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Retail road map

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ENOUGH

EUROPEAN FOOD CHAIN SUPPLY TO REDUCE GHG EMISSIONS BY 2050

1. NOMENCLATURE

AC	Alternating current
AD	Anaerobic digestion
AHU	Air handling unit
AI	Air impingement
AIS	Active insulation system
ANL	Argonne National Laboratory
ASD	Adjustable speed drive
ASH	Ani sweat heater
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAT	Best available technology
BS	British standard
CCHP	Combined Cooling Heat and Power
CES	Corporate environmental sustainability
CFD	Computational fluid dynamics
CHP	Combined heat and power
CHTC	Convective heat transfer coefficient
CI	Carbon intensity
CO_2	Carbon dioxide
COP	Coefficient of performance
CTES	Cold thermal energy storage
DC	Direct current
DCKV	Demand control kitchen ventilation
DDY	Design day in a year
DSR	Demand side response
DX	Direct expansion system
EC	European Commission
ECHA	EU European Chemicals Agency
EEB	European Environmental Bureau
EEI	Energy efficiency index
EER	Energy-efficiency ratio
EEV	Electronic expansion valve
EI	Energy intensity
EiF	Entry into force
EN	European norm
EPR	Evaporator pressure regulator
EPW	EnergyPlus weather
ESEER	European seasonal efficiency ratio
ETS	Emissions Trading System

EU	European Union
EVs	Electric vehicles
FAO	Food and Agriculture Organization of the United Nations
FC	Frequency converter
FEA	Finite element analysis
GHG	Greenhouse gas
GW	Giga Watts
GWP	Global warming potential
HC	Hydrocarbon
HFCs	Hydro fluorocarbons
HFOs	Hydrofluoro olefins
HTF	Heat transfer fluid
HVAC	Heating ventilation and air conditioning
HVAC&R	Heating, ventilation, air conditioning and refrigeration
IDF	Intermediate data format
IHX	Internal heat exchanger
IIR	International Institute of Refrigeration
IPCC	Intergovernmental panel on climate change
IR	Infra-red
ISO	International standards organisation
kWh	Kilo Watt hour
LBNL	Lawrence Berkeley National Laboratory
LCA	Life Cycle Analysis
LED	Light emitting diode
lm	Lumen
LPA	Liquid pressure amplification
LSHE	Liquid suction heat exchange
LT	Low temperature
LULUCF	Land use, land-use change, and forestry
MAC	Marginal abatement cost
MECs	Motor Efficiency Controllers
MEPS	Minimum Energy Performance Standards
MGT	Micro gas turbine
MS	Medium-sized
MT	Medium temperature
MW	Microwave
NG	Natural gas
NREL	National Renewable Energy Laboratory
OA	Outside air
ORNL	Oak Ridge National Laboratory
OSM	OpenStudio model

PCM	Phase change material
PF	Power factor
PFAS	Per- and polyfluoroalkyl substances
PHA	Polyhydroxyalkanoate
PLA	Poly(lactic acid)
PLC	Programmable logic controller
PNNL	Pacific Northwest National Laboratory
psi	Pounds per square inch
PSV	Passive stack ventilation
PTAC	Packaged terminal air conditioner
PU	Polyurethane
PV	Photo voltaic
PVC	Polyvinyl chloride
RAC	Room air conditioner
RDC	Refrigerated display cabinet
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RES	Renewable energy source
RH	Relative humidity
SBEM	Simplified building energy model
SCOP	Seasonal performance factor
SEC	Specific energy consumption
SHGC	Solar Heat Gain Coefficient
SHS	Superheated steam
SMPC	Stochastic Model Predictive Control
SS	Small-sized
SST	Saturated suction temperature
tCO_{2e}	Tonnes of CO_2 equivalent
T	Temperature
TE	Thermoelectric
TEC	Total energy consumption
TEV	Thermostatic expansion valve
TEWI	Total equivalent warming impact
TFA	Trifluoroacetic acid
TFC	Thermostatic flow control
TFC	Thermostatic flow control
TRL	Technology readiness level
TWh	Tera Watt hours
TXV	Thermostatic expansion valve
UK	United Kingdom
UNRCCC	United Nations Framework Convention on Climate Change

US	United States
UV	Ultra-violet
VAV	Variable airflow volumes
VFD	Variable frequency drive
VIP	Vacuum insulated panels
VSDs	Variable speed drives
WLD	Warm liquid defrosting

2. EXECUTIVE SUMMARY

In this road map we question how the retail food sector can decarbonise and rapidly reach net zero. As part of the work we provide independent reviews of 95 different technologies/strategies that retail stores could apply to reduce carbon emissions and energy consumption. Scope 1 and 2 emissions are covered which encompass emissions from direct fuel use (electricity/gas) and emissions from leakage of refrigerants. Scope 3 emissions are not included as these will originate mainly from the companies that supply supermarkets and their emissions are covered in other road maps being developed under the ENOUGH project.

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

Mathematical modelling was then used to assess impacts from 2020 through to 2050 taking into account changes due to global warming and changes in the grid carbon conversion factor as well as the impact of combined technologies/strategies. Three scenarios were considered for a medium (2,100 m^2) and a small (600 m^3) store:

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 carbon conversion factors were considered.
2. Minor retrofit (+ do nothing): shorter term options that could be applied for stores that were not due to be replaced in the near future or undergo major refurbishment.
3. Major retrofit ((+ do nothing + minor retrofit): more significant changes that would require the store to be closed for a period of time.

The impact of applying technologies to a completely new build supermarket was not considered as the vast majority of the technologies could be applied as part of a major retrofit to a supermarket.

The impact of the scenarios was applied to 6 locations (UK, France, Lithuania, Norway, Italy, Poland) which were selected for their varied climatic conditions, grid carbon conversion factors and their baseline use of fuels and refrigerants. Results from the reviews and modelling identified routes for stores to reduce emissions and enabled the creation of a road map thought to 2050.

The modelling predicted overall energy savings ranging from 55 to 94%. The savings were in Rome where 95% of the energy was saved in the medium store and 70% in the small store. This showed the benefits of solar panels in a country where there was abundant sunshine. The energy savings in other countries were broadly similar but the reductions were due to a variety of reasons and not always due to the application of the same technology.

Carbon emissions could be reduced by 61 to 97%. In medium stores the greatest reduction was seen in Rome and was mainly due to the energy saving potential from the solar panels. In the small stores the greatest percentage carbon reduction was seen in Oslo and this was mainly due to the high impact of reducing fugitive emissions (and moving from an HFO to R744) in a country where the electrical grid intensity was already very low.

From the work we recommend 6 major opportunities for supermarkets which are presented in the diagram below:


Recommendations
Opportunity 6
Use RES, especially solar in sunnier climates
Opportunity 5
Don't wait, early interventions will reduce cumulative global warming
Opportunity 4
Assess benefits of technologies according to specific location and operation
Opportunity 3
Purchase the most energy efficient equipment
Opportunity 2
Apply doors to open fronted chilled cabinets
Opportunity 1
Transition to natural refrigerants

3. ABOUT THIS ROAD MAP

Studies have estimated that 26-35% of global greenhouse gas emissions are a result of food and agriculture. Approximately 18-29% of these emissions are related to the food supply chain (the remaining proportion is related to land use, crop and animal production)[12]. The food industry is important both economically and is integral to many of the UNs sustainable development goals. The food sector often has a large impact on the GDP of a country, and this is especially the case in less developed countries.

Refrigeration has a significant role to play in creating secure, sustainable and resilient food chains. The International Institute of Refrigeration (IIR) estimate that 778 million tons of food is preserved by refrigeration in the world each year. Theoretically, 1,661 million tons should have benefited from refrigeration and so there is a significant shortfall in access to cooling. Approximately 13% of the food produced in the world is lost because of a lack of refrigeration which if correctly refrigerated could feed 950 million inhabitants per year[3]. In low-income countries most of the food is lost at the start of the chain and this is due to poor logistics, lack of cooling and poor handling and practices. In high income countries food is mainly wated at the consumer end of the cold chain. It is essential to limit food loss and waste as this not only contributes to carbon emissions but results in less food being available for consumption.

This road map focuses on the supermarket sector. In this report, supermarkets are often used to describe all sizes of food retailer, from convenience to hypermarket. There is evidence to suggest that the retail sector has relatively high scope 1 and 2 emissions[4] compared to other sectors of the food chain. In 2014 there were approximately 105 million retail food outlets covering 96,391 m^2 in Europe. As part of eco-design and labelling studies the European Commission (EC) estimated that the annual energy consumption of refrigerated products was estimated at 65 TWh in 2015, corresponding to 26 million tonnes of CO_2 equivalent[5]. Refrigeration is often the largest energy load in a supermarket. The energy consumption of supermarkets depends on business practices, store format, product mix, shopping activity and the equipment used for in-store food preparation, preservation, and display. The annual electrical energy consumption can vary widely from around 700 kWh/m^2 sales area in hypermarkets to over 2,000 kWh/m^2 sales area in convenience stores. The refrigeration systems

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[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).

[3] IIR. The Role of Refrigeration in Worldwide nutrition (2020), 6th Informatory Note on Refrigeration and Food.

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

[5] Moons, H., Villanueva, A., Calero, M., Ardente,F., Mathieux, F., Labanca, N., Bertoldi, P. and Wolf, O. (2014). Ecodesign for Commercial Refrigeration. Preparatory study update Final report. ISBN 978-92-79-39543-7 (PDF), ISSN 1831-9424 (online), doi:10.2791/11459.

account for between 30 % and 60 % of the electricity used, whereas lighting accounts for between 15 % and 25 % and the HVAC equipment and other utilities such as bakery use the remainder[6].

Previous work has shown that there is considerable potential to reduce emissions from supermarkets. 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 supermarket is feasible.

4. INTRODUCTION

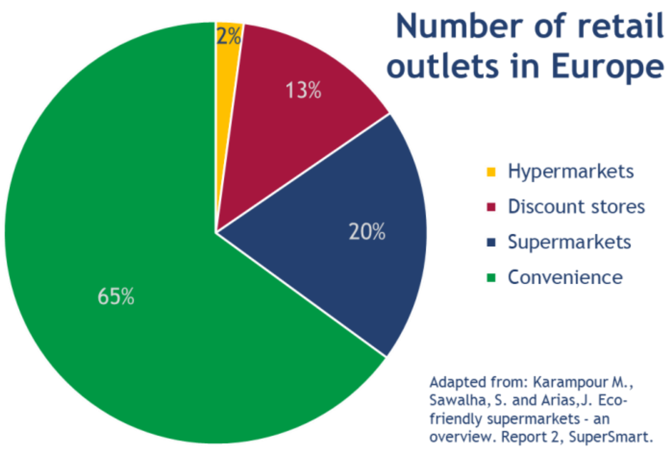
In June 2021, the EU adopted a European Climate Law which aims to reach net zero GHG in the EU by 2050. In addition, the EU has a goal of reducing emissions by at least 55% below 1990 levels by 2030 (including Land use, land-use change, and forestry - LULUCF). This is implemented through the 'Fit for 55' package which is a set of policy proposals by the European Commission to achieve the 55% reduction target[7]. 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;

[6] Kolokotroni, M., Mylona, Z., Evans, J., Foster, A. and Liddiard, R., 2019. Supermarket energy use in the UK. Energy Procedia, 161, pp.325-332.

[7] https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

- a maximum limit on the GHG content of energy used by ships calling at European ports through the FuelEU Maritime Initiative;
- the introduction of an overall EU target for carbon removals by natural sinks, equivalent to 310 million tonnes of CO_2 emissions by 2030; and
- a new EU Forest Strategy, setting out a plan to plant three billion trees across Europe by 2030.



Type	Typical size	Type of products
Hypermarket	>4,500 m²	Food products Non-food products
Supermarket	400-2,500 m²	Mainly food products Limited non-food products
Discounter	<1,000 m²	Food products Non-food products
Convenience store	<400 m²	Limited number of products, Predominantly food

All this impacts the food cold chain which has significant emissions of carbon. In particular supermarkets in Europe generate significant quantities of carbon emissions and so have a major role to play the aimed for 55% reduction target. Across Europe it is estimated that in 2022 there are 300,000 food retailers with a turnover of €2,4 trillion[8]. The majority of stores are small convenience stores of <400 m^2. Supermarkets and hypermarkets saw a decline in sales in 2021 with only online and discounters posted highest results than in the previous year. This was due mainly to the financial crisis, the COVID pandemic and some changes in consumer habits.

Supermarkets and hypermarkets can vary in size from 400-20,000 m^2 and have refrigeration capacities of between a few hundred Watts to 1.5 MW[9]. In Europe it is estimated that the carbon emissions from retail stores is ~26 megatons CO_{2e}. The emissions originate from the energy that is used to operate the display cabinets and the heating ventilation and air conditioning (HVAC) system plus emissions also from any gas used for heating and emissions from leakage of refrigerants. Refrigeration consumes the greatest proportion of the electricity energy in a supermarket with 35–50% of all energy used to power the refrigerated cabinets[10].

The focus of this report is to assess the technologies and strategies available to supermarkets to reduce their carbon emissions. This covers the emissions that they generate today and also how emissions moving forward 2050 could be reduced to ultimately assess how a supermarket could become zero carbon. During the work 95 different technologies and strategies were reviewed in detail to assess their opportunities to reduce carbon. This covered technologies that could be applied to the retail display cabinets, the HVAC system and also any cooking that is carried out in store.

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[8] https://www.retail-index.com/sectors/foodretailersineuropeandworldwide.aspx

[9] 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.

[10] Kolokotroni, M., Mylona, Z., Evans, J., Foster, A. and Liddiard, R., 2019. Supermarket energy use in the UK. Energy Procedia, 161, pp.325-332.

5. CURRENT TRENDS

1.1. The environment

The world is experiencing higher temperatures due to global warming. Globally mean near-surface temperature were 1.11 to 1.14 K 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 K (depends on data set used). 2020 was the warmest year in Europe since instrumental records began. In particular hight levels of warming were observed across Eastern Europe, Scandinavia and at eastern part of Iberian Peninsula[11].

United Nations Framework Convention on Climate Change (UNRCCC) member countries have committed to the Paris Agreement. This aims to limit global temperature increase to below 2°C (above pre-industrial levels) by 2050 and ideally to limit the increase to less than 1.5 K[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 K and at worst by 4.1 to 8.5 K (by 2071-2100, compared to 1981–2010). Areas of particular concern are north-eastern Europe, northern Scandinavia and inland areas of Mediterranean countries, whereas western Europe, especially in the United Kingdom, Ireland, western France, Benelux countries and Denmark expect the lowest levels of warming[11].

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

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

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

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

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

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

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

1.2. The move to natural refrigerants

There has been a significant move across European food retailers to move away from HFC refrigerants in the last decade. In particular CO_2 (R744) has been applied widely as a refrigerant in larger remotely operated systems (see below). In smaller integral systems there has been a transition to hydrocarbon refrigerants, in particular propane (R290). This is primarily due to national environmental pressure plus also legislative pressures from the European F-gas regulations (Regulation on the Use of F-Gases (EU 517/2014, 2014))[14] to reduce the GWP of refrigerants applied in food retail. 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. Except for primary cascade cycles (which are permitted to use refrigerants with GWP up to 1500) the regulation prohibits the use of any refrigerant with a GWP higher than 150 in centralised food retail refrigeration systems larger than 40 kW (applied since January 2022). From the same date refrigerators and freezers for commercial use (hermetically sealed equipment) cannot contain a fluorinated refrigerant with a GWP of greater than 150. Stationary systems which fall between the large (>40 kW) centralised systems and the hermetically sealed equipment are able to use HFC refrigerants with a GWP of <2,500 (with a derogation for equipment intended for application designed to cool products to temperatures below -50°C).

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. 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 1.

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

Table 1. 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 of 150 or more	1 January 2024	Now includes 'other fluorinated greenhouse gases'
12	Any self-contained refrigeration equipment	- that contains fluorinated greenhouse gases with GWP of 150 or more	1 January 2025	New clause
14	Stationary refrigeration equipment	- that contains, or whose functioning relies upon, fluorinated greenhouse gases with GWP of 2,500 or more 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 with GWP of 150 or more, except in the primary refrigerant circuit of cascade systems where fluorinated greenhouse gases with a GWP of less than 1,500 may be used	1 January 2022	Link to Annex 1 added

1.2.1. Carbon dioxide (R744)

Until 2020, worldwide there are several ten thousand stores employing CO_2-based systems and CO_2 is rapidly replacing older technologies in commercial refrigeration for new and refurbished stores. Results show that Europe has adopted CO_2 applications for commercial and industrial refrigeration at a much higher rate than any other region, largely due to the EU F-Gas Regulation and ambitious legislation in some European countries, by requesting a tax on refrigerants based on their GWP[15]. As store owners try to future-proof their refrigeration systems, CO_2 is quickly taking over as the preferred alternative in new supermarkets in Europe. In late 2018 it was estimated that there were 16,000 stores in Europe operating on transcritical CO_2. In 2020 this number had risen to 29,000 a growth of 81% since 2018 (Figure 1). In Europe, around 90% of installations are in supermarkets, 5% are in convenience stores and 5% are in not supermarket industrial sites.

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

Figure 1. CO_2 transcritical stores status in 2020 (Koegelenberg et al, 2020[16]).

Technology-wise, refrigeration systems are becoming more compact, simple to install and to service. The standardisation of CO_2 booster type refrigeration systems and the expansion of commercial availability by numerous providers have decreased the cost of the technology in recent years. CO_2 based systems saw a rise in energy efficiency of up to 25% and a decrease in their equipment costs of 30% between 2008 and 2016 (Gullo et al., 2018[17]). Much of the efficiency has been gained by use of mechanical subcooling, ejectors, vapor injection, and parallel compression to gain efficiency at higher ambient conditions (CO_2 operates trans-critically above 31°C) and the possibility to operate the evaporators in non-superheated mode, thereby raising the suction pressure of the compressors by several bars. CO_2 systems are therefore now able to compete on costs with HFC systems.

Further cost reduction is anticipated due to the increasing global development of the CO_2 refrigeration market and greater competition (Skacanova and Battesti, 2019[18]). Shecco have projected using research data collected from major heating, ventilation, air conditioning and refrigeration (HVAC&R) equipment manufacturers that continuous growth will continue in the European market going forward. Figure 2 shows 2 scenarios for CO_2 store growth by 2030. The cautious scenario assumes competition from other low-GWP refrigerant technologies. The projections estimates that there will be a total of 65,000-85,000 stores employing CO_2 technology in

More information -
Read more about low GWP refrigerants in:
Refrigerant - Carbon dioxide (CO2, R744)

[16] Koegelenberg, I., Laumen, Z., Stausholm Chritiansen, T., Yoshimoto, D., Dusek, J., Aleu, P. and Cooper, N. World Guide to Transcritical Refrigeration, Part II. https://issuu.com/shecco/docs/r744-guide-part2.

[17] Gullo, P., Tsamos, K.M., Hafner, A., Banasiak, K., Yunting, T.G. and Tassou, S.A., 2018. Crossing CO2 equator with the aid of multi-ejector concept: A comprehensive energy and environmental comparative study. Energy, 164, pp.236-263.

[18] Skačanová, K.Z. and Battesti, M., 2019. Global market and policy trends for CO2 in refrigeration. International Journal of Refrigeration, 107, pp.98-104.

Europe by 2030 and that there will be between 4,000 and 6,000 new CO_2 stores opening each year between 2020 and 2030.

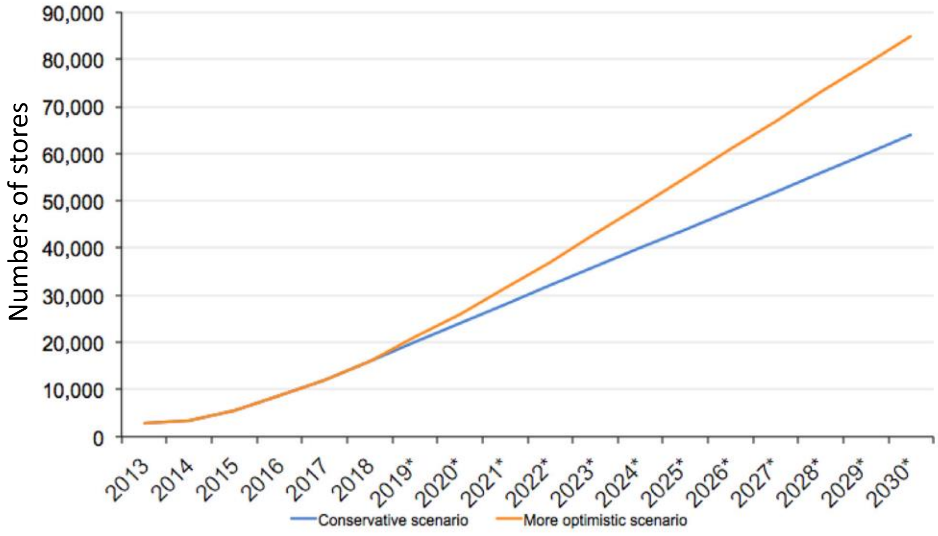

Figure 2. Projected number of CO_2 transcritical stores by 2030 in Europe (Skačanová and Battesti, 2019).

1.2.2. Hydrocarbons

For smaller integral refrigeration systems 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 500 g, depending on the exact refrigerant applied.

> More information -
> Read more about hydrocarbon refrigerants in:
> Refrigerant - HC refrigerants

1.2.3. The application of low/lower GWP refrigerants

Although the market trend is to move to natural refrigerants, there is also an uptake of low GWP HFC/HFO alternatives. These are chemical blends with low or lower GWP than the traditional HFC refrigerants such as R404A that have historically been applied (Table 2). Many of the blends are flammable or mildly flammable (mainly A2L classification). The charge for flammable or mildly flammable refrigerant is controlled through either EN 60335-2-89:2010+A2:2017 or IEC 60335-2-89:2019. For mildly flammable alternatives (A2 and A2L), the limit in the EN standard is 150 g but this is increased to up to 1.2 kg in the IEC standard. For larger charges, EN378 must be applied (Figure 3).

Much of the current use of low GWP alternatives is to retrofit existing remotely operated supermarket estates (there is little value in retrofitting integral refrigeration systems which are hermetically sealed). Many new refrigerants have higher pressures, higher flammability and exhibit glide and so are not drop in options for existing systems. Some refrigerants classified as A1 are more suitable for direct retrofitting, to keep existing systems in operation before a complete replacement with a natural working fluid system is economically feasible for the owner. These include R407A, R407C, R407F, R448A, R449A or R452A as replacements for R404A; and R450A R544 and R513A for R134a in systems <40 KW that are not hermetically sealed. However, these are only short-term options to comply with legislation that is likely to become more stringent in the future.

More information -
Read more about low GWP refrigerants in:
#Refrigerant - HFO refrigerants and blends

Some supermarkets are converting HFC systems to operate with A2L refrigerants such as R454A. This requires careful assessment of risks and risk mitigation to ensure that any flammability risks are mitigated.

