2500 W	EnergyPlus™ default
	Insulated floor heat transfer U: 0.207 $W/m^2.K$		EnergyPlus™ default
	Insulated surface U facing zone: 0.235 $W/m^2.K$		EnergyPlus default
	Stocking door U facing zone: 0.3785 $W/m^2.K$		EnergyPlus default

14.3.9 Model calibration with QSR

The overall annual energy consumption from the model was validated against the real QSR data. The modelled total annual energy consumption was found to be lower by 44.6% compared to the validation data. The QSR didn't provide any information regarding electrical equipment and therefore, EnergyPlus default values were used. However, the QSR manager mentioned that kitchen equipment accounted for the highest portion of energy usage overall, exceeding that of HVAC systems. Therefore, an assumption was made that the difference might be the quantity of electrical load in the kitchen. To

[38] CO_2 Product Guide 2021 for Refrigeration. Emerson. Applications co$_2$-product-guide-2021-for-refrigeration-applications-en-gb-4217772.pdf (emerson.com)

[39] Petersen, Michael; Pottker, Gustavo; Sethi, Ankit; and Yana Motta, Samuel F., "Refrigerants With Low Environmental Impact For Commercial Refrigeration Systems" (2018). International Refrigeration and Air Conditioning Conference.

[40] The refrigerant charge was calculated using the F-Gas refrigerant charge calculator excel file - Guidance on impact of the fluorinated gas regulation for users of stationary refrigeration, air conditioning and heat pump. Taken from: General Guidance F Gas and Ozone Regulations. Information Sheet GEN 5: Refrigerant Quantity, April 2012.

[41]https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2105061125_ukghgi-90-19_Main_Issue_1.pdf

address this, an adjustment was made by increasing the electrical load in the kitchen (an increase of 2.55-fold) to fit the actual QSR total energy consumption. The calibration was only carried out on total energy consumption, as the QSR had no sub-metering.

Table 16 presents the monthly energy consumption from the real QSR and the monthly energy consumption predicted by the model after calibration.

Table 16. Monthly data of the validation and simulated UK QSR after calibration

Month	Real QSR (kWh)	Simulated QSR (kWh)	% difference
Jan	45,338	47,362	4.5%
Feb	41,340	43,003	4.0%
Mar	42,098	46,646	10.8%
Apr	47,900	45,307	-5.4%
May	48,345	47,064	-2.6%
Jun	45,860	45,794	-0.1%
Jul	51,763	48,122	-7.0%
Aug	50,597	47,761	-5.6%
Sep	46,010	45,440	-1.2%
Oct	45,865	46,628	1.7%
Nov	44,210	45,193	2.2%
Dec	46,051	47,294	2.7%
Total	**555,377**	**555,614**	**0.04%**

14.3.10 Modelling technologies

The impact of various carbon saving technologies incorporated in the QSR were examined individually and together to assess their effects. The technologies examined were:

- Technology 1: Low GWP refrigerant (GWP=150) for the cold stores. It was assumed that the energy consumption would be the same as that of the baseline running on R448A.
- Technology 2: Increase dead band temperature of the HVAC by 2K, by increasing cooling and decreasing heating set points by 1 K each.
- Technology 3: 20% more efficient refrigeration and kitchen equipment.
- Technology 4: Maintenance/operational practices. The sole difference from technology 3 was the % efficiency in refrigeration and kitchen equipment, which was assumed to be 10%.
- Technology 5: Economiser in the HVAC. Economizers were integrated into the HVAC of both the kitchen and dining areas. These used outside air to provide free cooling when the external air conditions were favourable, instead of relying on the mechanical cooling of the air conditioning.
- Technology 6: Renewable Energy Sources. Solar photovoltaic (PV) panels were installed on the QSR's roof, covering an area equivalent to the roof's total area. The electricity generated was calculated using the RETScreen software tool. RETScreen uses published local data for daily solar radiation on a horizontal surface in $kWh/m^2/day^{-1}$ for each month. Using the location (London)

and orientation of the panels together with their efficiency (assuming a 15% efficiency), the output for each month was calculated. The total output for the year was the sum of these values.

- Technology 7: All the technologies above were combined in a single model.

14.3.11 Adapted medium usage QSR

Mudie et al. (2013) presented comparisons of benchmarks among various licensed restaurants and pubs. Annual electricity use was plotted against total floor area and kitchen area. Their research revealed that establishments with a comparable total floor area had annual energy consumption ranging from 180,000 to 560,000 kWh. Similarly, establishments with a kitchen area similar to the QSR, had annual energy consumption ranging from 120,000 to 560,000 kWh.

The above QSR was considered a high usage store, due to the QSR being in the top 10% sales of the chain, thus having a very high turnover. In order to study the impact of a medium usage QSR, an adapted model was developed where only kitchen equipment was adjusted, using EnergyPlus default values for equipment in the kitchen. Other parameters like refrigeration system, hot water system and equipment in the other areas remained unchanged.

The same technologies were applied to this adapted QSR.

14.3.12 Location

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™ weather site are for TMY, TMY2, and TMY3 generations (historical weather files). Each of these "generations" of TMY data were collected over old specific ranges of years before 2009. To use weather files related to 2020 and project to 2050, https://weathershift.com/ was used to shift the historical EnergyPlus™ weather files to 2020 and forward to 2050.

To simulate the QSR at different locations, the weather files at the 6 locations were used. These locations were London (UK), Paris (France), Kaunas (Lithuania), Warsaw (Poland), Oslo (Norway) and Rome (Italy).

14.4 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. TEWI is based on the following relation:

$$TEWI = (GWP \times m \times L) + (E \times \beta) \qquad \text{Eq. (3)}$$

Where *TEWI* is the mass of CO_2e produced during a year (kg); $(GWP \times m \times L)$ are direct emissions of CO_2e due to refrigerant leakage; $(E \times \beta)$ are indirect emissions of CO_2e associated with electrical energy consumption; *GWP* is the Global Warming Potential of the refrigerant; *m* is the refrigerant charge of the QSR (kg); *L* is the leakage rate per year; *E* is the electrical energy consumption per year of the QSR (kWh/year); β is the CO_2e equivalent emissions per kWh of electrical energy produced (kg CO_2e/kWh). A GWP of 1273 (100-year horizon) for R448A was taken from the IPCC AR5 report (2013). Electrical carbon emission factors for the UK between 2020 and 2050 were taken from BEIS (2023) (Table 17).

Table 17. Predicted electrical carbon factors for the UK.

	2020	2025	2030	2035	2040	2045	2050
β (kg CO_{2e}/kWh)	0.197	0.131	0.049	0.020	0.016	0.008	0.003

14.5 Bibliography for modelling

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