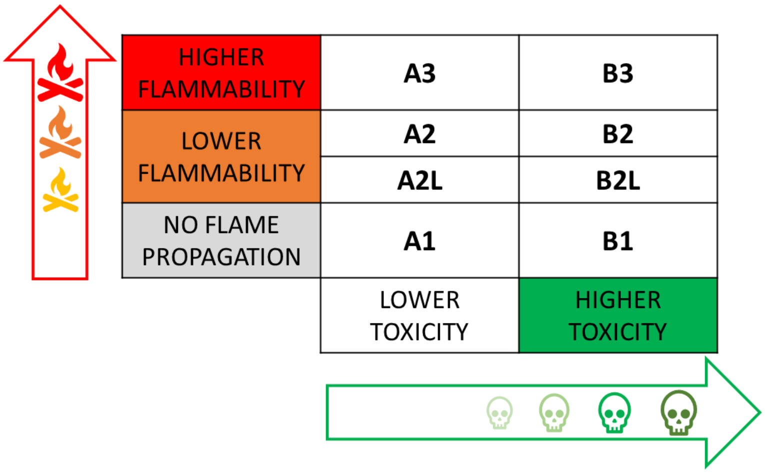

Figure 3. Toxicity and flammability classification of refrigerants.

Table 2. Typical lower GWP refrigerants applied in supermarkets, their type, classification and GWP.

Refrigerant	Type	Classification	GWP [19]	AR reference
R1234ze(Z)	HFO	A2L	0.315	6
R1234yf	HFO	A2L	0.501	6
R1234ze(E)	HFO	A2L	1.37	6
R1270	HC	A3	2	4
R290	HC	A3	3	4
R455A	HFC/HFO blend	A2L	145	4
R454C	HFC/HFO blend	A2L	148	4

[19] 100 year horizon

Refrigerant	Type	Classification	GWP [19]	AR reference
R454A	HFC/HFO blend	A2L	239	4
R450A	HFC/HFO blend	A1	601	4
R513A	HFC/HFO blend	A1	631	4
R32	HFC	A2L	771	6
R448A	HFC/HFO blend	A1	1387	4
R449A	HFC/HFO blend	A1	1397	4
R134a	HFC	A1	1530	6
R407C	HFC	A1	1700	4
R407F	HFC	A1	1824	4
R410A	HFC	A1	2100	4
R407A	HFC	A1	2107	4
R452A	HFC/HFO blend	A1	2140	4

Some HFC and HFO refrigerants are also considered to be per- and polyfluoroalkyl substances (PFAS). PFAS substances are known to be highly persistent in the environment, contaminating groundwater, surface water and soil, and causing serious health effects. In Europe the current working definition of a PFAS substance is that it contains at least one fully fluorinated methyl (CF_3) or methylene (CF_2) group not directly attached to any hydrogen, chlorine, bromine or iodine atom. This covers refrigerants such as R134a which is still used in supermarkets and is one of the constituents of R404A which may still remain in a few supermarkets. PFAS substances include products such as trifluoroacetic acid (TFA). TFAs are deposited on land and in water where there is the potential to accumulate in terminal water bodies and plants. Currently it is unclear whether TFAs have significant environmental impact, but ultimately, under the precautionary principle, the risk should be mitigated if possible. The overall impact of these issues related to refrigerants is the subject of ongoing debate and object of a joint proposal of five EU Countries to ECHA[20]. Responsible end-users, reporting annually their sustainability achievements (taxonomy), will find it more difficult to justify use of PFAS polluting refrigerants.

In early February 2023 the EU European Chemicals Agency (ECHA) published a proposal from Denmark, Germany, the Netherlands, Norway and Sweden to restrict PFAS chemicals under the EU's chemicals REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation. This proposes a restriction on the manufacture, use and sale of certain f-gas substances and blends. Refrigerants included are both HFCs and HFOs and include HFC-125, HFC-134a, HFC-143a, HFO-1234yf, HFO-1234ze(E), HFO–1336mzz(Z) and HFO-1336mzz(E). If accepted the proposal would apply 18 months after entry into force (EiF). This is quite some time away as the ECHA's scientific committees for Risk Assessment and for Socio-Economic Analysis first need to check that the proposed restriction meets the REACH legal requirements. This should occur in March 2023. If the proposal passes this test then a scientific evaluation of the proposal will start by the committees. Consultation will be held over

[20] https://echa.europa.eu/registry-of-restriction-intentions/-/dislist/details/0b0236e18663449b.

approximately a 12-month period so that the ECHA can consult with industry (the period may be extended in this case due to the complexity of the issues). After that the European Commission and EU Member States will decide on potential restrictions. However, irrespective of whether this initiative becomes a legal requirement, there is now considerable ongoing risk when applying HFC and HFO refrigerants.

1.3. Changes in shopping habits

Consumer shopping habits changed rapidly in the COVID-19 pandemic. The use of internet shopping saw rapid increases during the pandemic in some countries. For example, in the UK pre-pandemic ecommerce accounted for 8.7% of all grocery sales. This rose to 15.4% in the pandemic and has since fallen back to 13.3% of all grocery sales[21]. Increases in ecommerce during the pandemic in other European countries were not as significant and this was partially related to the ability of retailers in these countries to service the home delivery demand. Figure 4 shows the sales growth in home delivery in European countries between 2019 and 2020. In all cases sales growth increased or remained stable with an overall increase in growth of 36.6% (overall online sales growth from 19.5% in 2019 to 56.1% in 2020). Certain countries (in particular, The Netherlands, Norway, Sweden, Turkey and the UK) all saw particularly high growth in ecommerce sales in 2020.

Although demand for home delivery has decreased it appears that a significant number of consumers who used home delivery during the pandemic will continue to use home delivery or a click and collect service. More than 50% of consumers intend to continue ecommerce shopping for at least some part of their grocery needs[1].

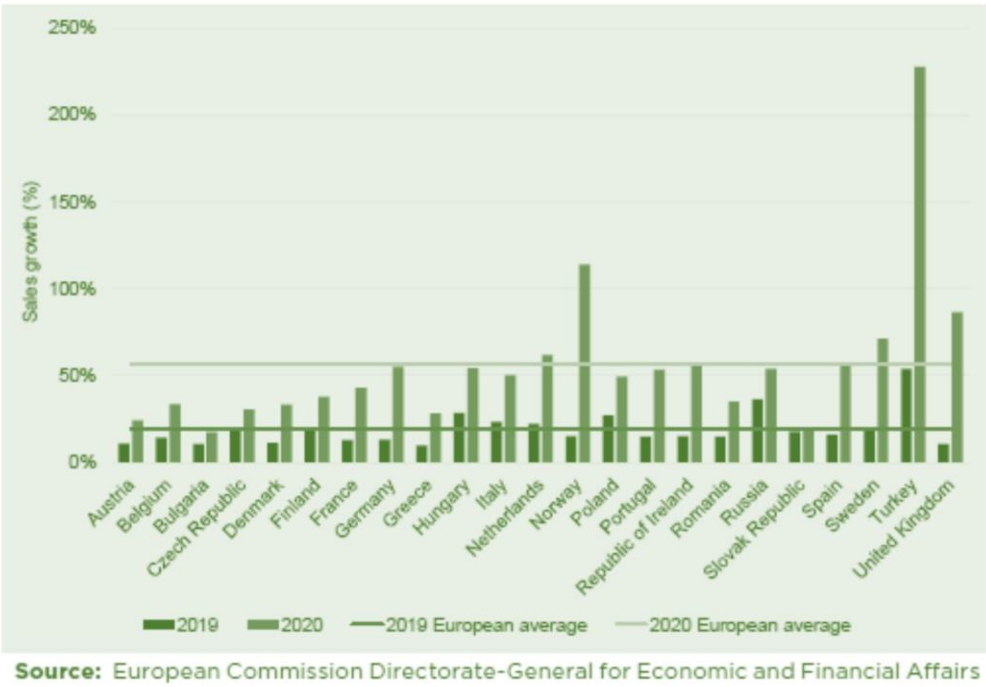

Figure 4. Online food and grocery sales 2019 versus 2020.

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

Changes in shopping habits have also affected shopping location. Consumers have switched to more local sources, partly due to the pandemic, but also due to personal and sometimes financial motives. This was partially due to the pandemic where consumers wished to stay closer to home (or may even had restrictions on their movements) and potentially had more time to visit multiple smaller retailers[22].

1.4. Changes in eating habits

Rising energy costs have had an impact on consumer cooking habits. According to a report from BBC Good Food, since the pandemic (where consumers cooked more) many consumers are reporting using the hob less and microwave more to save energy[23]. Consumers are also reporting that they cook meals that require less cooking and cook less energy intensive meals. In extreme cases some consumers are reporting that they no longer use their oven. Consumer trends are to plan meals better and batch cook to better utilise energy. There is also an increase in the purchasing of frozen food. This is likely to have been partially driven by changes in shopping habits in the pandemic (fewer shopping trips and the wish to store foods in case of lock downs). This also drove an increase in purchase of non-perishable foods. Increased energy costs and the financial crisis are also reported to be having an impact on food waste in the home with 3 in 5 consumers in the UK stating that they are reducing the amount of food they waste and consequently are buying less food[24].

There is a general trend for consumers to consume perceived 'healthier' plant based and more sustainable options. Before the financial crisis (which has changed food choices to those more based on cost) a survey conducted by research company Toluna showed there was a reduction in the consumption of meat-based products with 50% of people saying they have started or were continuing to reduce their meat intake. Since 2019 meat eaters have reduced from 83% to 78%[25]. There is also a growing trend for veganism and vegetarianism (7% saying they planned to consume a vegan diet and 12% a vegetarian diet). There is a growing need for alternative plant-based products which are generally perceived by consumers as being healthy[26].

There is a growing trend for health-based foods. Consumers are also becoming more aware of how their food choices affect the environment and so are more aware of sustainability and interested in provenance and sourcing of foods they buy. In particular packaging has a high profile with consumers who are much more concerned about single use packaging than in the past. One developing trend is for personalisation of food where consumers use technology to select foods that suit their health, welfare and lifestyle choices[27].

All these trends have an impact on supermarkets who will provide choices to consumers according to demand. Currently the major trend is to provide customers with cheaper alternatives and deals to reduce the cost of eating. Although this has been exacerbated by the financial crisis it is a trend that has been ongoing for several years. In the past consumers still bought treats and would trade up to

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

[23] https://www.bbcgoodfood.com/article/bbc-good-food-nation-survey-results-2022.

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

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

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

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

more expensive options for special occasions. This has reduced due to lack of disposable income. Although current supermarket trends are very much driven by food costs, there is still a strong trend for consumers to be very aware of sustainability issues and want brands and supermarkets to be honest in their claims and avoid greenwashing.

1.5. Saving energy and the financial crisis

The financial crisis has impacted both retailers 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 amount of expenditure varies quite considerably between European countries with some countries spending over 25% of their income on food and others as little as 8% (Figure 5)[28]. Household incomes in real terms are decreasing due to increasing prices and limited rises in salaries and benefits. In the UK, household income is projected to decrease by 7% in real terms over 2 years, according to the Office for Budget Responsibility. This is the case for most EU countries where wages will decline in real terms in 2022[29].

Reducing energy consumed also saves cost. With increases in global energy cost 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 has an overall energy reduction for the supermarket as a whole.

More information -
Read more about integration in:
Boreholes and ground sink condensers
Thermal store

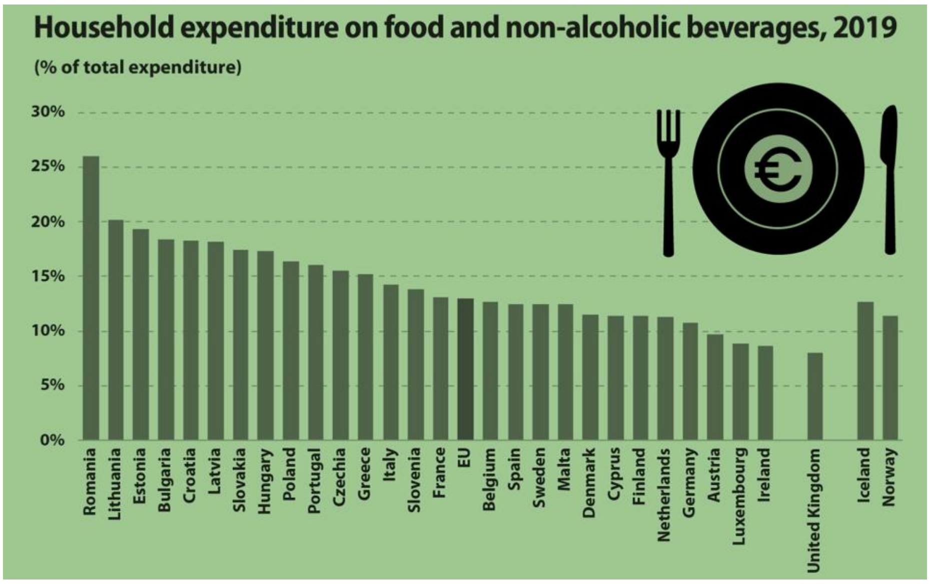

Figure 5. Household expenditures per country in Europe in 2019.

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

[29] Proutat, J-L. European household account: a turbulent story. Eco flash, N°22-11 29 June 2022.

1.6. Legislative pressures

Several pieces of legislation apply directly to carbon emissions in supermarkets. The main regulation that influences energy consumption is Ecodesign. F-gas regulations influence fugitive emissions (see section 5.2).

1.6.1. Energy labelling (Ecodesign)

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[30].

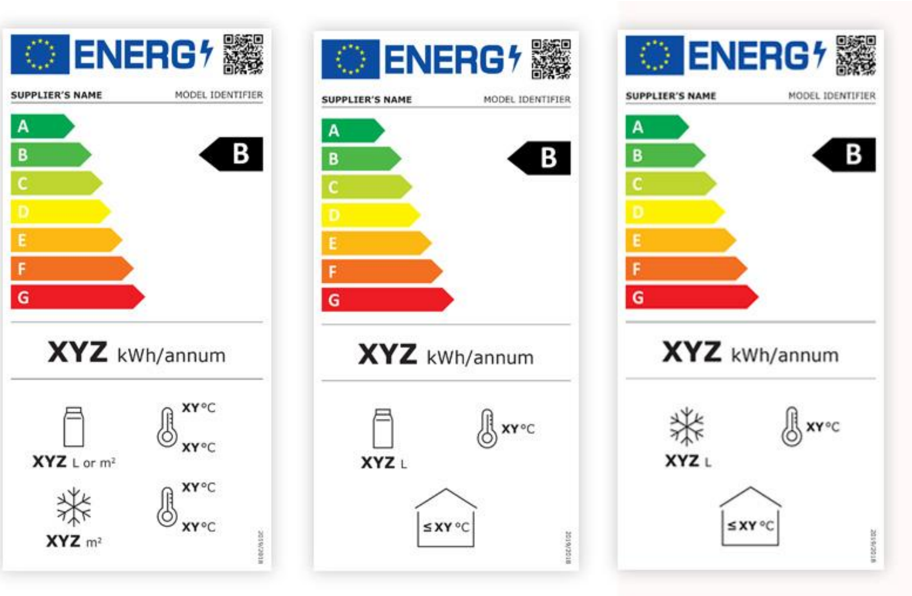


Figure 6. Energy label for (left to right: refrigerating appliances with a direct sales function, except for beverage coolers and ice-cream freezers, beverage coolers, ice-cream freezers.

The energy used by retail display cabinets is legislated via energy labelling and the application of Minimum Energy Performance Standards (MEPS). Regulations for refrigerating appliances with a direct sales function (commercial refrigerated cabinets) came into force on 1 March 2021 and are covered by:

- Commission Delegated Regulation (EU) 2019/2018 of 11 March 2019 supplementing Regulation (EU) 2017/1369 of the European Parliament and of the Council with regard to energy labelling of refrigerating appliances with a direct sales function.
- Commission Regulation (EU) 2019/2024 of 1 October 2019 laying down Ecodesign requirements for refrigerating appliances with a direct sales function pursuant to Directive 2009/125/EC of the European Parliament and of the Council.

The regulations cover refrigerated display cabinets, beverage coolers, ice cream freezers, gelato-scooping cabinets and vending machines. The regulations are expected to lead to energy savings of 48

[30] 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.

TWh in 2030[31]. There is a legal requirement to label the energy efficiency of all refrigerating appliances with a direct sales function if they are sold in Europe (the UK has similar regulations that currently mirror the EU regulations). Retail display cabinets are labelled from A to G (A being the most efficient and G the least). For most supermarket cabinets the label is calculated as an energy efficiency index (EEI) using the EN ISO 23953-Refrigerated display cabinets test standard.

Several types of environmental impact are considered within the Eco-design preparatory phase and include:

1. Material, energy and water resources.
2. Waste.
3. Emissions to air, water and soil.
4. Hazardous substances.
5. Physical impacts in the use phase.

These impacts can occur in manufacturing, use or end of life. 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.

Increasingly there is greater emphasis on maintainability and access to spare parts. For example, in the Ecodesign regulation for refrigerating appliances with a direct sales function there are requirements placed on spare parts and re-use of components. From 1 March 2021 certain spare parts must be available for a minimum of eight years after the last unit of the model is placed on the market. The listed items must be able to be replaced with commonly available tools without permanent damage to the appliance and instructions for fitting the items must be readily available. The items must also be publicly available on the free to access website of the manufacturer; importer or authorised representative at the latest two years after the first unit of the model is placed on the market. Spare parts must be delivered within 15 working days of an order for the component being received. Certain components should be fitted by professional repairers and there is a process for repairers to register with manufacturers, importers or authorised representatives to be able to access maintenance information.

1.7. Temperature control

In supermarkets, there are primarily two temperature ranges for the food: medium temperature (MT) for chilled food preservation and low temperature (LT) for frozen goods. Depending on national and international food safety laws, chilled food is generally kept between -1°C and 8°C. Frozen food has less regulation but is generally kept below -18°C if quick frozen and below -12°C in other cases. The

[31]https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/energy-efficient-products/refrigerators-direct-sales-function_en

refrigerant evaporation temperature range is normally between -15°C and 5°C for the MT level and between -30°C and -40°C for the LT level to provide the necessary food temperatures.

6. FUTURE ISSUES AND TRENDS

1.8. Increased use of renewables

Increased use of renewable energy in supermarkets is a growing trend[32]. This is partially to support the charging of electric vehicles (EVs) for both consumers and home delivery but also to mitigate the large increases in energy seen over the past 6 months. If supermarkets can also store energy (electrically or thermally) it enables them to increase demand side response (DSR) periods or use the stored energy at periods when energy costs are higher. The energy demanded by the supermarket can be quite varied over time and economically there is an optimum level of renewable power that can be justified. The share of the energy produced with the PV plant can be increased dramatically (20 to 70%) by applying some form of energy storage[33].

> More information -
> Read more about renewables in:
> Renewable energy (solar electricity)

1.9. Integration (of heating and cooling)

A supermarket should be considered as a complete energy system (including the building HVAC, hot water, lighting, food retail and food service refrigeration) and the best overall energy use evaluated[34]. This includes the integration of systems to share heat and coolth efficiently.

Retailers have already considered the integration of heat from the refrigeration system to provide store heating (if required) or hot water. Generally, this has been from CO_2 systems where the opportunities for heat reclaim are greater. 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[35]; Sawalha, 2013[36]).

> More information -
> Read more about integration and heat reclaim in:
> Heat pumps and heat reclaim
> Cold air retrieval
> Recover exhaust heat

[32] https://www.tescoplc.com/news/2020/from-solar-farms-to-electric-delivery-fleets-tesco-takes-action-to-hit-net-zero-in-uk-by-2035/

[33] 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.

[34] 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.

[35] 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).

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

1.10. Integration into electricity grid

Retailers 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. 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 often paid to remove load from the grid making DSR an economic proposition for retailers. Generally, retailers can switch off the refrigeration to cabinets for approximately 30 minutes (a typical defrost period) before temperatures start to rise to unacceptable levels. Potential exists to incorporate thermal cold storage or battery energy storage into supermarkets to extend this period.

More information -
Read more about DSR in:
Dynamic demand

1.11. Training and skills

Skills to maintain and operate supermarkets is paramount. Skills cover not only the maintenance and optimisation of the refrigeration systems, HVAC system and supermarket buildings but also how equipment is managed and operated. The reviews expand on issues such as the way display cabinets are loaded with food and operated and the opportunities to select better operating equipment that will save carbon.

Most supermarkets are maintained by facility management companies on behalf of the retail chains. Few retailers employ their own service engineers or personnel who oversee maintenance or installation of new equipment. There is a shortage of skilled technicians, and in particular 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)[37] and has resulted in some retailers making the decision to continue using lower GWP HFC or HFO alternatives, not realising the environmental- and economic benefits of clean cooling solutions.

In supermarkets it is common for the display cabinet refrigeration system and HVAC system to be overseen by separate teams, often with specialist skills. If there is a lack of coordination between the management of the refrigerated cabinets and the HVAC system this can restrict integration of systems which limits the uptake of carbon saving 'cross over' technologies. This is partially due to a skills gap where system designers, end-users, and engineers are not skilled across a range of systems but is also related to the way supermarket estates are managed.

More information -
Read more about low GWP refrigerants in:
Training and maintenance

1.12. Circular economy

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

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

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

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

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

More information -
Read more about re-use and recycling in:
Packaging
Waste technologies and impact of changes (landfill, AD, incineration etc)

7. SUPERMARKET SYSTEMS

1.13. Overall energy use

Smaller sized retail stores tend to have higher energy intensities. This is because smaller stores sell more perishable food in proportion to other goods and therefore have a higher capacity of refrigeration system per floor area. In the UK, for an average supermarket sales floor area of 469 m^2 a mean energy intensity (calculated as the ratio of electrical energy consumption throughout the sales floor area) of 866 $kWh/m^2/yr$ was shown by Foster at al. (2019)[38]. From another study with larger stores (Foster et al., 2018)[39] an average energy intensity of 566 $kWh.m^2/yr$ was given for a sales floor area of 3,306 m^2.

1.14. Systems applied

Depending on the size of the supermarket and the quantity and type of fresh and/or frozen food products, there are most commonly three types of refrigeration systems:

[38] Foster, A., Brown, T., Evans, J. and Maidment, G., 2019. Relationship between specific energy consumption and size of supermarket stores. Refrigeration Science and Technology, 2019, pp.4973-4980.

[39] Foster, A., Evans, J. and Maidment, G.G., 2018, April. Benchmarking of supermarket energy consumption. In 5th IIR International Institute of Refrigeration Conference on Sustainability and the Cold Chain.

a) Self-contained, 'plug-in' or integral display cases, in which the refrigeration system is built into the cabinet and the condenser heat is discharged into the sales area. This type of equipment is commonly used in smaller stores but may also be used in larger stores in combination with a water loop system to cool the condensers or air conditioning systems (to remove the heat from the cabinets which is discharged into the store) that often incorporate the use of free cooling from outside ventilation. Typically, self-contained display cases are factory assembled and have a refrigerant charge of between, 0.1 and 1 kg.

More information -
Read more about water loop systems in:
Water loop systems (plus R1270)

b) Remotely operated systems are generally divided into condensing units and distributed systems or centralised systems each of which may be directly or indirectly operated:
   - Condensing units and distributed systems consist of a condenser and one or two compressors that are installed on the roof or in a small machine room. In small supermarkets and convenience stores, refrigeration is provided by condensing units to a few of the display cabinets. In these systems heat is rejected to ambient. Typically, refrigeration capacities range from 1 kW to 20 kW. Systems are factory built but are installed on-site, where pipework to connect the cabinets and condensing unit are added. Most systems have a charge of between 2 and 15 kg.

- Centralised systems are applied in medium or larger supermarkets (>400 - 20,000 m^2). Systems supply a large number of cabinets from one or several large central systems in a plant room. Pipe runs are often long as the cabinets are located long distances from the refrigeration plant.

Remotely operated systems may be direct or indirect systems.

- Direct systems are most common in most European countries. In these systems the refrigerant circulates from the machinery room via a common liquid supply to the display cabinets where it evaporates and returns through a common suction line as a vapour to the compressor rack (set of multiple compressors) in the machinery room (Figure 7). Racks of medium sized compressors or a smaller number of larger compressors are applied. Due to their larger size, they have a greater compression efficiency (60-70%) compared to smaller compressors which are used in integral cabinets (where compression efficiency is generally ~40-50%). Using a rack of compressors enables the overall system to have modulation and less compressor cycling. The condensers are situated outside the building (often on the roof). Most usually the condensers are air cooled but may occasionally be water cooled or adiabatically cooled. Traditionally it is common to have a separate refrigeration system for the chilled/medium cabinets (MT) and the frozen/low cabinets (LT). However, many R744 systems operate using a coupled booster system where both MT and LT are operated from compressors that are applied at 2 levels in series (Figure 8). This is a simpler and less costly option that is available for both large and smaller stores. Cascade systems can also be applied where an evaporator-condenser heat exchanger connects the LT and MT systems (Figure 9). Traditionally the chilled cabinets will have an evaporation level of -10°C±4K and frozen cabinets -32°C±4K. There are, however, examples of R744 based display cabinets that can operate with evaporating temperatures much higher than this. For example, chilled display cabinets are available where the evaporating temperature can be close to 0°C, which increase the energy efficiency of the system significantly, and eliminates the demand for defrosting. Centralised direct systems often have a large refrigerant charge of 100 to 3,000 kg. Consequently, if there is a leak of refrigerant this can be significant. Historically leakage was 15-20% of the charge per year, but this has reduced considerably due to improved design and maintenance, environmental, legislative and financial pressures to achieve leakage rates of 5% per year.

- Indirect systems use a heat transfer fluid (HTF) or secondary refrigerant that is cooled via a heat exchanger by the primary refrigeration system and then pumped to the display cabinets where heat is extracted, and the fluid is then returned to be re-cooled. The heat transfer fluids typically applied are single phase liquids (such as brine or glycol), ice slurry or CO_2. The primary refrigeration system is either in a plant room or on the roof of the store. Using a HTF means that the primary systems needs less refrigerant charge and that the charge is contained in a small area where it can be better manged and controlled. Consequently, it is simpler to apply a flammable or toxic refrigerant to the primary circuit as the refrigerant is not distributed to areas where customers are present or areas where there may be sparking components. The negative is that there are thermal losses in the system and pumping energy can be significant, especially for low temperature systems where the HTF may be extremely viscous. However, the advantage is that it is simple to incorporate thermal storage into the system which allows efficient use of renewable energy and integration into the grid. Generally indirect systems are less energy efficient than direct systems and are more costly to install.

  Another indirect system that is occasionally applied is the direct use of centrally cooled air to directly cool a chilled display cabinet.

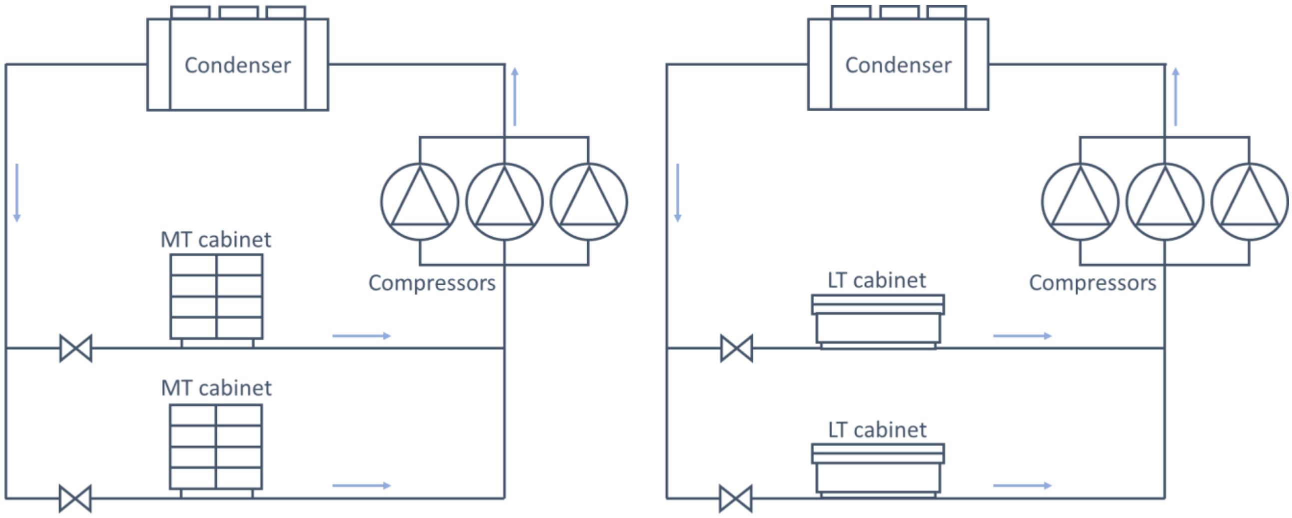


Figure 7. Simple direct expansion (DX) system.

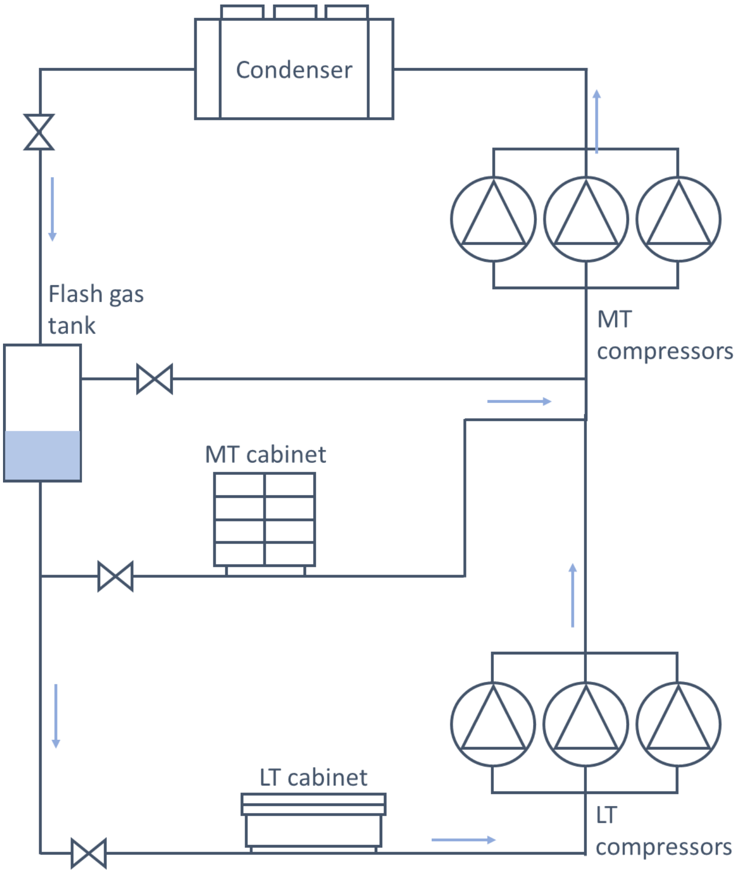


Figure 8. R744 booster system.

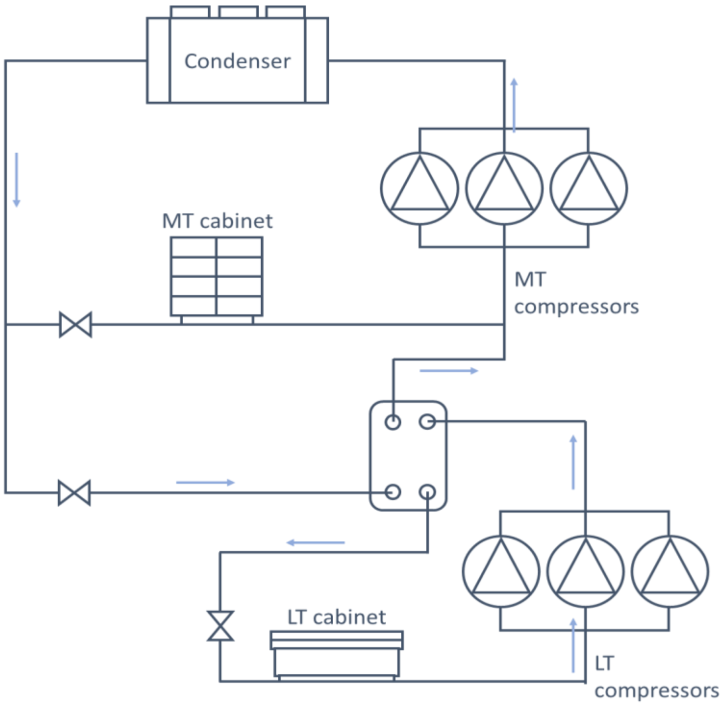


Figure 9. Cascade system.

8. BEST AVAILABLE TECHNOLOGY (BAT)

What are the most efficient display cabinets currently available? The most efficient (lowest energy efficiency index (EEI)) commercial refrigerated cabinets from Topten[40] are labelled as A, B or C according to their type. (Figure 10).

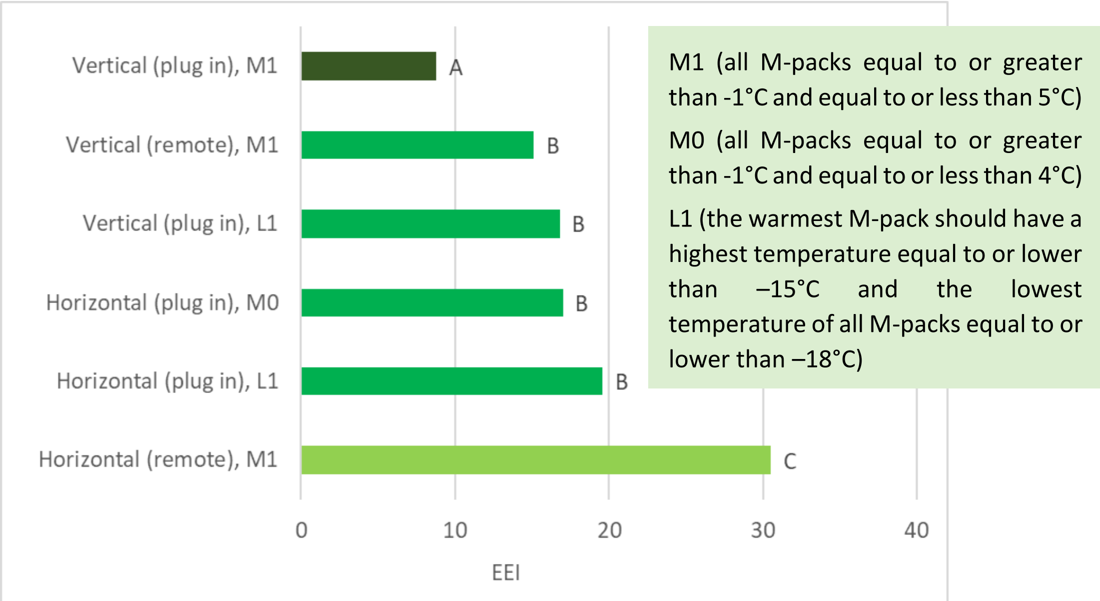


Figure 10. Most efficient refrigerated cabinets listed on Topten.

All cabinets listed on Topten apply natural refrigerants. Therefore, all remote cabinets use R744 and all integrals use R290. Efficiency is achieved by applying:

- Doors on all vertical cabinets (hinged doors).
- Double glazing on chilled cabinets and triple glazing and low e glazing on frozen cabinets.
- LED lightsome all cabinets.
- Off cycle defrost on chilled cabinets.
- Energy efficient fans on all cabinets.
- Variable speed drives (VSDs) on some integrals.
- 70 mm wall thickness on frozen cabinets.

More information -
Read more about efficient display cabinets in:
Cabinet replacement with high efficiency version

[40] https://www.topten.eu/

9. TECHNOLOGIES/STRATEGIES

Energy saving technologies/strategies were initially identified and listed. In total 95 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 greenhouse gas emissions that a technology could save and any constraints around the use/application of the technology were reported. In addition, the cost for application of the technology and the technology readiness level (TRL) level were listed if available. If a technology was not currently available, the approximate time until it could be deployed was estimated (Table 3).

SCOPE 1 EMISSIONS

Scope 1 covers emissions from sources that an organisation owns or controls directly – for example from burning fuel.

SCOPE 2 EMISSIONS

Scope 2 are emissions that a company causes indirectly when the energy it purchases and uses is produced.

The 95 technologies and strategies were classified according to whether they could be applied rapidly to a current supermarket (minor retrofit) or would require more extensive modification (major retrofit) (Table 4). Whether savings were scope 1 or 2 were assessed. The TRL level of the technology is noted in Table 4. 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.

Table 3. 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

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

Technology	Sector in supermarket	TRL level	Where applied:		Carbon savings	
			Minor retrofit	Major retrofit	Scope 1	Scope 2
Display cabinets:						
Adiabatic condensers	Refrigeration	8-9	✓	✓		✓
Aerofoil air-guide	Refrigeration	8-9	✓	✓		✓
Anti-fogging glass	Refrigeration	8-9	✓(as part of doors)	✓		✓
Anti-sweat heater control	Refrigeration	8-9	✓(as part of doors)	✓		✓
Boreholes and ground sink condensers	Refrigeration	8-9		✓		✓
Cabinet lighting controls -dimming/ switching/ occupancy sensors	Refrigeration	8-9	✓	✓		✓
Cabinet replacement with high efficiency version	Refrigeration	8-9		✓		✓
Centralised air distribution	Refrigeration	5-7		✓		✓
Defrost on demand	Refrigeration	8-9	✓	✓		✓
Defrost type	Refrigeration	Varied		✓		✓
Distributed refrigeration system	Refrigeration	8-9		✓		✓
Doors on cabinets	Refrigeration	8-9	✓	✓		✓
Dynamic demand	Refrigeration	8-9	✓	✓		✓
Economisers	Refrigeration	8-9		✓		✓
Ejectors	Refrigeration	8-9		✓		✓
Electronic expansion valves	Refrigeration	8-9		✓		✓
Expanders	Refrigeration	1-4		✓		✓
Fan motor outside of cabinet	Refrigeration	1-4		✓		✓
Flooded evaporators (added to R744)	Refrigeration	8-9		✓		✓

Technology	Sector in supermarket	TRL level	Where applied:		Carbon savings	
			Minor retrofit	Major retrofit	Scope 1	Scope 2
Heat from light outside cabinet	Refrigeration	5-7		✓		✓
Heat pipes	Refrigeration	1-4		✓		✓
Hydrophilic and hydrophobic coating on evaporators	Refrigeration	1-4		✓		✓
Improved axial fans	Refrigeration	5-7	✓	✓		✓
Improved cabinet loading	Refrigeration	8-9	✓	✓		✓
Improved cabinet location	Refrigeration	n/a	✓	✓		✓
Improved glazing	Refrigeration	8-9	✓(as part of doors)	✓		✓
Increased cabinet set point	Refrigeration	n/a	✓	✓		✓
Internet shopping	Refrigeration	5-7		✓	✓	✓
Lighting (cabinets) - efficiency	Refrigeration	8-9	✓	✓		✓
Lighting (store) - efficiency	Refrigeration	8-9	✓	✓		✓
Liquid pressure amplification (LPA)	Refrigeration	5-7	✓	✓		✓
Liquid-suction heat exchangers	Refrigeration	8-9		✓		✓
Loading (food) – reducing heat load	Refrigeration	8-9	✓	✓		✓
Magnetic refrigeration	Refrigeration	1-4		✓		✓
Motor Efficiency Controllers (MECs)	Refrigeration	8-9	✓	✓		✓
Nanoparticles in refrigerant	Refrigeration	1-4		✓		✓
Night blinds and covers	Refrigeration	8-9	✓	✓		✓
Novel heat exchanger designs	Refrigeration	5-7		✓		✓
Peltier cooling	Refrigeration	5-7		✓		✓
Pipe insulation	Refrigeration	8-9		✓		✓
Pipe pressure drops minimisation	Refrigeration	8-9		✓		✓
Recommissioning	Refrigeration	8-9	✓			✓
Reducing/floating head pressure	Refrigeration	8-9	✓	✓		✓
Reducing thermal radiation	Refrigeration	8-9	✓	✓		✓
Refrigerant - Carbon dioxide (CO_2, R744)	Refrigeration	8-9		✓	✓	✓
Refrigerant - HFO refrigerants and blends	Refrigeration	8-9	✓	✓	✓	✓
Refrigerant - HC refrigerants	Refrigeration	8-9		✓	✓	✓
Secondary systems	Refrigeration	8-9		✓	✓	✓
Shelf risers and weir plates	Refrigeration	8-9	✓	✓		✓
Short air curtains	Refrigeration	8-9		✓		✓
Store dehumidification	Refrigeration	8-9		✓		✓
Store temperature control (increase/decrease set points)	Refrigeration	8-9	✓	✓		✓

Technology	Sector in supermarket	TRL level	Where applied:		Carbon savings	
			Minor retrofit	Major retrofit	Scope 1	Scope 2
Strip curtains	Refrigeration	8-9	✓	✓		✓
Suction pressure control	Refrigeration	8-9	✓	✓		✓
Tangential fans	Refrigeration	8-9		✓		✓
Thermal store	Refrigeration	8-9	✓	✓		✓
Thermostatic flow control (TFC)	Refrigeration	1-4		✓		✓
Training and maintenance	Refrigeration	8-9	✓	✓		✓
Trigeneration	Refrigeration	5-7		✓		✓
Two stage compression	Refrigeration	8-9		✓		✓
Vacuum insulated panels (VIP)	Refrigeration	5-7		✓		✓
Variable Speed drives (VSDs)	Refrigeration	8-9		✓		✓
Water loop systems	Refrigeration	8-9		✓		✓
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		✓		✓
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		✓		✓

Technology	Sector in supermarket	TRL level	Where applied:		Carbon savings	
			Minor retrofit	Major retrofit	Scope 1	Scope 2
Heat pumps, heat reclaim and radiant heat	HVAC	8-9		✓	✓	✓
Natural/passive ventilation	HVAC	8-9		✓	✓ (gas)	✓ (elec)
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	✓	✓		✓
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)

1.15. 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%, <10% saving

High (H): >10% saving

Payback time:

<1 year

<3 years

<5 years

>5 years

Neutral/limited information

Negative payback (only a carbon saving)

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

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

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

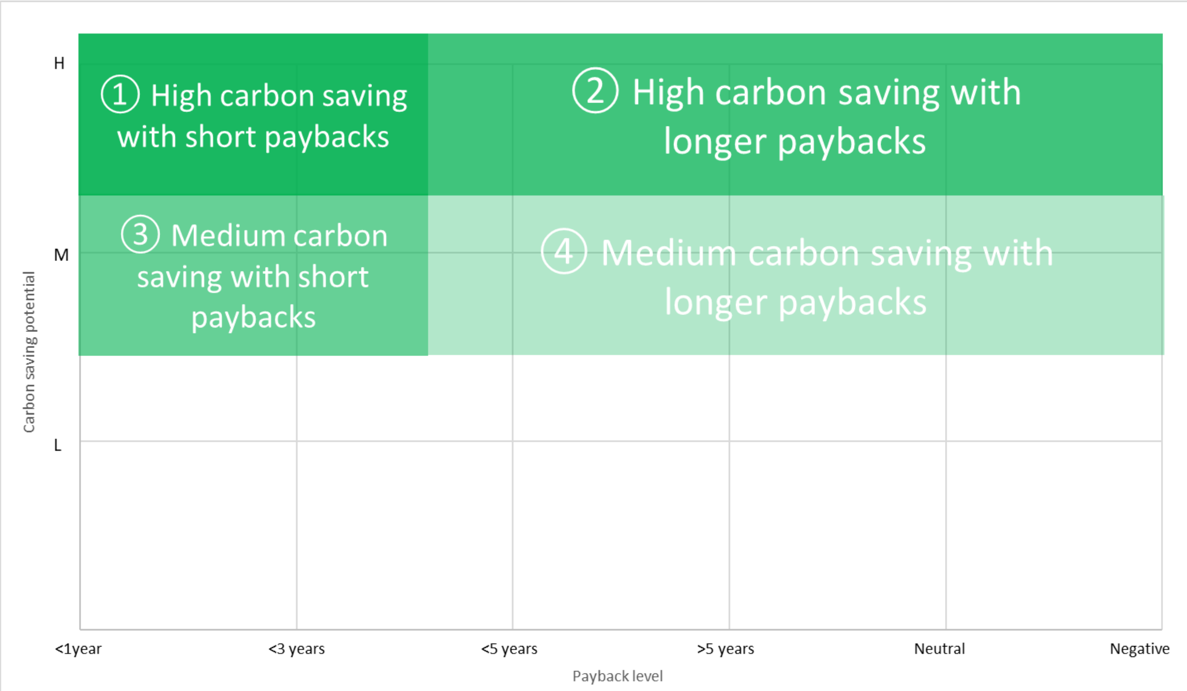


Figure 11. Potential carbon savings and payback sectors.

Technologies with a TRL of 8-9 were assessed using the above methodology. Results are presented in Figure 12, Figure 13, Figure 14 and Figure 15. It should be noted that several technologies had overlapping impacts or could not be applied in tandem. For example, if doors were applied to cabinets there was no benefit of also applying aerofoils, strip curtains or night blinds and covers. 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.

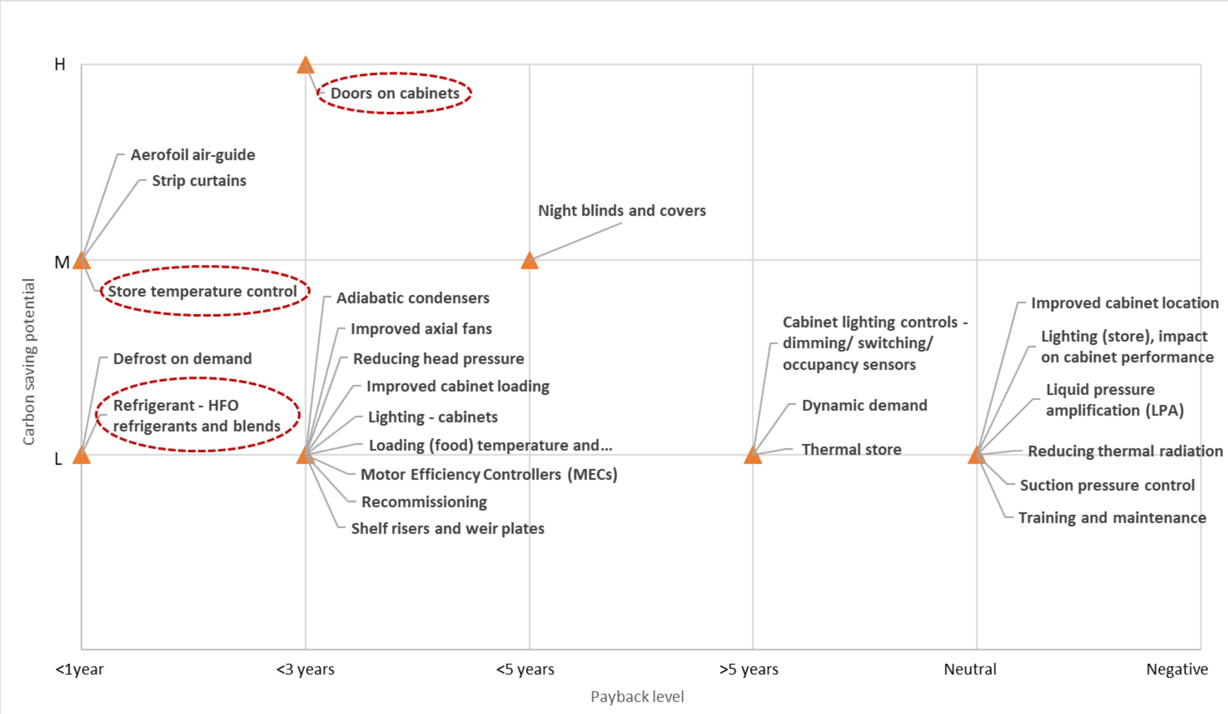


Figure 12. Refrigeration minor retrofit options.

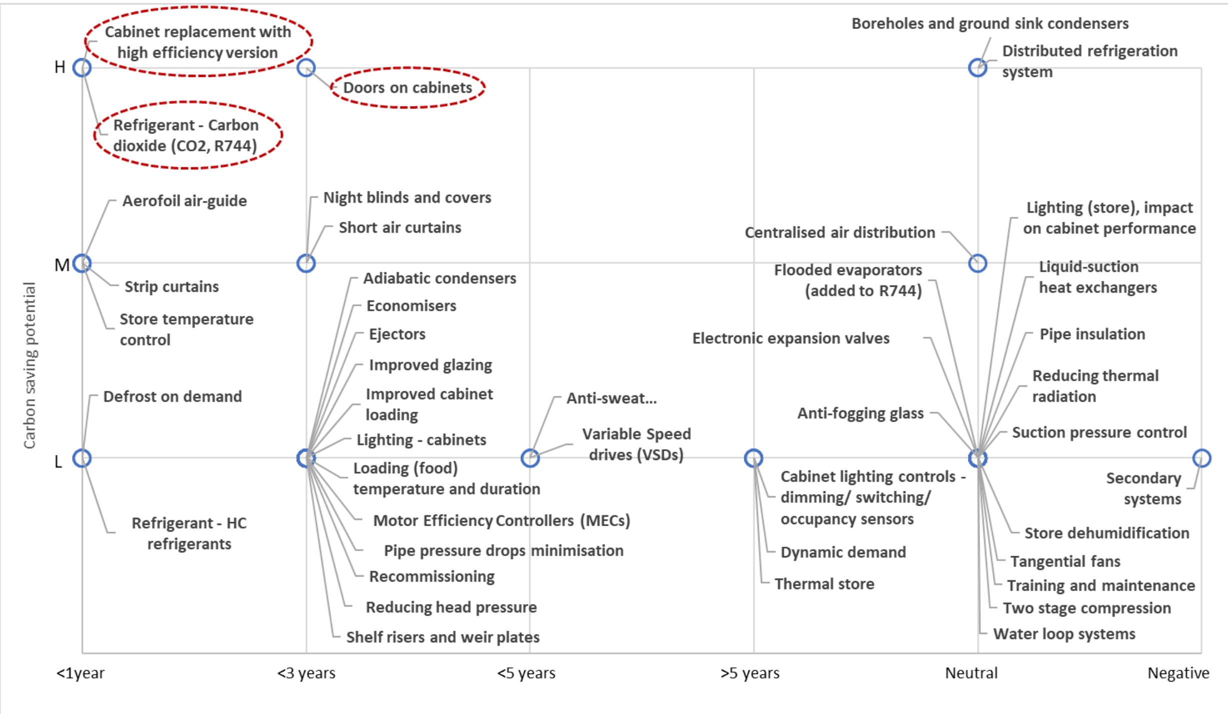


Figure 13. Refrigeration major retrofit options.

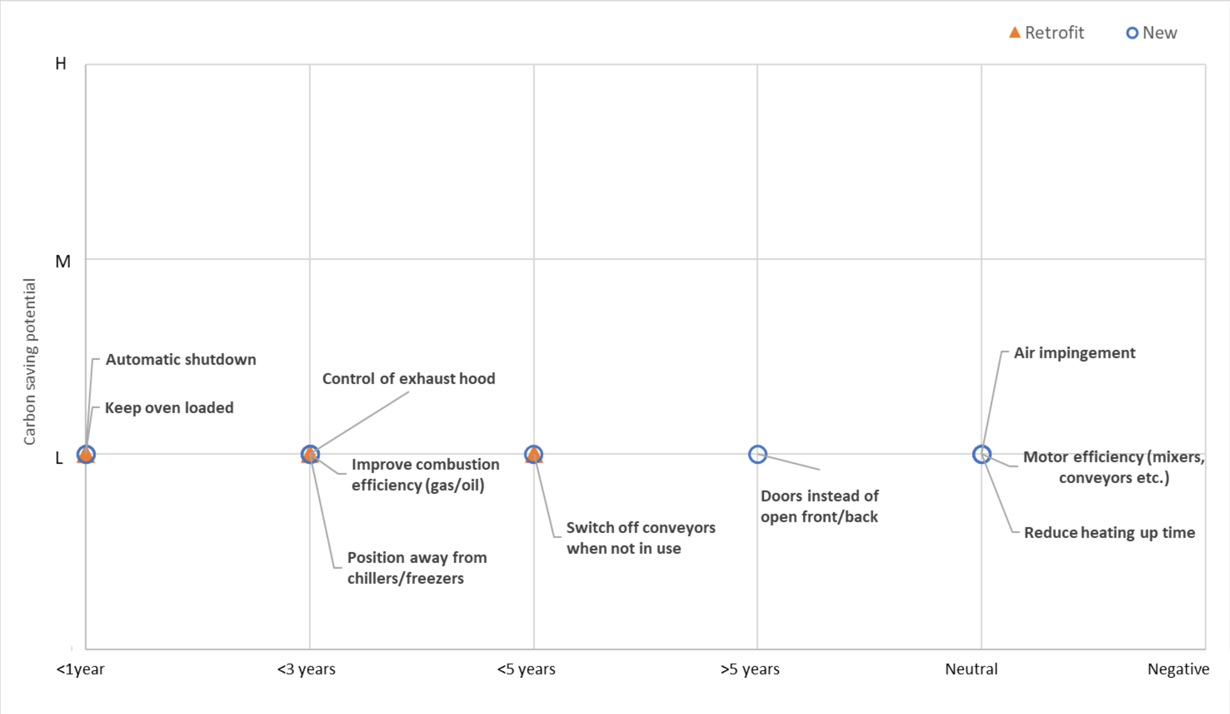


Figure 14. Options to cooking.

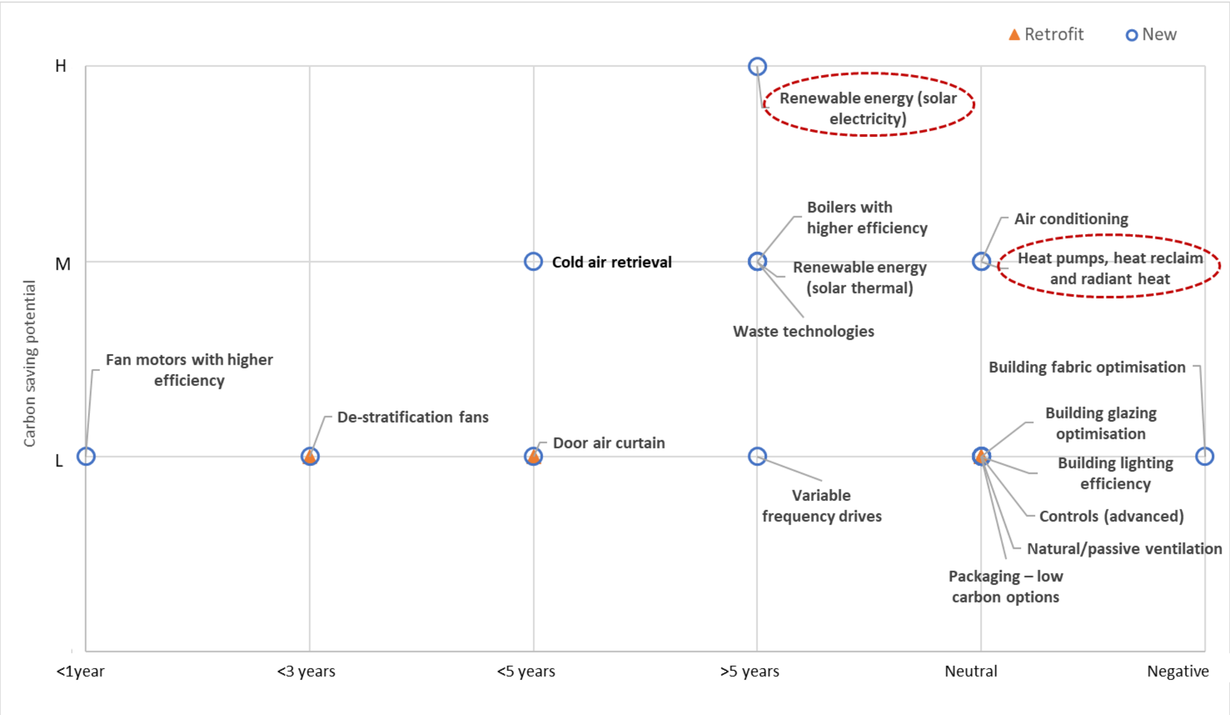


Figure 15. Options for Air conditioning and building fabric.

1.16. What strategies should we apply to get to zero carbon in supermarkets?

The options with the most potential were then applied into an Energy Plus model of a typical European small (600 m^2) and a larger (2,100 m^2) supermarket in 6 European countries (UK, France, Lithuania, Norway, Italy, Poland) to assess their individual and combined potential to reduce carbon emissions.

Why we modelled a typical supermarket

To be able to assess the technologies and strategies for a whole supermarket we need to consider the interactions between all the heating and cooling systems in a store and also whether there are interactions between individual technologies. For example, one technology may reduce the need for cooling in a store, 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. For example, adding doors to cabinets will reduce the impact of store heating technologies as the cabinets will add less cooling to the store. 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 for the display cabinets, HVAC (heating and cooling) and other store items such as cookers and cold store.

1.16.1. Scenarios

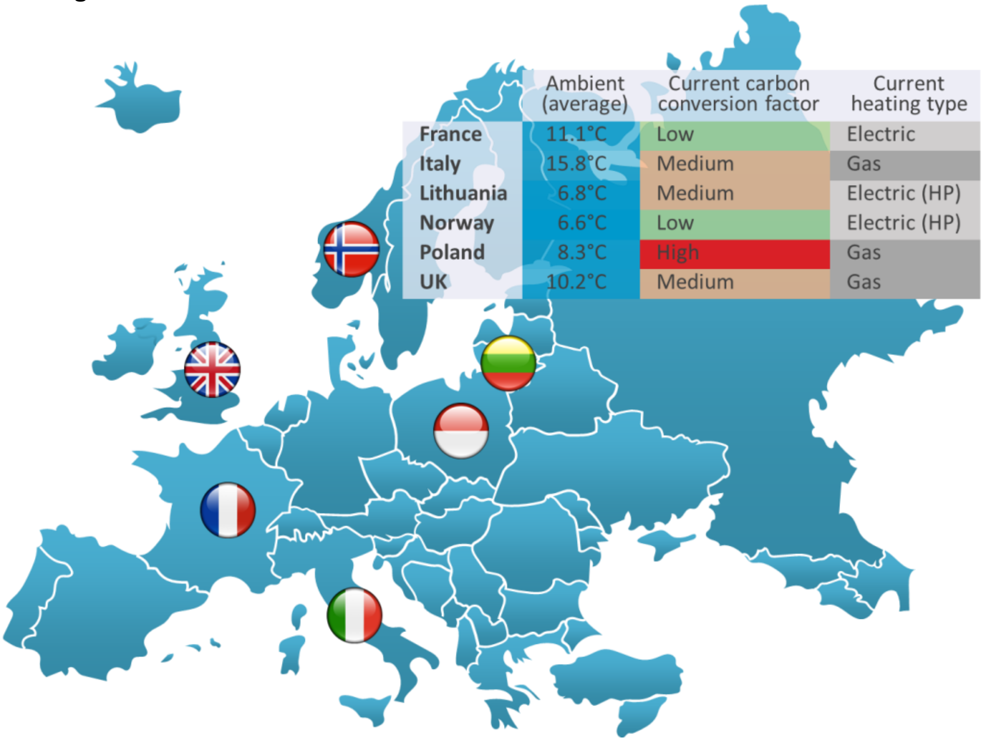
Three scenarios were considered in the modelling:

4. Do nothing
5. Minor retrofit
6. Major retrofit

The impact of building a completely new supermarket was not considered as no technologies reviewed had sufficiently high carbon savings or sufficiently low paybacks.

1.1.1.1 Do nothing

This considered the carbon savings if supermarkets 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 carbon 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



	Ambient (average)	Current carbon conversion factor	Current heating type
France	11.1°C	Low	Electric
Italy	15.8°C	Medium	Gas
Lithuania	6.8°C	Medium	Electric (HP)
Norway	6.6°C	Low	Electric (HP)
Poland	8.3°C	High	Gas
UK	10.2°C	Medium	Gas

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.

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

1.1.1.2 Minor retrofit

Retrofit options can be considered as a shorter-term option for supermarkets. Minor retrofits are really only suitable for stores that are not due to be replaced in the near future or undergo major refurbishment. 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. Doors on cabinets (we did not consider aerofoils, strip curtain or night blinds, which came out as having higher carbon savings, as these are not applied with doors)
2. HFO refrigerants (small stores)
3. Increase dead band of the store ambient temperature by 2K

Each retrofit option was applied from 2020 onwards, in addition to the 'do nothing' scenario, individually to assess benefits for each store type, country 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.

1.1.1.3 Major retrofit

Some technologies would be more difficult and may require the store closing for a period of time, these are considered a major retrofit. Technologies applied were in addition to the 'do nothing' and 'minor-retrofit' scenarios and considered energy consumption and carbon emissions for the 2 supermarket types through to 2050. The technologies applied were:

1. Apply R744 to smaller supermarkets (it was assumed that all new supermarkets would apply natural refrigerants)
2. 20% better cabinets
3. Change heating to heat pumps from gas or resistive electrical heating (for relevant scenarios)
4. RES (solar)

As in previous scenarios, each technology was applied individually and then all technologies were applied together.

1.16.2. 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 a significant factor in reducing global warming. By applying the 3 scenarios we calculated the total carbon savings that can be achieved from 2020 to 2050 and the impact of accelerating the move to climate friendly technologies. For example, the accumulated carbon emissions from 2020 to 2050 in a worked example would be for (Figure 16):

Do nothing: 1718 tCO_{2e}

Minor retrofit: 1042 tCO_{2e}

Major retrofit: 375 tCO_{2e}

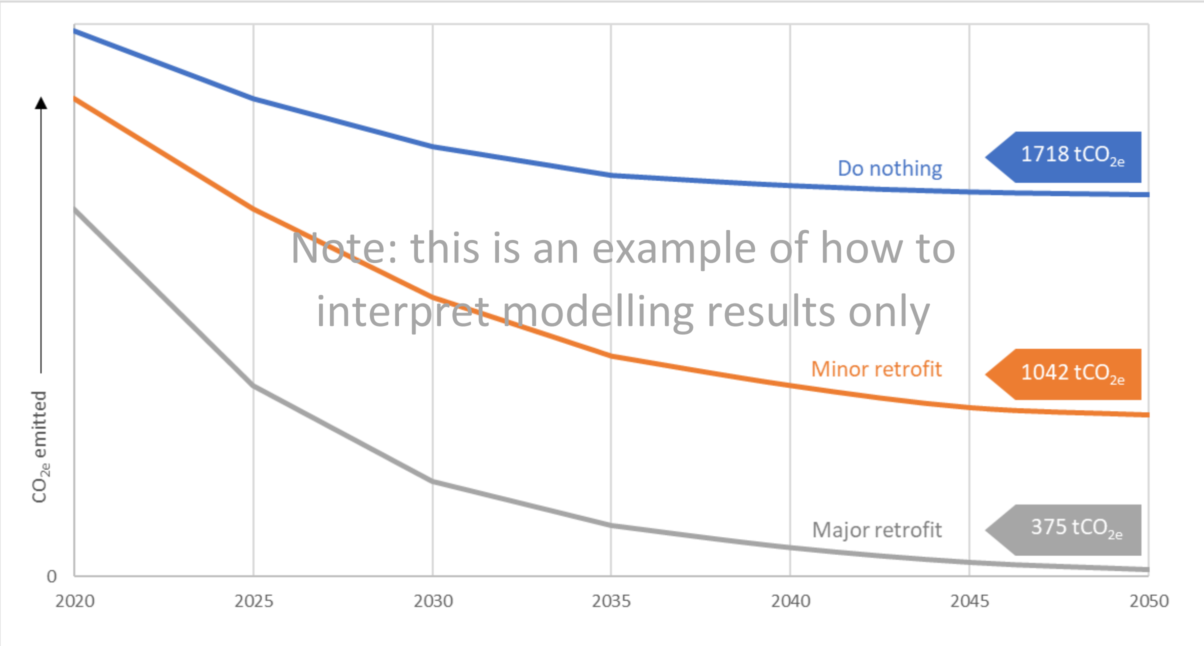


Figure 16. Diagram showing impact of when technologies are applied (example only).

Other options can then be selected to assess impacts of when changes are made on accumulated carbon savings (Figure 17). For example:

- If the store 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.

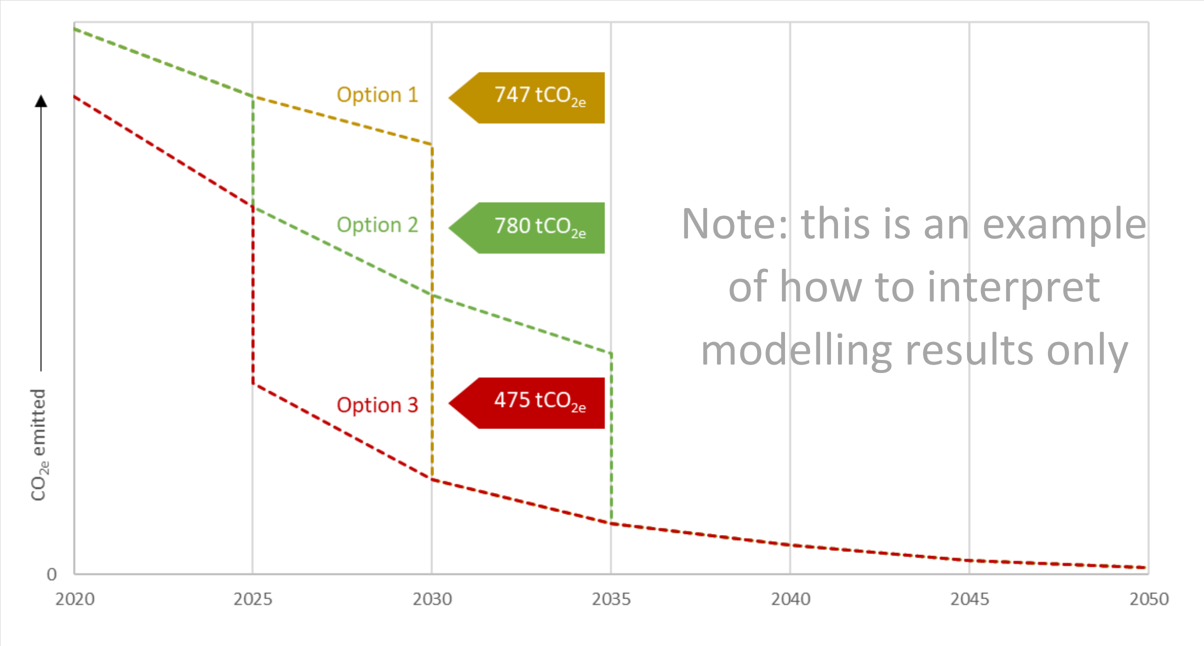


Figure 17. Diagram showing impact of when different scenarios are applied (example only).

1.16.3. Assumptions applied in the modelling

Openstudio with EnergyPlus 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 12.

The modelling was based on a medium sized (total store size of 2,100 m^2) supermarket case study in Paris. The inputs to the model are shown in Section 12.4.8.

A smaller supermarket (600 m^2) was also modelled. The smaller supermarket was assumed to use R448A refrigerant instead of R744, and the quantity of refrigerant was assumed to be 232 kg.

These two sizes of supermarkets were then modelled at different locations, where the weather file of each location was used. The 6 locations were, Paris (France), London (UK), Kaunas (Lithuania), Warsaw (Poland), Oslo (Norway) and Rome (Italy).

The type of heating was also changed to what tended to be used in those countries. Heating was natural gas for UK, Italy and Poland, electric resistive heating for France and electric heat pump for Lithuania and Norway (nominal COP of 2.75).

1.16.4. Scenario 1: do nothing

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

Impact of climatic temperature change: Figure 18 (2,100 m^2 store) and Figure 19 (600 m^2 store) show 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 (display cabinets).

Overall differences between energy consumed in 2020 and 2050 were small (less than 2% for both the larger and small store). The low impact of increasing climatic temperature was due to a balance between the heating and cooling demands on the supermarkets. As climatic temperatures increased there was less energy demand for heating, but this was balanced by the increased energy demand for cooling and refrigeration.

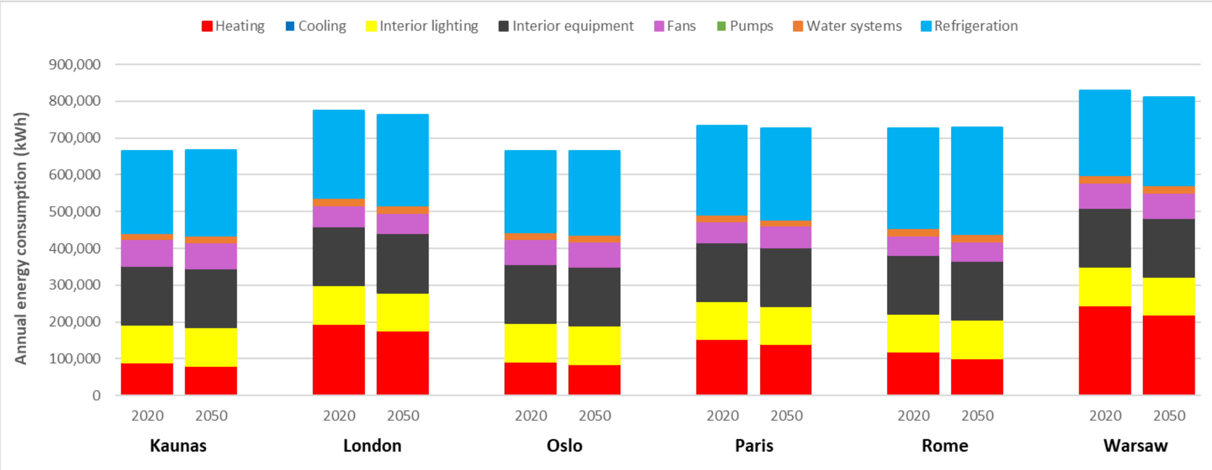


Figure 18. Impact of climatic temperature change on annual energy consumption between 2020 and 2050 for the 2,100 m² supermarket in the 6 locations studied.

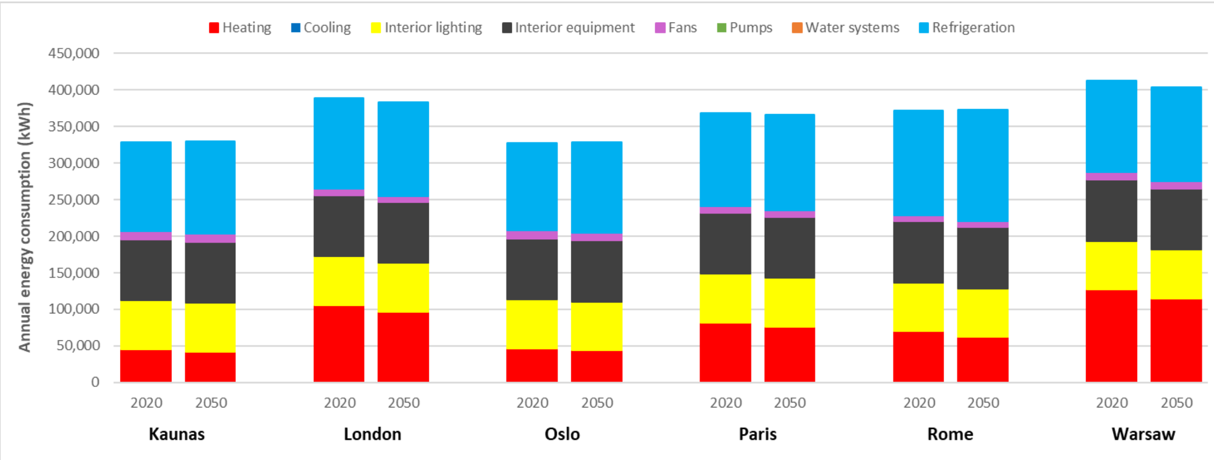


Figure 19. Impact of climatic temperature change on annual energy consumption between 2020 and 2050 for the 600 m² supermarket in the 6 locations studied.

Impact of changes to electrical grid conversion factors: over time the carbon intensity of the electricity grid is predicted to decrease considerably. Figure 20 presents (where available) the changes to the grid intensity factors in the 6 countries. Information on predicted grid carbon conversion factors was only available for 4 of the countries modelled (France Lithuania, Poland (to 2040 only) and the UK). 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 reduce considerably, it is still the highest of the 6 countries considered in 2040.

Figure 20. Grid electrical carbon conversion factors for the 6 countries studied (where available).

The significant changes to carbon intensity over time had a major impact on emissions for the supermarkets studied. Figure 21 presents the total carbon emissions for the 2,100 m^2 store and Figure 38 presents the total emissions for the 600 m^2 store. Although carbon emission factors reach almost zero in the UK by 2050 the store emissions did not reach zero in the UK by 2050 due to the assumption that store heating will still be fuelled by natural gas. In France and Lithuania where heating is provided by electricity, the total emissions reached almost zero for the medium stores by 2050. Although forward emission figures for Norway were unavailable, the store in Oslo would also be close to zero emissions in 2050 as it seems unlikely that the 2020 carbon intensity would increase. None of the small stores reached close to zero emissions and this was due to them using R448A as the refrigerant (GWP of 1387) and sometimes gas heating.

Although the carbon emitted at an instantaneous point in time is important, it is equally important, if not more, to consider the total carbon emitted over a period of time. The accumulated carbon emitted between 2020 and 2050 when the ‘do nothing’ scenario was applied is presented in

Do nothing scenario

If the case study supermarkets make no changes to how they operate between 2020 and 2050, it is only possible to reach close to net zero if the grid carbon conversion factor is almost zero, no gas is used for heating and the refrigerant applied has a very low GWP. Near net zero would only be achieved in 2050 for the medium case study stores in Lithuania and Norway.

The accumulated carbon emitted up to 2050 should be considered and not just the final emissions in 2050. The rate at which change occurs is therefore important and should be considered in any carbon reduction assessment.

Table *5* for the 2 supermarket configurations. Clearly Paris has the lowest accumulated carbon emissions and Warsaw the highest.

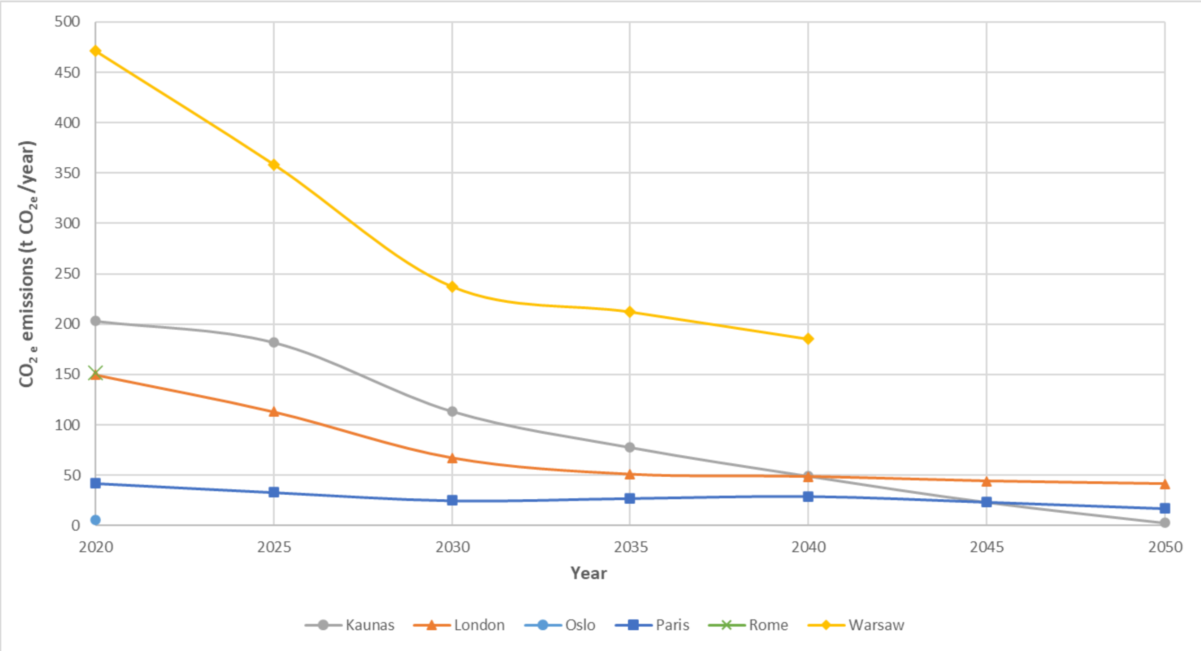


Figure 21. Impact of grid carbon emission factor change on total carbon emitted by the 2,100 m^2 supermarket in the 6 locations studied.

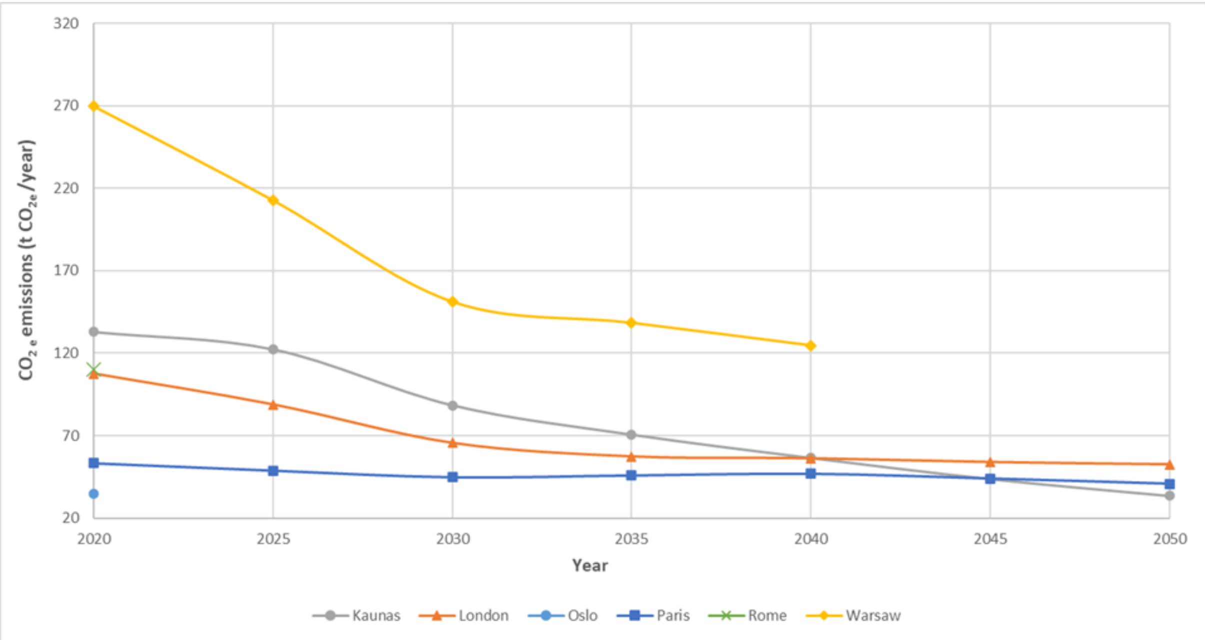


Figure 22. Impact of grid carbon emission factor change on total carbon emitted by the 600 m^2 supermarket in the 6 locations studied.

Table 5. Accumulated carbon emitted between 2020 and 2040/2050 for Kaunas, London, Paris and Warsaw for the BAU scenario.

	Accumulated tCO_{2e} emitted between 2020 and 2040/2050	
	2,100 m^2 supermarket	600 m^2 supermarket
Kaunas (2050)	2,759	2,346
London (2050)	2,090	2,006
Paris (2050)	835	1,391
Warsaw (data for 2040 only)	5,713	3,545

1.16.5. Scenario 2: minor retrofit

Initially each retrofit technology was applied individually and then in combination to the 2 store formats (2,100/600 m^2) and the impact assessed to 2050 assuming the same changes as applied in the 'do nothing' scenario. The following technologies were applied, and the following assumptions were made:

Increase store ambient dead band temperature by 2K: The store cooling set point was increased by 1°C and the heating set point reduced by 1°C.

HFO refrigerants: This was only applicable to the small store format as R744 was applied to the large store format. A refrigerant with a GWP of 150 was assumed.

Doors on cabinets: Doors were added to the open fronted chilled cabinets.

The impact of the technologies alone and combined on energy consumption are shown in Figure 23 (2,100 m^2 store) and Figure 24 (600 m^2 store). The impact of the technologies alone and in combination on carbon emission are shown in Figure 25 (2,100 m^2 store) and Figure 26 (600 m^2 store).

The impact that the technologies applied had in combination on carbon emissions between 2020 and 2050 are presented in Figure 27 (2,100 m^2 store) and Figure 28 (600 m^2 store) where available information was available for grid carbon conversion factors.

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

Increase store ambient dead band temperature by 2K

ENERGY: Changing the store dead band temperature had varied impacts in the different countries but within a country resulted in relatively similar percentage savings in energy in both sized stores. Energy savings were greater in countries that applied either gas or direct electrical resistive heating (London, Paris, Rome and Warsaw) and lowest in those that applied heat pumps (Olso and Kaunas). This was because of the electrical conversion efficiency of the heat pumps which had a COP of 2.75, versus direct electrical heating with a conversion of 1, and gas with a conversion of 0.8.

CARBON EMISSIONS: Reductions in emissions again tended to be greatest in countries where gas or electric resistive heating was applied. The exception was Warsaw, and this was due to the high grid carbon emissions factors in Poland (0.75 kg CO_{2e}/kWh for electricity versus 0.184 kg CO_{2e}/kWh for gas). This meant that although increasing the store dead band was beneficial, the benefits were not as great in terms of reducing carbon emissions as the grid conversion factor was so much higher for electricity than gas. This will obviously change moving forward as the electrical grid conversion factor is predicted to reduce in Poland. The impact of increasing the dead band temperature in the store was most beneficial in countries that benefited from the increase and decrease in the set point. Some location such as Oslo and Kaunas only benefitted from reducing the heating set point as they were colder locations.

HFO refrigerants

CARBON EMISSIONS: HFO refrigerants were only added to the small stores and only had an impact on carbon emissions (not energy use). The overall impact on carbon emissions from the whole supermarket of changing to a low GWP refrigerant was greatest in the countries with the lowest grid emission conversion factors (Oslo and Paris). In these locations changing to a low GWP refrigerant reduced overall carbon emissions by 82% in Oslo and 53% in Paris. In Warsaw which has the highest grid electricity conversion factor, the saving was only 11%.

Doors on cabinets

ENERGY: The impact of adding doors was always higher in the small store as a greater proportion of the energy was used for refrigeration. Individually adding doors saved between 18 and 35% of the overall store energy. The impact of adding doors reduced the need for heating in the stores. The stores with heat pumps saw less reduction in energy than the stores which heated using resistive electrical heating (Paris) of gas (London, Rome and Warsaw). This was due to the greater thermal conversion efficiency of the heat pumps as described above.

CARBON EMISSIONS: Adding doors to the cabinets reduced the need for heating in the stores and so tended to be most beneficial in the coldest countries (Lithuania, Norway and Poland). Adding doors to the small stores in Oslo whilst the small stores still operated on R448A had only a small impact as the grid carbon conversion factor was low and the refrigerant, so the refrigerant emissions dominated the carbon emissions.

Overall impact

ENERGY: Overall energy savings from applying changes to the store dead band and adding doors reduced energy use by between 19 and 37%. Overall impacts were always higher in the locations that applied gas or electrical resistance heating.

CARBON EMISSIONS: Reductions in carbon emissions varied from 18 to 84%. Reductions were always higher in the small stores due to changing from R448A (with a GWP of 1387) to an HFO refrigerant with a GWP of 150. Percentage carbon reductions were particularly high in Oslo and Paris due to the low grid carbon intensities in these countries which meant that the carbon emissions were dominated by fugitive emissions and not electrical energy use. In the medium stores, the greatest percentage reductions in carbon emissions were in London, Paris and Rome where gas or electrical resistance heating was applied. Gas was also applied in Warsaw but due to the high electrical grid carbon intensities the same level of carbon savings were not apparent.

As in the BAU scenario Paris had the least carbon accumulated emissions (to 2050), while Warsaw had the most (to 2040).

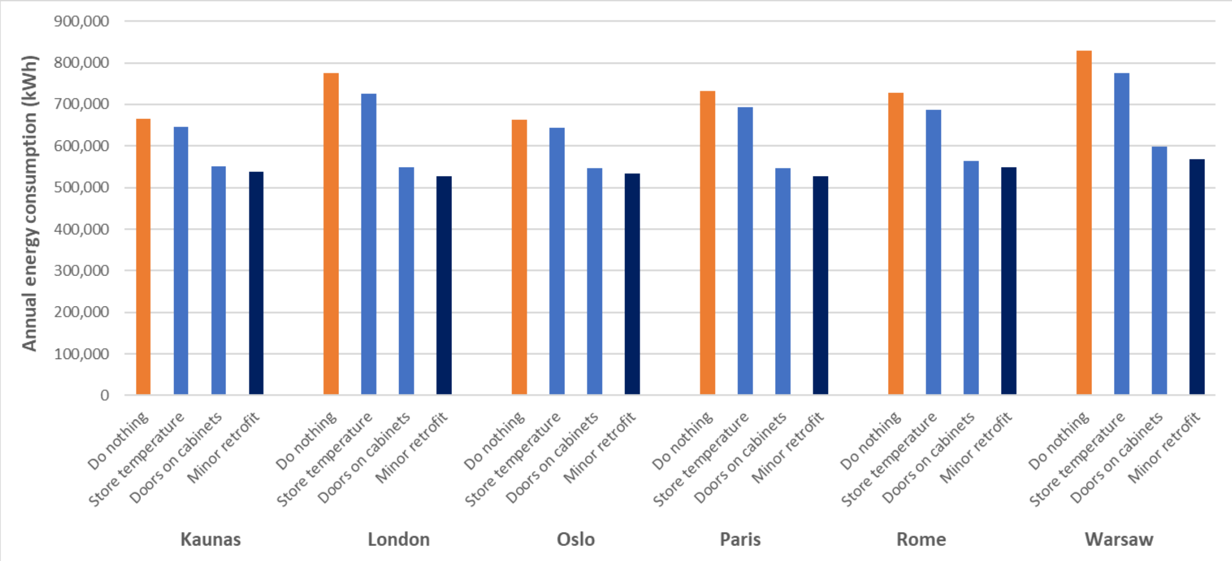


Figure 23. Impact on annual energy consumption of the minor retrofit options applied individually and combined for the 2,100 m² stores in the 6 countries in 2020.

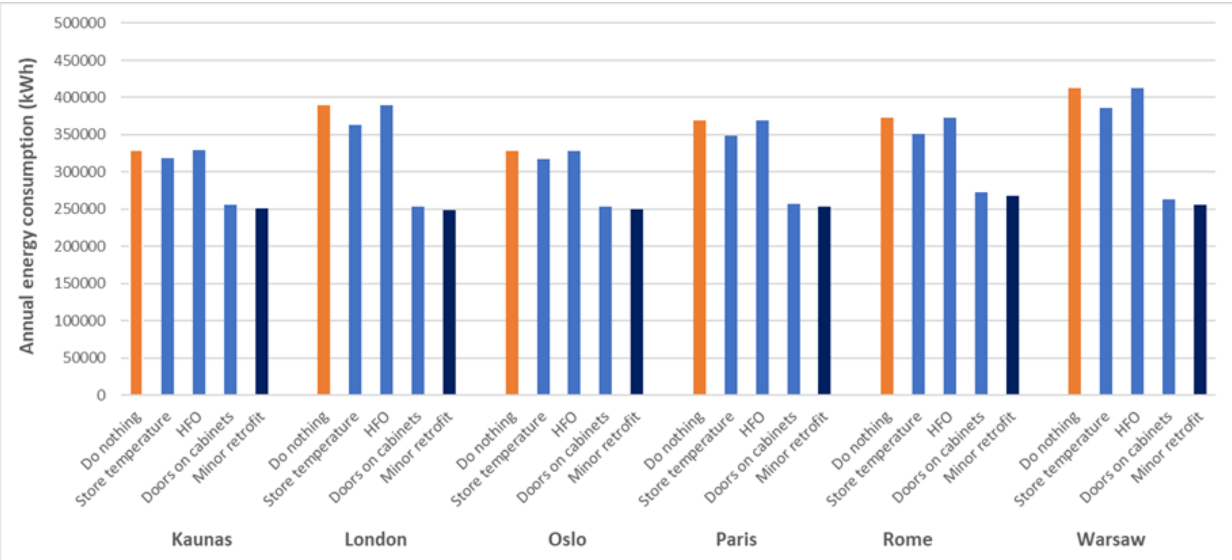


Figure 24. Impact on annual energy consumption of the minor retrofit options applied individually and combined for the 600 m² stores in the 6 countries in 2020.

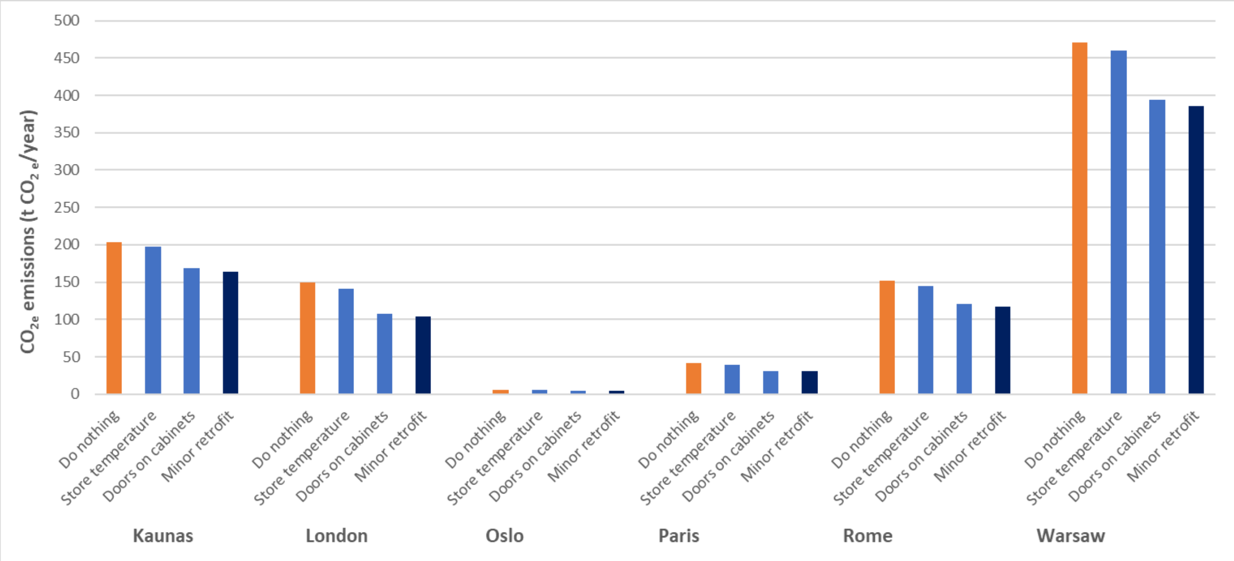


Figure 25. Impact on annual carbon emissions in 2020 for the minor retrofit options applied individually and combined for the 2,100 m^2 stores in the 6 countries in 2020.

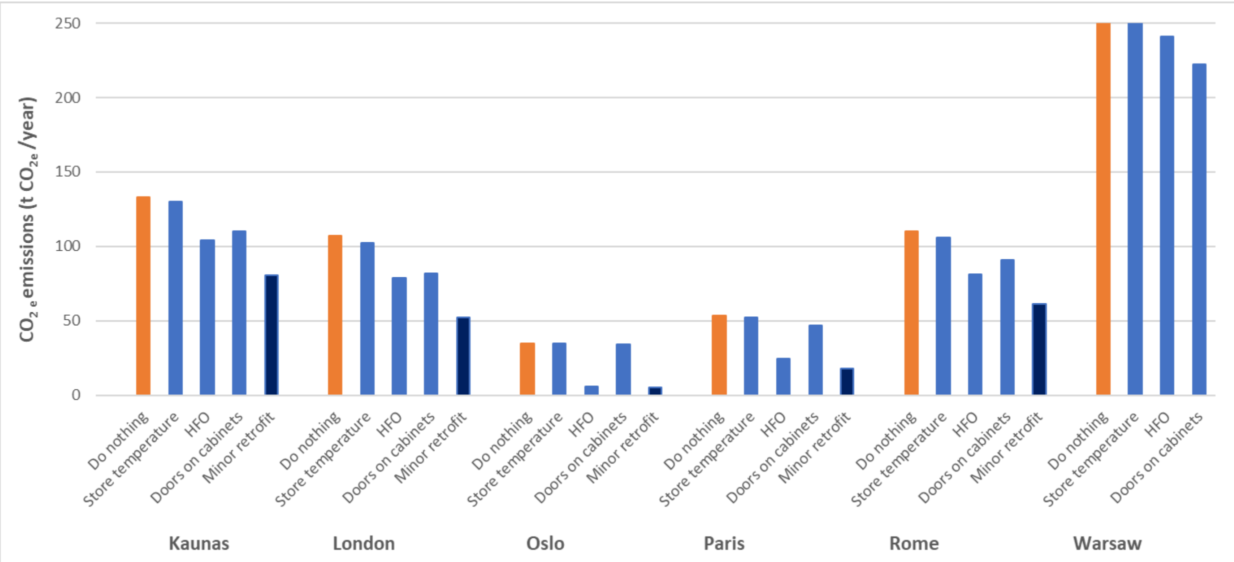


Figure 26. Impact on annual carbon emissions in 2020 for the minor retrofit options applied individually and combined for the 600 m^2 stores in the 6 countries in 2020.

Table 6. Energy use and carbon emissions for the minor retrofit scenarios in 2020.

		Medium store						Small store					
		Kaunas	London	Oslo	Paris	Rome	Warsaw	Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline (BAU)	kWh/year	665,511	774,882	664,181	732,956	727,371	829,152	328,828	389,056	327,803	369,144	372,569	412,450
	tCO_{2e}/year	203.3	149.9	5.4	42.0	152.1	471.2	132.8	107.5	34.8	53.3	110.1	269.8
Store dead band	kWh/year	645,733	725,285	644,039	692,842	687,182	776,007	318,939	362,750	317,844	349,053	351,192	385,950
	% change	3.0%	6.4%	3.0%	5.5%	5.5%	6.4%	3.0%	6.8%	3.0%	5.4%	5.7%	6.4%
	tCO_{2e}/year	197.6	140.7	5.2	39.5	144.6	459.8	129.8	102.6	34.7	52.2	106.1	263.8
	% change	2.8%	6.1%	3.0%	6.0%	4.9%	2.4%	2.3%	4.5%	0.3%	2.2%	3.6%	2.2%
HFO (small store only)	kWh/year	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	tCO_{2e}/year	n/a	n/a	n/a	n/a	n/a	n/a	104.1	78.8	6.1	24.6	81.4	241.1
	% change	n/a	n/a	n/a	n/a	n/a	n/a	21.6%	26.7%	82.5%	53.8%	26.1%	10.6%
Doors on chilled cabinets	kWh/year	551,917	547,862	547,311	546,594	564,308	598,788	255,633	253,328	253,200	257,339	272,311	262,581
	% change	17.1%	29.3%	17.6%	25.4%	22.4%	27.8%	22.3%	34.9%	22.8%	30.3%	26.9%	36.3%
	tCO_{2e}/year	168.9	107.3	4.4	31.2	120.4	394.6	110.4	82.0	34.2	46.9	90.7	222.2
	% change	16.9%	28.4%	17.6%	25.8%	20.8%	16.3%	16.9%	23.7%	1.7%	12.0%	17.6%	17.6%
Combined minor retrofit	kWh/year	536,994	527,729	532,742	528,194	549,515	568,527	251,544	249,044	249,233	253,222	267,958	256,106
	% change	19.3%	31.9%	19.8%	27.9%	24.5%	31.4%	23.5%	36.0%	24.0%	31.4%	28.1%	37.9%
	tCO_{2e}/year	164.4	103.5	4.3	30.3	117.4	385.8	80.5	52.5	5.5	18.0	61.1	191.0
	% change	19.1%	31.0%	19.6%	27.9%	22.8%	18.1%	39.4%	51.1%	84.3%	66.3%	44.5%	29.2%

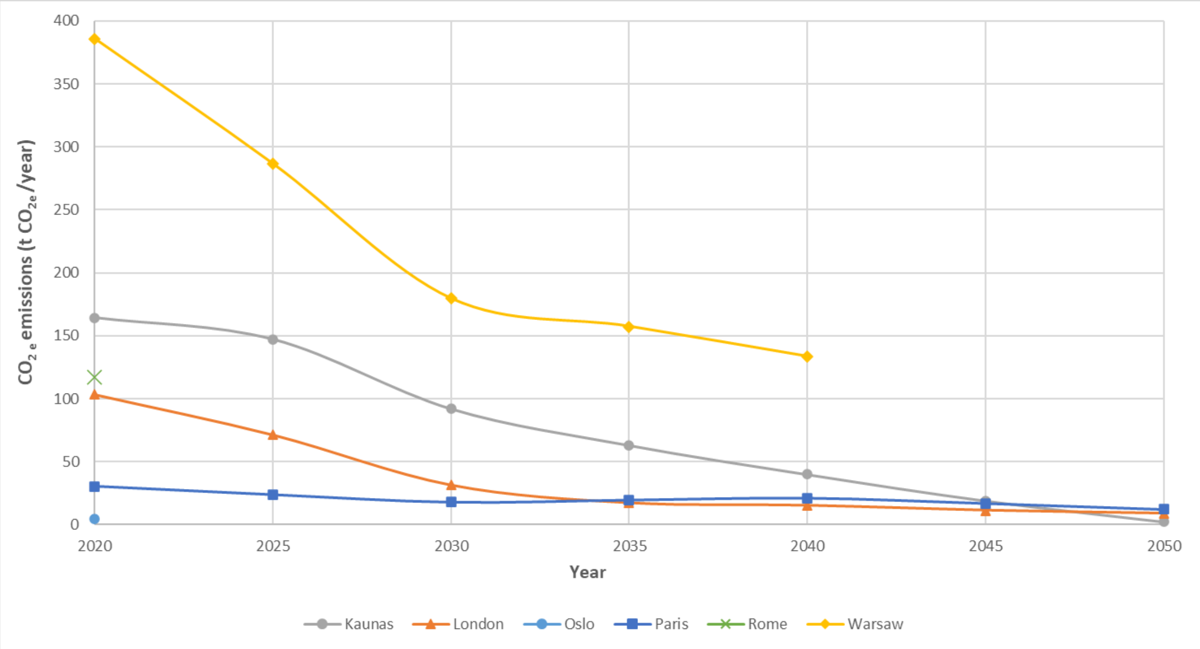


Figure 27. Impact on carbon emissions of the combined minor retrofit options for the 2,100 m² stores in the 6 countries from 2020 to 2040/50 (where data available).

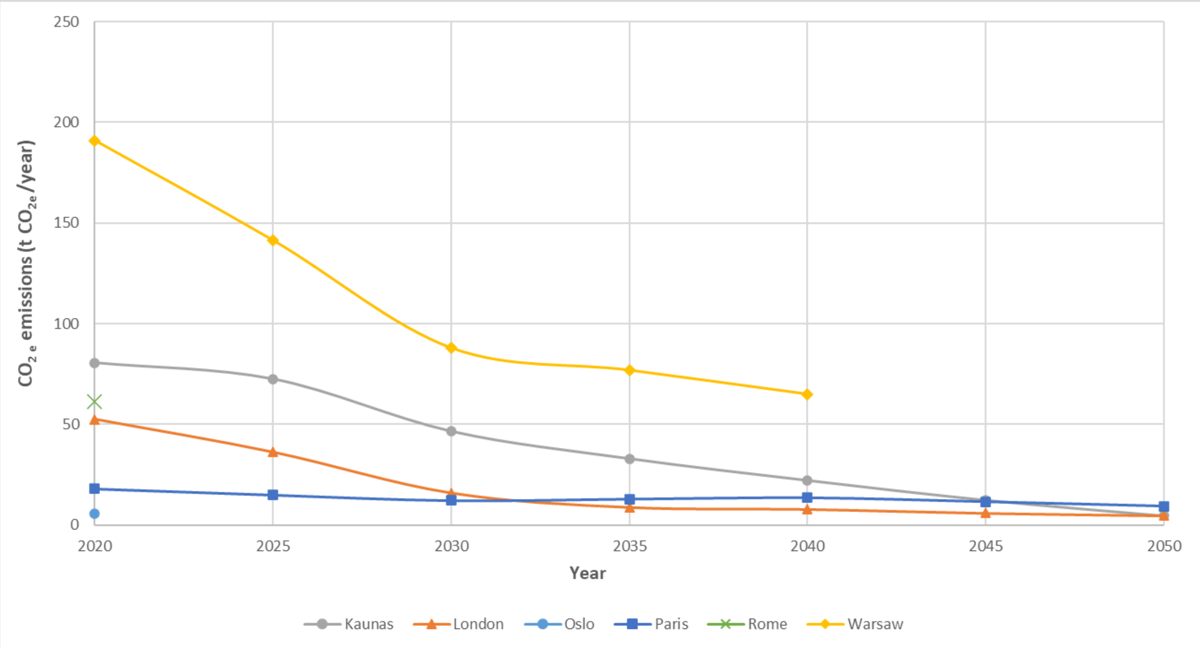


Figure 28. Impact on carbon emissions of the combined minor retrofit options for the 600 m² stores in the 6 countries from 2020 to 2040/50 (where data available).

Table 7. Accumulated carbon emitted between 2020 and 2040/2050 for Kaunas, London, Paris and Warsaw for the combined minor retrofit scenario.

	Accumulated tCO_{2e} emitted between 2020 and 2040/2050	
	2,100 m² supermarket	600 m² supermarket
Kaunas (2050)	2,231	1,177
London (2050)	1,003	523
Paris (2050)	602	404
Warsaw (data for 2040 only)	4,450	2,253

1.16.6. Scenario 3: major retrofit

Major retrofit technologies were then added to the minor retrofit options. As before, each retrofit technology was applied individually and then in combination to the 2 store formats (2,100/600 m²). The following technologies were applied, and the following assumptions were made:

Change heating to heat pumps from gas/resistive electrical heating (for relevant scenarios): Gas heating/resistive electrical heating (where applied) was replaced by electrical heating from heat pumps.

Better cabinets: Cabinet with 20% less energy consumption was applied (both chillers and freezers).

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

Apply R744 to smaller stores: The GWP of the refrigerant for small stores was reduced to 1. The following assumptions were made:

The impact of each technology and the technologies combined on energy consumption are presented in Figure 29 (2,100 m² store) and Figure 30 (600 m² store). The impact of the technologies alone and in combination on carbon emission are shown in Figure 31 (2,100 m² store) and Figure 32 (600 m² store).

Projected emissions between 2020 and 2050 for the 2,100 m² and 600 m² stores are shown in Figure 33 and Figure 34 respectively.

Energy and carbon emissions for each scenario are presented in Table 8.

Table 9 displays the accumulated carbon emitted from 2020 to 2040/2050 when applying the 'combined major retrofit' scenario for the two supermarket configurations.

Move to electricity from gas for heating (for relevant scenarios)

ENERGY: Applying heat pumps in London, Paris, Rome and Warsaw reduced energy use by between 1 and 6% in the medium stores but had minimal impact in the small stores. Heat pumps had limited benefit in Rome as there was very little need for heating once the minor retrofit options had been applied (only 2,028 kWh/year in the medium store and 264 kWh/year in the small store). The greatest energy savings were seen in Warsaw due to it being the coldest location where heat pumps were applied.

CARBON EMISSIONS: Heat pumps often had quite limited impacts on reducing carbon emissions. Savings of 2% were found in the medium stores in London and Paris but no savings were seen in Rome due to the limited need for heating. Applying a heat pump in Warsaw actually had a negative impact as even though the heat pump had a higher energy conversion than gas (0.75 $kgCO_{2e}$/kWh for electricity versus 0.184 for gas $kgCO_{2e}$/kWh), the high electrical grid carbon conversion factor resulted in greater carbon emission than if gas was applied. This will change moving forward as the grid carbon intensities in Poland are predicted to decrease and this will then make heat pumps a more viable option.

Better cabinets

CARBON EMISSIONS: Applying more energy efficient cabinet resulted in overall energy savings of between 6 to 8% across all the location and store sizes considered.

CARBON EMISSIONS: Reduction sin emissions broadly followed the reduction in energy. The exception was in the small Oslo store where percentage reductions in carbon emitted were lower due to the low grid carbon intensity in Norway and the impact of the fugitive emissions from the HFO refrigerant applied.

RES (solar)

ENERGY: Benefits in terms of energy reductions were seen when applying solar panels to the roof of the stores. Annual savings of between 35 and 84% were found. The greatest savings were in Rome due to the sunny location and the least in Oslo due to the limited sunlight.

CARBON EMISSIONS: The reduction in carbon emissions related to the application of RES broadly mirrored the benefits found for energy.

Apply R744 to smaller stores

ENERGY: Applying R744 to the small stores (instead of an HFO) always had a minimal negative impact on energy consumption.

CARBON EMISSIONS: The impact on carbon emitted was greater than the impact on energy, especially where the electrical grid intensity was low (Norway).

Overall impact

ENERGY: Overall energy savings ranged from 55 to 94%. The most successful application of the technologies was in Rome where 95% of the energy was saved in the medium store and 70% in the small store. This was primarily due to the impact of adding solar panels in a country where there was abundant sunshine. The energy savings in other countries were broadly similar but the reductions were due to a variety of reasons and not always due to the application of the same technology.

CARBON EMISSIONS: Carbon emissions could be reduced by 61 to 97%. In medium stores the greatest reduction was seen in Rome and was mainly due to the potential to apply solar panels. In the small stores the greatest percentage carbon reduction was seen in Oslo and this was mainly due to the high impact of fugitive emissions (and moving from an HFO to R744) in a country where the electrical grid intensity was already very low.

As in the BAU and minor retrofit scenarios Paris had the least carbon accumulated emissions (to 2050), while Warsaw had the most (to 2040). The accumulated emissions in Warsaw were higher in 2040 than they were in any of the other countries examined in 2050. This was due to the electrical grid intensity remaining higher in Poland.

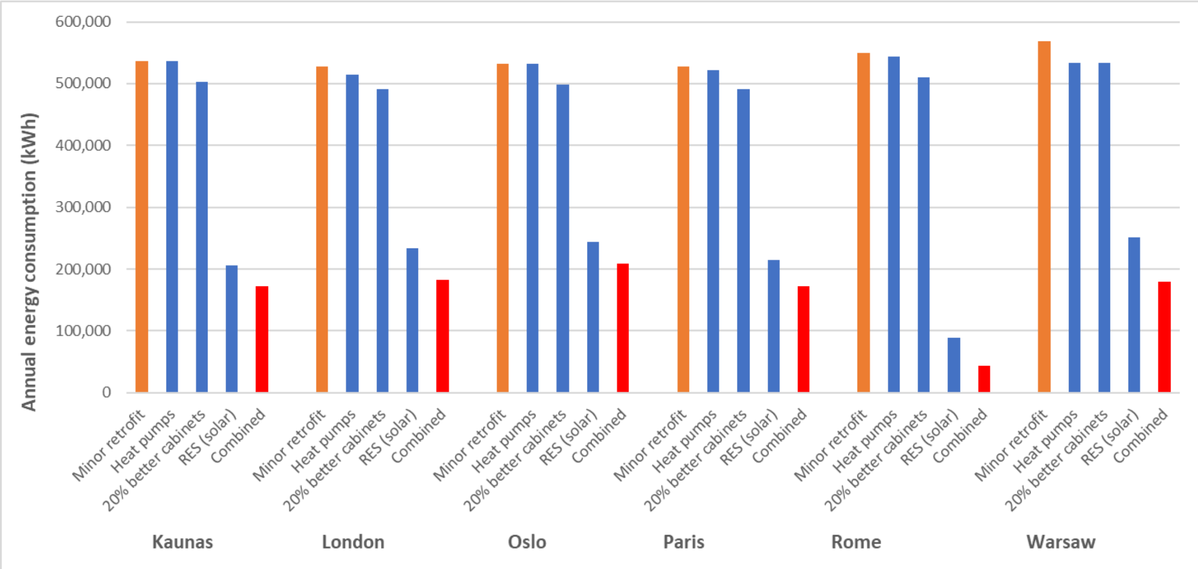


Figure 29. Impact on annual energy consumption of the major retrofit options applied individually and combined for the 2,100 m² stores in the 6 countries in 2020.

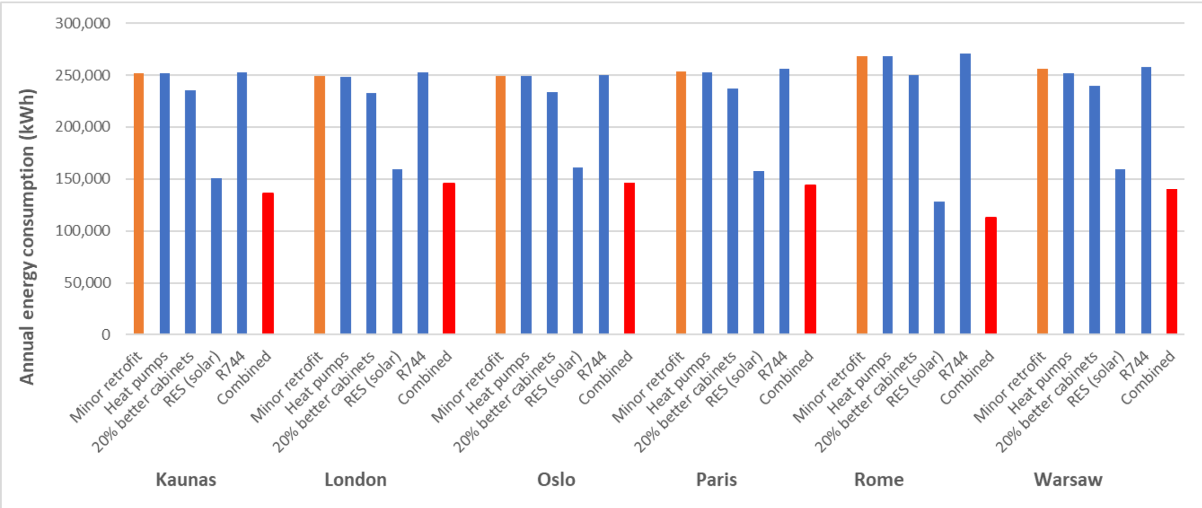


Figure 30. Impact on annual energy consumption of the major retrofit options applied individually and combined for the 600 m² stores in the 6 countries in 2020.

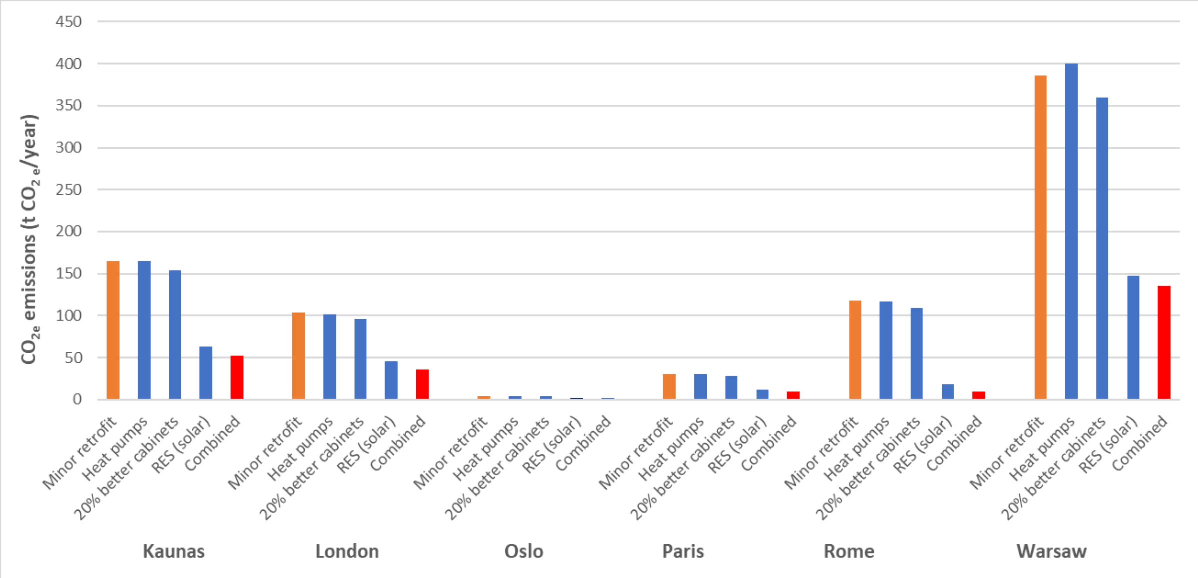


Figure 31. Impact on annual carbon emissions in 2020 for the major retrofit options applied individually and combined for the 2,100 m^2 stores in the 6 countries in 2020.

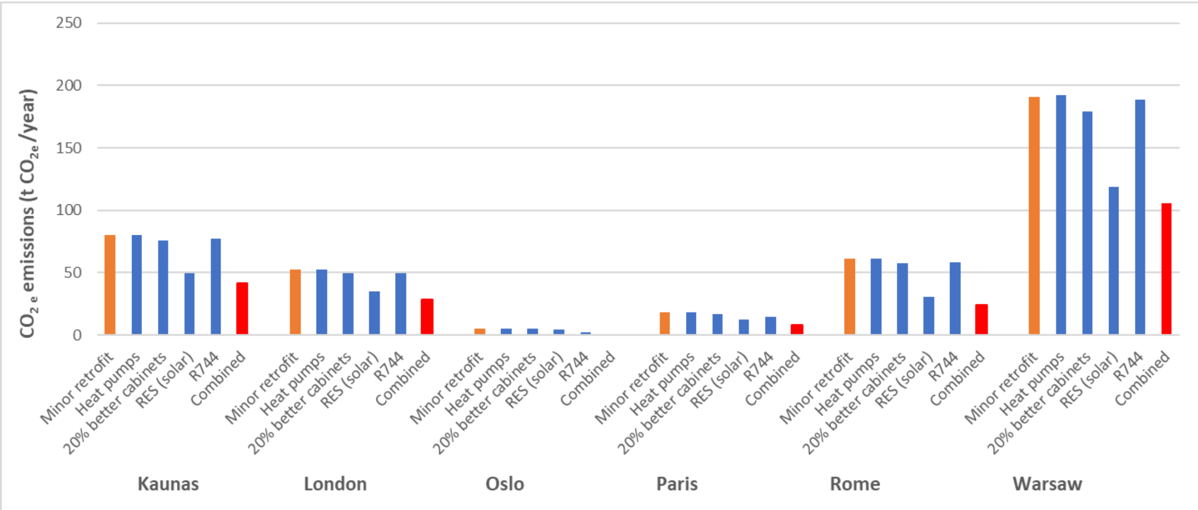


Figure 32. Impact on annual carbon emissions in 2020 for the major retrofit options applied individually and combined for the 600 m^2 stores in the 6 countries in 2020.

Table 8. Energy use and carbon emissions for the major retrofit scenarios in 2020.

		Medium store						Small store					
		Kaunas	London	Oslo	Paris	Rome	Warsaw	Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline (minor retrofit)	kWh/year	536,994	527,729	532,742	528,194	549,515	568,527	251,544	249,044	249,233	253,222	267,958	256,106
	tCO_{2e}/year	164.4	103.5	4.3	30.3	117.4	385.8	80.5	52.5	5.5	18.0	61.1	191.0
Heat pumps	kWh/year	536,994	513,769	532,742	522,394	543,600	532,983	251,544	248,117	249,233	252,806	268,028	251,559
	% change	0.0%	2.6%	0.0%	1.1%	1.1%	6.3%	n/a	0.4%	n/a	0.2%	0.0%	1.8%
	tCO_{2e}/year	164.4	101.3	4.3	29.8	116.9	399.8	80.5	52.4	5.5	18.0	61.2	192.1
	% change	0.0%	2.2%	0.0%	1.6%	0.4%	-3.6%	n/a	0.3%	n/a	0.1%	-0.1%	-0.6%
20% better cabinets	kWh/year	502,126	491,556	498,083	491,702	510,601	533,088	235,541	232,935	233,387	236,811	250,349	239,959
	% change	6.5%	6.9%	6.5%	6.9%	7.1%	6.2%	6.4%	6.5%	6.4%	6.5%	6.6%	6.3%
	tCO_{2e}/year	153.7	96.4	4.0	28.1	109.0	359.2	75.6	49.3	5.3	17.0	57.3	178.9
	% change	6.5%	6.9%	6.5%	7.4%	7.1%	6.9%	6.1%	6.0%	2.3%	5.2%	6.2%	6.3%
RES (solar)	kWh/year	206,494	233,029	243,442	214,394	88,715	250,927	151,044	159,444	161,233	157,822	127,858	159,506
	% change	61.5%	55.8%	54.3%	59.4%	83.9%	55.9%	40.0%	36.0%	35.3%	37.7%	52.3%	37.7%
	tCO_{2e}/year	63.2	45.4	2.0	12.3	18.3	147.6	49.7	34.9	4.8	12.5	31.0	118.6
	% change	61.5%	56.1%	54.0%	59.5%	84.4%	61.7%	38.2%	33.6%	12.9%	30.4%	49.3%	37.9%
R744	kWh/year	n/a	n/a	n/a	n/a	n/a	n/a	252,369	252,936	250,400	256,289	270,897	257,672
	% change	n/a	n/a	n/a	n/a	n/a	n/a	-0.3%	-1.6%	-0.5%	-1.2%	-1.1%	-0.6%
	tCO_{2e}/year	n/a	n/a	n/a	n/a	n/a	n/a	77.2	49.8	2.0	14.7	58.2	188.7
	% change	n/a	n/a	n/a	n/a	n/a	n/a	4.0%	5.1%	63.0%	18.2%	4.6%	1.2%
Combined major retrofit	kWh/year	171,626	182,896	208,783	172,099	43,886	179,944	135,701	145,805	146,321	143,745	112,759	140,550
	% change	68.0%	65.3%	60.8%	67.4%	92.0%	68.3%	46.1%	41.5%	41.3%	43.2%	57.9%	45.1%
	tCO_{2e}/year	52.6	36.1	1.7	9.9	9.5	135.0	41.5	28.7	1.2	8.3	24.3	105.4
	% change	68.0%	65.1%	60.3%	67.3%	91.9%	65.0%	48.4%	45.3%	78.2%	54.1%	60.3%	44.8%

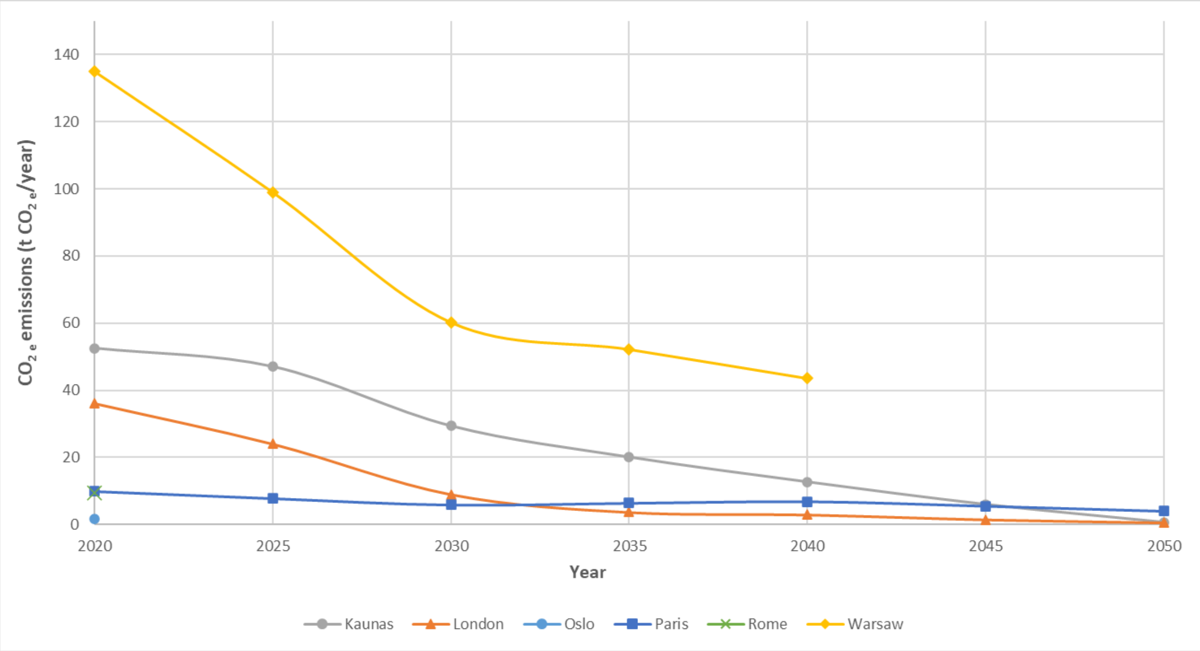


Figure 33. Impact on carbon emissions of the combined major retrofit options for the 2,100 m² stores in the 6 countries from 2020 to 2040/50 (where data available).

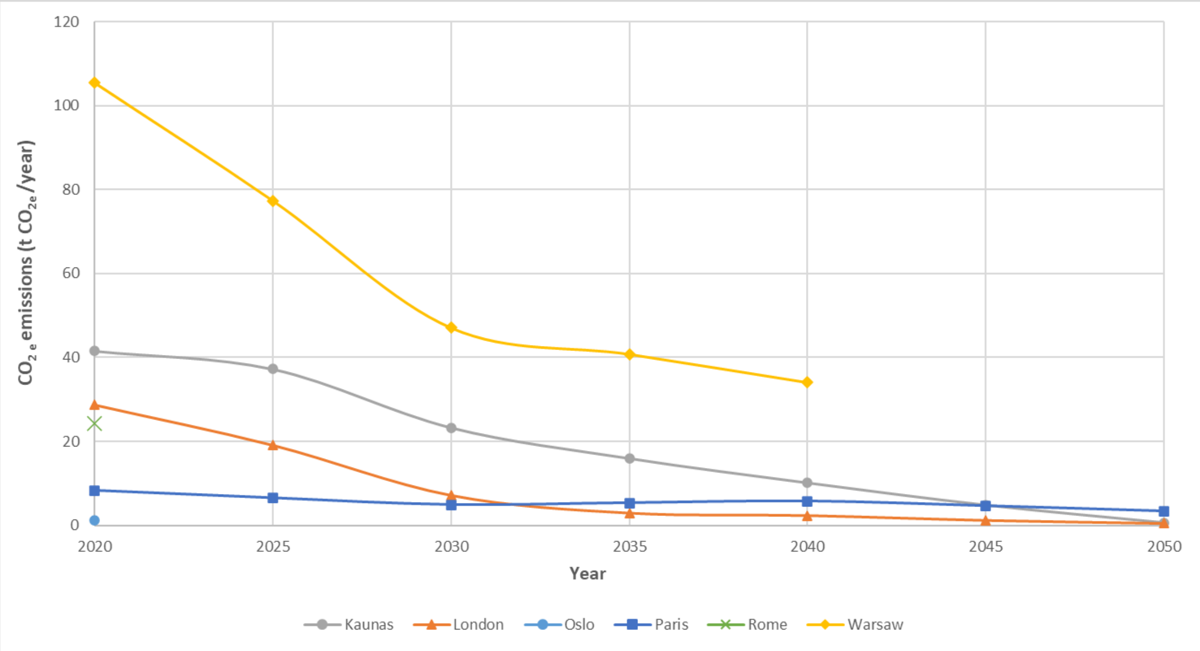


Figure 34. Impact on carbon emissions of the combined major retrofit options for the 600 m² stores in the 6 countries from 2020 to 2040/50 (where data available).

Table 9. Accumulated carbon emitted between 2020 and 2040/2050 for Kaunas, London, Paris and Warsaw for the combined major retrofit scenario.

	Accumulated tCO_{2e} emitted between 2020 and 2040/2050	
	2,100 m^2 supermarket	600 m^2 supermarket
Kaunas (2050)	713	562
London (2050)	294	234
Paris (2050)	196	163
Warsaw (data for 2040 only)	1,514	1,177

1.16.7. Overall impact of making changes

The impact of applying both all retrofit options is presented in Table 10. Significant overall savings in energy and carbon emissions are predicted of at least 59%. In some cases, stores could become almost carbon neutral with savings of up to 97%. Energy savings and carbon savings were not always directly related and so one was not a good predictor of the other.

Table 10. Energy use and carbon emissions for all interventions (BAU, minor and major combined) in 2020.

		Medium store						Small store					
		Kaunas	London	Oslo	Paris	Rome	Warsaw	Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline (original BAU)	kWh/year	665,511	774,882	664,181	732,956	727,371	829,152	328,828	389,056	327,803	369,144	372,569	412,450
Combined (minor and major retrofit)	kWh/year	171,626	182,896	208,783	172,099	43,886	179,944	135,701	145,805	146,321	143,745	112,759	140,550
	% change	74.2%	76.4%	68.6%	76.5%	94.0%	78.3%	58.7%	62.5%	55.4%	61.1%	69.7%	65.9%
Baseline (original BAU)	tCO_{2e}/year	203.3	149.9	5.4	42.0	152.1	471.2	132.8	107.4	34.8	53.3	110.1	269.8
Combined (minor and major retrofit)	tCO_{2e}/year	52.6	36.1	1.7	9.9	9.5	135.0	41.5	28.7	1.2	8.3	24.3	105.4
	% change	74.1%	75.9%	68.1%	76.4%	93.8%	71.3%	68.7%	73.2%	96.6%	84.5%	78.0%	60.9%

1.16.8. Impact on carbon emissions of making changes

The total carbon emitted between 2020 and 2050 for the 2,100 m² and 600 m² stores in Warsaw, Kaunas, London and Paris are shown in Figure 35 and Figure 36 respectively.

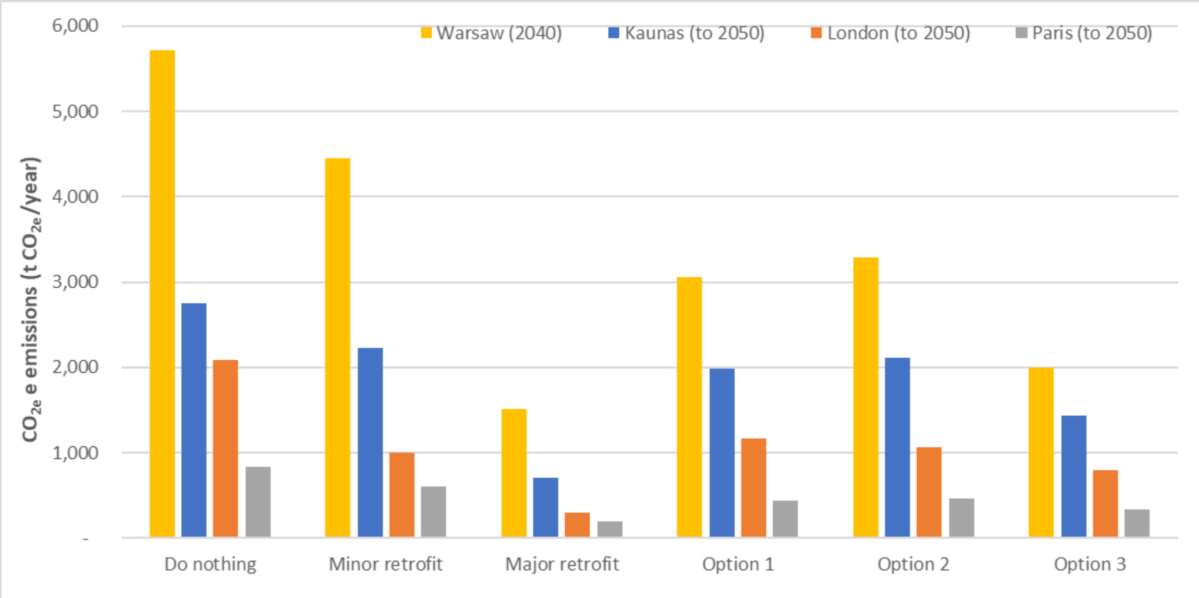


Figure 35. Carbon emitted by the 2,100 m² stores in different countries from 2020 to 2040/50.

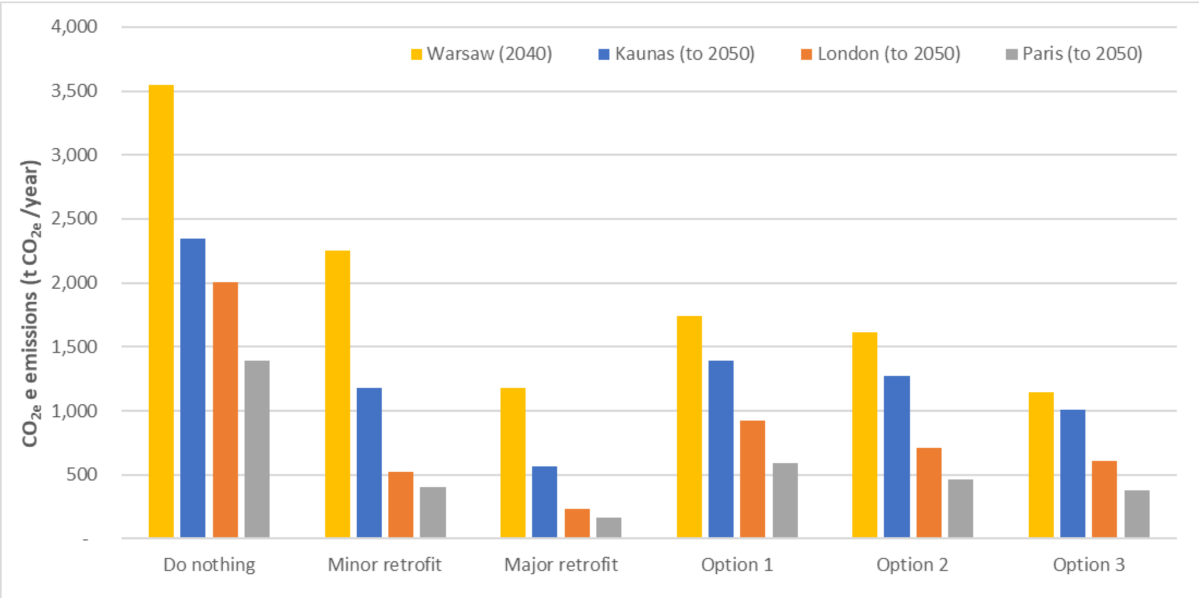


Figure 36. Carbon emitted by the 600 m² stores in different countries from 2020 to 2040/50.

1.17. Recommendations

The modelling provided a direct comparison between the impact of each intervention in each country, but it should be borne in mind that interventions could be applied in a varied order, and some may have more, or less impact, than calculated in our representative scenarios. The overall results do, however, provide a comparison between the scenarios applied which helps to elucidate the differences between the locations and baseline assumptions for each supermarket in each country.

Our recommendations

- *Apply technological interventions as rapidly as possible to ensure cumulative carbon emissions are maximised.*
- *Apply doors to open fronted cabinets to save energy and carbon.*
- *Always apply natural refrigerants, if possible, in new store applications.*
- *Allow the store ambient dead band temperature to increase by plus or minus 1°C to save energy and carbon.*
- *Always purchase the most efficient equipment that is available on the market.*
- *Consider the use of renewable energy resources (especially solar in sunnier climates).*
- *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.*

A great deal of decarbonisation should occur naturally though dramatic reductions in the electrical grid carbon 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 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 supermarkets will also be much lower carbon emitters in 2050[41]. 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 still is at a relatively high level in 2040 (no data for 2050 could be identified for Poland).

Although decarbonisation of the electrical grid has a huge impact on carbon emission from supermarkets in most European counties there are still carbon emissions in 2050 and so the aim to be zero carbon requires additional interventions. One intervention in the countries still using gas for heating (Italy, Poland and the UK) is to move to electrical heating. Using heat pumps is an obvious option but the stage when the technology is applied has a huge impact. As technologies that reduce the heating load are applied (in particular doors on cabinets and allowing the store ambient

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

temperature to have a wider dead band) there is less need for heating. Combined with global warming which further reduces the need for heating, this makes the commercial argument for heat pumps less as the need for heating reduces. For example, in Rome the need for heating is almost zero in 2050 and so it is unlikely that a commercial argument for a heat pump could be made. In addition, the emission intensity for electricity needs to be lower than that for gas which In Poland is currently not the case, and so in this example moving to electrical heating was not the lowest carbon short term option.

The impact of applying technologies on carbon emissions was very related to the electrical grid carbon intensity in a country. For example, in Norway with a very low electrical grid carbon intensity the impact was much less than in Poland where the electrical grid carbon intensity was high. Application of technologies had a greater impact on energy used and therefore cost to operate the supermarket. The greatest impact was from adding doors to the open fronted cabinets. Allowing a greater ambient dead band also had benefits for minimal cost. Always purchasing the most efficient cabinets had impact and should be something that supermarkets always consider during a purchasing process.

In the scenarios modelled it was assumed that all the medium sized stores applied R744 as the refrigerant. In the small stores R448A was replaced with R744 during a major retrofit. The choice of refrigerant has an impact on carbon emissions but limited impact on energy used. Even though the argument for moving to an ultra-low GWP refrigerant may be marginal cost wise, it is strongly recommended that natural refrigerant options are applied moving forward to prevent legacy issues if new legislation is applied that restricts the use of HFCs and HFOs in the future.

Ultimately it was impossible to achieve net zero in supermarkets with technological interventions alone. The use of renewable energy (solar panels) had a very positive impact, especially in the sunnier countries such as Italy. By applying solar panels and other technical interventions the carbon emissions in 2020 could be reduced by at least 94% in Italy (this could obviously be higher in all countries if more solar panels had been applied). In less sunnier counties the impact of solar panels was reduced and so to reach very close to zero carbon more time was required and only achieved in 2045 for the UK and 2050 for Lithuania. Emissions were low in France but never achieved net zero.

Although France did not achieve net zero in 2050 the impact of having a low electrical grid carbon intensity meant that cumulative emissions from 2020 to 2050 were much lower than in other counties. Overall cumulative carbon reduction is as important, if not more so, than final reduction. Therefore, applying carbon reducing technologies early is one of the most important recommendations we make.

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 a number of factors which included the country electrical grid carbon intensities and their rate of change over time, the ambient conditions in the country and the type of heating applied.

To achieve near net zero carbon emission in supermarkets will require a range of initiatives. Supermarkets themselves are incentivised to reduce energy costs and are keen to project a green and environmental image. Policy and legislation are driving the change to natural refrigerants and the latest f-gas proposals are very much focussed on the application of natural refrigerants. Energy used by commercial refrigeration is being driven by Eco-design regulations and these regulations need to continue to challenge manufacturers to produce energy efficient cabinets. Legislation or industry agreements need to accelerate the use of doors on cabinets and to make cabinets with doors the norm in all supermarkets. Use of other technological interventions need to be incentivised as many have marginal paybacks and their application is resulting in higher cumulative carbon emissions.

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 supermarkets exists and is feasible. None require building a completely new supermarket and can be applied during minor or major retrofits. The diagram below shows what we consider to be the priority areas for supermarkets to focus on.

10. DETAILED TECHNOLOGY/STRATEGY REVIEWS

1.18. Refrigeration

1.18.1. Adiabatic condensers

Adiabatic condensers operate by spraying water into the air supply of air-cooled condensers. The water is often sprayed on a pad through which the air flows, avoiding build-up of mineral deposits on the condenser fins. This has the effect of cooling the air (due to evaporation of the water droplets) that cools the condenser, reducing condensing temperature and pressure, saving compressor energy and increasing refrigeration capacity. This has the greatest benefit in the summer months when condensing temperatures are high. During the winter there may be no benefits.

The cooling effect is related to the relative humidity (RH), so the benefit is higher in dry weather (low RH) and there will be no benefit when RH is 100%. Therefore, you would expect the condensers to only work for part of the year. However, as soon as air is warmed up, its relative humidity drops, allowing for the application of the evaporative cooling. Therefore, in the instances where the condenser is divided into de-superheating, condensing and subcooling sections, the water spray can be applied between the de-superheating and condensing sections when the RH of the air is lower than the ambient air. Thus, the benefit from the evaporative cooling can be achieved even in areas where the RH of the ambient air is high.

With a perfectly efficient adiabatic condenser, the air will cool from the dry bulb to the wet bulb temperature. Baltimore Aircoil Company (2015) states that cooling temperature on the condenser can be reduced by approximately 1 to 2°C above the wet bulb temperature. Unlike evaporative condensers, all the water should be evaporated and therefore none needs to be recycled, which avoids the requirement for treatment. The need to make sure that all water is evaporated requires correct control of water temperature and air flow rate, which will be dependent on ambient conditions. The quantity of water used is much less than that used by evaporative condensers.

Martínez et al. (2020) placed evaporating cooling pads before the condensing coils of an air-cooled chiller in a hospital in Spain. This reduced condensation temperature by 11°C, increasing the relative humidity by 50%. The European seasonal efficiency ratio (ESEER) increased by 30.9%. They calculated a payback of less than 2 years, assuming pads would need to be replaced every 4 years and not considering financial penalties of using too much power. This was for a chiller running on average 12 hours per day for 92 summer days. A supermarket refrigeration system runs 24 hours a day and the benefits of reduced condensing temperature during the night and not in the summer may be less than the costs of running the water system.

The cooling systems in a large office building were surveyed using the REAL Zero methodology (Rodway 2009). It was found that the systems using adiabatic cooling of the condensers had experienced lower levels of refrigerant leakage compared with other systems that used air cooling of the condensers. It was concluded that this was due to the higher discharge pressures, compared with the adiabatically cooled condensers for similar ambient conditions.

Problems

Water evaporation can lead to scaling. Another problem is dust and other contaminants in the supply air; they are more likely to pass through a dry condenser than through a condenser with a wet surface, contributing to a faster clogging of the condenser.

Legislation

There is no direct legislation for adiabatic condensers, unlike evaporative condensers. However, the safety of each system should be considered, especially in relation to Legionella.

Case Studies

Hill Phoenix has installed 20 Advansor trans-critical CO_2 systems in Canada (Wallace 2014). Using adiabatic gas coolers, they have been able to keep the operating pressures lower for longer in the warmer climates. However, actual savings have not been reported.

Financial

An analysis of a large supermarket system in the US (Scott, Bellon, and Chappell 2017) showed energy cost savings of between $0.17 to $4.75 per sq ft of supermarket for California climate zone 16 (high, mountainous and semiarid region above 5,000 feet in elevation) and 7 (southernmost coastal region of California) respectively with the optimal control strategy. This gave a cost benefit ratio of between 11.7 and 333.

Scope 1 emissions savings (% or another quantifiable metric)	Limited data.
Quality of scope 1 emissions information	Some data consider that there is less leakage from adiabatic condensers due to lower pressures, however, no data was found to quantify savings.
Scope 2 emissions savings (% or another quantifiable metric)	Up to 31% in Spain during summer days. It is unlikely that supermarkets in most European locations can achieve the same levels of savings. Calculations indicate that savings on refrigeration plant energy consumption are 5-10%.
Quality of scope 2 emissions information	There is no doubt that adiabatic cooling can save energy. However, determining the saving depends on climatic conditions and design of condenser.
TRL level	TRL8-9
Maintainability issues	Evaporative pads need to be replaced, approximately every 2 years.
Legislative concerns	Minimal possibility of Legionella due to zero aerosol formation. No stagnant water accumulation as water distribution system is one through.
Payback time (years)	<2 in the most beneficial situations.

1.18.2. Aerofoil air-guide

The use of guides or deflectors on open fronted cabinets has the potential to reduce air infiltration and consequently the energy consumption of the cabinet refrigeration systems. The design of the deflectors is thought to influence the levels of energy savings achieved. Work to evaluate the impact of aerofoil deflectors (Foster, A., McAndrew, and Evans 2014) has shown overall energy savings. Adding the aerofoil deflectors reduced maximum temperatures in a cabinet tested to the EN23953 test standard (at climate class 3) by 0.6 °C as well as reducing the energy consumption by 15%. As these tests were conducted on cabinets with an integrated refrigeration system, this reduction in energy was on the total energy consumption of the cabinet. When the cabinet controller was adjusted so that the maximum pack temperatures were the same for the two tests, the air deflectors reduced energy consumption by 17%. It should be noted that open fronted cabinets do not have the same air curtain geometry and therefore different results may be seen when the technology is applied to different cabinets. It may be required to optimise the aerofoils, either by their distance from the end of the shelf and/or their orientation to the air flow.

From Aerofoil Energy Ltd web-site (https://www.aerofoil-energy.co.uk) they state that they have sold over 1.4 million Aerofoils, which have been installed in over 4,000 supermarket stores. They now cover 80% of the addressable market for Aerofoils in the UK. They claim they are delivering energy savings of 40% in the laboratory to 25% in typical store conditions.

Other "shelf-edge" technology exists which use flat profiled extrusions to do the same thing, however, Aerofoil Energy Ltd, argue that they are less efficient than using an aerofoil profiled extrusion.

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)	23% of compressor energy.
Quality of scope 2 emissions information	Energy savings have been independently validated by one scientific paper. Take up of the technology by many stores who conduct their own assessment also suggests that they save energy, however, it is not clear what the overall savings are over many real-life scenarios.
TRL level	TRL8-9
Maintainability issues	May possibly get damaged by customers, but there is no information on this.
Legislative concerns	None.
Payback time (years)	Limited published information but if the aerofoils save 25% of the energy and each aerofoil costs ~€25 per shelf, the payback will be less than 6 months.

1.18.3. Anti-fogging glass

Fogging of glass reduces the visibility of products on display, making it hard for shoppers to find the product they are looking for and potentially preventing impulse purchases and reducing sales.

In frozen food display cabinets, defogging is usually speeded up by an air curtain flowing along the internal glass surface and by anti-sweat heaters embedded in the door frame or in the glass itself. In chilled display cabinets, the use of anti-fog coatings is more widespread (D'Agaro, Croce, and Suzzi 2021).

Typically, fog is only formed at the cold (cabinet facing) side of the door which is exposed to the supermarket ambient environment only upon opening the door. Anti-fogging glass is typically a standard glass with a film bonded to the surface. Anti-fog coatings have hydrophilic properties such that any water on the surface does not bead up and create fog.

Although electric resistance heaters are not commonly installed on chilled cabinets in UK supermarkets, frozen glass display cabinets may have three types of electric resistance heaters installed (case mullion, door frame and glass pane). These range from 100 to 200 W per door (Rauss, Mitchell and Faramarzi, 2008). They showed that a cabinet with glass door heaters, could have its antisweat heat reduced from just over 400 W to under 150 W. It should be noted that an efficient glass door may not have glass heating and therefore there would be no benefit in installing for the anti-fogging film.

Anti-fogging films can be implemented in conjunction with electrical heat but laboratory testing has shown that some anti-fog films can delaminate if the cases are allowed to return to room temperature. This is believed to be due to moisture migrating under the coating and then freezing and separating the coating from the glass surface. Delamination could obscure the view of the products and be worse than fogging. Some anti-fog coatings may lose their hydrophilic properties if washed or soaked in water (Rauss, Mitchell, and Faramarzi 2008).

Anti-fog coatings have historically been prone to degradation through cleaning or contact with skin (people holding doors open). According to (WeeTect 2018) typically last 12 to 24 months, dependant on usage and exposure.

According to (FSI Coating Technologies 2022) this technology has a typical cost of $40 per door and is warranted for 5 years.

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)	Potential to remove all glass heating in frozen cabinets.
Quality of scope 2 emissions information	Only one academic publication showing potential to save energy.
TRL level	TRL8-9
Maintainability issues	Need to be regularly replaced (every few years).
Legislative concerns	None.
Payback time (years)	Unknown.

1.18.4. Anti-sweat heater control

Anti-sweat heaters (ASH) are electric resistance heaters that are installed in the frames and doors of refrigerated cases to reduce condensation and fogging which can also lead to frost and ice build-up on door gaskets etc. ASHs prevents fogging on the doors keeping the door clear for viewing the food products. They also reduce puddling on floors, corrosion and mould/mildew formation on gaskets. Anti-sweat heaters are less common on chilled cabinets.

ASHs tend to provide heat to three areas, glass heaters (to prevent condensation), mullion heaters (to keep doors from freezing shut) and door frame heaters (also to keep doors from freezing shut plus transfer some heat to the glass).

The amount of heat required by an anti-sweat heater to maintain a clear door will be a function of the cabinet design (which influences the rate of cooling or clearing of the mist through internal air condition and movement) and the ambient air in the supermarket. Where the ambient air dew point is lower than the coldest surface temperature of the glass, there is no need for anti-sweat heaters.

ASH control modulates the ASHs so they are not running all the time but still keep the display cabinet free from condensation. This is done by monitoring the dew point temperature in the ambient around the cabinet. Where the store dew point is lower than surfaces being heated, there is no requirement for trim heating. Various systems are on the market to regulate the trim heater, either with a proportional or on/off control.

Hudomalj et al. (2017) estimated that ASH control accounted for anywhere from 68% to as much as 87%, which is dependent on environmental conditions, namely dew point temperature.

Hackel et al. (2015) stated typical savings of reducing anti-sweat usage of 57 kWh/ft of MT and 26 kWh/ft of LT cabinets. They also quoted a typical cost of $25 per ft giving a payback of 3.9 and 1.1 years for MT and LT cabinets respectively.

According to Monier et al. (2007) energy savings through anti-sweat heater control for low temperature supermarket display cabinets can be in the range of 6 % of the TEC in real life 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)	68 to 87% of ASHs or 6% of TEC of low temperature cabinet.
Quality of scope 2 emissions information	High. A number of peer reviewed publications which agree.
TRL level	TRL8-9
Maintainability issues	None know.
Legislative concerns	None.
Payback time (years)	3.9 years for MT and 1.1 years for LT cabinets.

1.18.5. Boreholes and ground sink condensers

Exchanging heat from the refrigeration condensers to the ground during the summer months can save considerable energy. Such systems can be open- or closed-loop. In open-loop systems, water within the ground (from a borehole) is used directly to provide cooling. In closed-loop systems, heat exchangers are constructed within the ground to exchange the heat.

Soil needs to be moist for effective heat transfer (Kauffeld, 2016). This can be especially relevant when using CO2 as a refrigerant. Rejecting heat to ambient air from a CO_2 pack will cause the pack to operate transcritically for part of the year, significantly reducing its efficiency whereas the use of a borehole or ground sink condenser enables a constant, and relatively cool, temperature sink for the “waste” heat from the condenser.

Leiper et al. (2014) reported energy savings of 24.6% in a study comparing two similar stores; one running CO2 refrigeration with gas coolers in outside air and the other with ground coupling sinking the heat to boreholes.

Mateu-Royo et al. (2018) conducted field measurements from medium size supermarkets in Sweden and carried out a techno-economical comparative analysis for integrating geothermal storage in CO_2 refrigeration systems compared with standard CO_2 trans-critical booster system. They found that that a hybrid CO_2 trans-critical booster system with ground source heat pump (GSHP) as an integrated geothermal solution has 6% lower annual energy use compared to a stand-alone CO2 system with heat recovery.

Karampour et al (2019) investigated the energy efficiency of geothermal storage integration into the state-of-the-art CO_2 trans-critical booster systems. The results showed that for a stand-alone supermarket, heat recovery from the CO_2 system should be prioritized over extracting heat from the ground, which this heat extraction can be done either by an extra evaporator in the CO_2 system or by a separate ground source heat pump. Geothermal sub-cooling in summer can provide about 3.5% refrigeration annual energy savings saving compared to the reference system.

Scope 1 emissions savings (% or another quantifiable metric)	It is likely that extra piping will increase direct emission, however, if it allows CO_2 to be used instead of HFCs it would decease emissions.
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	3.5 to 24.6% reported.
Quality of scope 2 emissions information	High.
TRL level	TRL8-9
Maintainability issues	None.
Legislative concerns	Planning regulations may cause issues.
Payback time (years)	No information.

1.18.6. Cabinet lighting controls -dimming/ switching/ occupancy sensors

Lighting is only needed when a customer is looking at the product, which is likely to be a small proportion of the time. When nobody is looking in the cabinet, lighting energy is wasted, and it is also a heat load that the refrigeration system needs to remove.

Turning the lights off or dimming the lights during non-busy periods is simple, as most cabinet lighting systems in stores can be switched on and off at different times of the day, with obvious savings on energy, refrigeration load and potentially the life of the lamps. This is becoming more common practice as lighting is often centrally controlled in large stores.

For closed cabinets, door openings can be detected. For open cabinets, movement detection (occupancy) sensors/detectors can be used. Intelligent controllers can learn the busy periods and predict when to switch/dim lights.

There is considerable potential in stores with a variable trading profile to implement this technology. It is readily available and could be transferred from other areas of the cold chain (e.g. cold storage) where it is currently used. Lighting occupancy sensors are particularly compatible with LED lighting as this can be rapidly switched on and off, unlike more conventional fluorescent lighting.

LEDs can be dimmed in one of two ways. Analogue dimming means that the drive current to the LED is reduced, reducing the LED power in proportion. This is a simple solution, but the colour temperature may vary as the drive current varies, reducing the quality of the light. The quality of the light is an important factor for the retailer and therefore this is not acceptable. A better solution, which is currently available at low cost, is pulse-width modulation (PWM). This drives the light with full current pulses. The width of the pulses varies the brightness of the lamp. Provided the pulse rate is high enough (approximately 200 Hz), the eye does not perceive the pulsing at all but only the overall average. PWM dimming may be implemented in the power supply or in the driver. 25% brightness is achieved by having the pulses on for 25% of the total time.

Wang et al., (2017) investigated refrigerated case lighting controls compared to a baseline. The effect of case lights being shut off during the period from 1 hour after the store closes until 1 hour prior to the store opening (i.e., 11:00 p.m. to 5:00 a.m. 7 days per week) was modelled using a building energy simulation model. On-site energy savings of between 0.3 and 0.6% were predicted for US stores in different regions.

Diebel et al. (2013) replaced the fluorescent lighting (T8 with electronic ballasts) for a five-door case in a middle aisle of a store with LED lighting. The connected lighting load for each five-door case was 352 W. Operating hours for the case lighting were from 5 a.m. to 11 p.m. on weekdays and from 6 a.m. to 11 p.m. on weekends (for a total of 6,205 hours of operation per year). The case lights were turned off between 11 p.m. and 5 a.m. through the use of an energy management system. The connected lighting load for the case with the LED lighting was reduced to 189 W. The LED system also included dimming power supplies that were controlled by motion sensors. When no customers were near the case, the LEDs were dimmed down from maximum output. When a shopper approached the case, the LEDs were smoothly ramped up to full output. The motion sensors reduced the lighting power of the LED lamps by 43%. This was on top of the considerable saving by changing from fluorescent to LED lights. 80% of surveyed customers did not notice the dimming system. Of the 20% who did notice, most said it would not affect their shopping experience. This finding suggests that ramping is superior to low-high switching, in that switching between high and low output may be distracting to shoppers.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	0.3 to 0.6% of on-site energy savings. Reduction in cabinet LED light energy by 43%.
Quality of scope 2 emissions information	Medium
TRL level	TRL8-9
Maintainability issues	None
Legislative concerns	None.
Payback time (years)	No information.

1.18.7. Cabinet replacement with high efficiency version

Replacement of refrigerated cabinets with the most energy efficient cabinets on the market is an effective way to reduce energy consumption. This could involve replacing cabinets with cabinets which appear identical but have more efficient fan motors, evaporators etc., or changing cabinets to ones which will operate differently, for example changing from open to closed and vertical to horizontal cabinets.

A study by Moons et al (2014) confirmed that commercial refrigeration display appliances still had large potentials for improvement of energy efficiency and reduction of other environmental impacts through better design. An overall reduction of 50% of the energy use of these appliances in the EU is seen as realistically achievable by 2030.

Refrigerating appliances with a direct sales function (which include super-market cabinets, cabinets for scooping ice-cream, refrigerated vending machines, beverage coolers and ice-cream freezers) have had a European energy label and minimum energy performance (MEP) since March 2021. These are covered by COMMISSION REGULATIONS (EU) 2019/2018 and 2019/2024. These regulations define an energy efficiency index (EEI) for different types and sizes of appliance. No units can be sold with an EEI above 80% and 100% for ice cream freezers and all other appliances with a direct sales function respectively. These MEP EEIs drop to 50% and 80% in September 2023.

TopTen.eu is a web site that list the most energy efficient devices available within the EU. It shows the EEIs for the best available technology BAT (at 3/3/22) for the following types of equipment shown in the Table below.

Cabinet type	EEI (%)
Remote vertical display cabinet	22.9
Plug-in vertical display cabinet	6.4
Plug-in horizontal display cabinet	19.6

Moons (2014) assumes the average stock EEI before energy labelling would be 100%. Making this assumption assumes that energy consumption of Remote vertical display cabinet, Plug-in vertical display cabinet, and Plug-in horizontal display cabinet could be reduced by 77.1, 93.6 and 80.4% by replacing the current cabinets with the BAT.

Scope 1 emissions savings (% or another quantifiable metric)	None identified. However, more modern, and more efficient cabinets are likely to contain less refrigerant charge and likely to leak less refrigerant.
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Depends on the efficiency of the cabinet being replaced. However, 77 to 94% reduction should be possible.
Quality of scope 2 emissions information	High
TRL level	TRL8-9
Maintainability issues	None
Legislative concerns	None.
Payback time (years)	Less than 1 year.

1.18.8. Centralised air distribution

Conventional refrigeration systems provide cooling to refrigerated cabinets by direct expansion of a refrigerant in an evaporator inside the refrigerated appliances.

Yu et al. (2009) tested a cabinet with a centralised air supply. In this system, the cabinet was supplied with air from an air handling unit via a duct. Yu et al. (2009) found that the centralised air distribution system could easily control the air curtain velocity, decrease the frost magnitude, increase the defrost cycle from 6 h to 9 h, and reduce the maximum product temperature rise in the defrost cycle from 3.0 °C to 2.0 °C.

Asda/Wall-Mart are rolling out the Mistral Air system, developed by installing partner CBES across its stores (Gaved, Andrew 2016). They claim that without piped refrigerant, and the fans and condensers of the display case, maintenance call outs can be reduced significantly. Asda claim energy savings of 11 to 15% over conventional models. They also claim that refrigerant charge could be reduced by as much as 40%.

The removal of the evaporator from the cabinet offers potential advantages. Fitting the evaporator inside the cabinet can cause constraints on its size. Therefore, the evaporator is often smaller than ideal. This can lead to low evaporating temperatures and difficulties with defrosting. It is not possible to allow all of the useful part of the evaporator to extend to the edges of the cabinet due to space requirements for end turns, expansion valves and space requirements for servicing and fitting. This can lead to air flow and poor temperature at the edges of the cabinet. The air ducted system cabinets also do not have fans as these are replaced by one large centralised fan.

Another advantage of this system is that the evaporator condensate drain is external from the cabinet. Removal of the drains from the shop floor has considerable benefits in regard to water leakage and maintenance.

Often HVAC systems utilise free cooling by taking air from outside and using it to cool buildings. A similar system can be used with centralised air distribution systems if the outside ambient air temperature is below the evaporator return temperature for the refrigerated cabinets. Centralised systems also contain the refrigerant in one area and so it is possible that direct emissions can be reduced as it is simpler to prevent leaks and to identify leaks if they should occur. In addition, a low GWP refrigerant such as a hydrocarbon or ammonia could be used in the centralised plant.

The practicality of this arrangement needs to be considered. The ducting will take up more space than the refrigerant piping. Noise and condensation from the ducting will need to be considered. Yu et al. (2009) found that balancing the cabinets so that all cabinets, whether at the beginning or end of the duct run, get the same air flow is critical.

Scope 1 emissions savings (% or another quantifiable metric)	40% or more if it allows a lower GWP refrigerant (but only applied to chilled cabinets so overall saving across supermarket is less).
Quality of scope 1 emissions information	Low.
Scope 2 emissions savings (% or another quantifiable metric)	11 to 15%
Quality of scope 2 emissions information	Low
TRL level	5-7
Maintainability issues	Maintenance of cabinet should be easier as less water and moving parts.
Legislative concerns	None
Payback time (years)	Unknown

1.18.9. Defrost on demand

Avoiding unnecessary defrosting can save considerable amounts of energy. Most conventional defrosts are scheduled at pre-set times (every 6-12 hours is typical). Defrost on demand controls minimise the number of defrosts needed by a cabinet. This has the effect of reducing direct energy consumption, and also leads to reduced heat gain in the cabinet and reduce maximum product temperatures.

Demand defrost can work by either predicting frost formation by processing measured conditions (fin surface temperature, air humidity and air velocity) and/or frost accumulation symptoms such as pressure drop and refrigerant properties (de Aguiar, Gaspar, and da Silva 2018).

Defrost on demand has been tested by a number of researchers. The Electric Power and Research Institute (California, USA), in partnership with Johnson Controls/Encore, has developed a new demand defrost controller for supermarket refrigerated display cases (Hindmond and Henderson 1998). Field demonstrations were carried out in supermarkets in Minnesota, New Jersey and Florida. At the Minnesota store, the time between defrosts increased by a factor of four in the winter. The total time in defrost dropped by as much as 66% and on an annual basis by 34%. In New Jersey the time between defrosts increased from one day to the maximum limit of three days, which reduced defrost heater operation by 63% on an annual basis. Analysis showed energy savings of 25,000 kWh per year, increasing to 38,000 kWh per year if indirect savings in compressor use are included.

Tassou, Datta and Marriott (2001) showed that, using relative humidity as a control parameter, the defrost frequency can be reduced considerably without affecting cabinet performance and product integrity. The results from field measurements and laboratory tests showed that the defrost frequency of four cycles per day, normally employed for medium temperature multideck display cabinets in the UK, is only required in extreme conditions (ambient above 22 °C and 60% RH). As this occurs rarely, defrosts can be reduced based on environmental conditions.

Lawrence and Evans (2008) tested an algorithm that detects the need for a defrost from the pattern of refrigerant flow (or evaporator exit superheat). The results were compared with those from a conventional 3 defrosts per day cabinet setup. The tests were deliberately performed in higher temperatures and greater humidity than would normally prevail in UK supermarkets. Even so, it was found that the mean time for "defrost required signals" being given was 38.8 h. The energy used per year for a single 2.5 m frozen well cabinet with a defrost every 38.8 h was 538 kWh whereas the energy used with a defrost every 8 h was 1960 kWh. This means that the 38.8 h defrost represents energy savings of 72.5%. In a supermarket with 40 cabinets, the annual savings would therefore be 56,880 kWh.

Optical sensors (fibre-optic) use the reflective properties of ice. They cannot just detect presence of moisture but also its type, e.g., liquid, ice and frost. A commercially available optical frost sensor is available (New Avionics).

Practical application of defrost on demand systems has been varied with some systems showing no benefits and others showing savings of 40% of the defrost energy.

Scope 1 emissions savings (% or another quantifiable metric)	None.
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	Up to 72.5% of defrost energy.

Quality of scope 2 emissions information	M
TRL level	8-9
Maintainability issues	Unknown.
Legislative concerns	None.
Payback time (years)	Application of the technology is a controls issue and so is inexpensive to apply. Assumed that if widespread adoption paybacks of <1 year are achievable.

1.18.10. Defrost type

Behfar et al (2018) conducted an online questionnaire and found the most typical defrost type for medium-temperature cabinets is off-cycle defrost. Electric defrost is the second most common option. Hot gas defrost is the least common option for medium-temperature cabinet defrost. By far the most common defrost type for low-temperature cabinets is electric defrost. Hot gas defrost is the second most common option. Off-cycle defrost was not mentioned by any respondents for low-temperature cabinets.

Hot/cool gas

Hot gas defrosts use the compressor discharge to defrost the evaporators. Refrigerant gas is introduced downstream of the thermostatic expansion valve (TEV). This is more efficient thermally than electric heaters as heat is added inside the evaporator tubes rather than conducted from outside.

For a hot gas defrost to work, the compressor needs to run whilst the cabinet is defrosting. For pack systems this is not an issue, as only one or perhaps a few of the many cabinets will be defrosted at a time. For integral cabinets this requires a **reverse cycle defrost**. The refrigeration system is reversed by the use of valves. The evaporator now becomes a condenser and the heat of condensation melts the ice.

On evaporators with a distributor, the distributor creates too high a pressure drop, therefore an auxiliary side connector must be used to allow the defrost gas to bypass the distributor.

Cole (1989) showed that typical hot gas defrosts are only about 20% efficient (this is the proportion of energy that actually goes into melting the ice). 60% of the energy escapes into the ambient air and 20% to heat the metal. It was stated that the maximum theoretical efficiency is 60 to 70%.

Lawrence and Evans (2008) found electric defrosts to be only 15% efficient in a 2.5 m frozen food well display cabinet at climate class 3 (temperature of 25 °C and relative humidity of 60%).

Hot gas defrosts are also more thermodynamically efficient than electric heaters. The COP of the refrigeration system during defrost was found to be between 4.1 and 4.5 in a study by Zaid (2013) compared to an electric defrost which has an effective COP of 1. For multi evaporator systems the hot gas is free (no extra energy required) as it is a waste product from refrigerating the other evaporators.

Hot gas defrost results in lower overall surface temperatures within the evaporator. Temperatures will increase less, meaning that less refrigeration energy is used to re-cool the cabinet. Zaid (2013) showed defrosts were between 64% and 80% shorter for low and medium temperature applications respectively. Potentially, this can mean that the set-point temperature could be increased as there would be less temperature increase during defrost. Due to the lower surface temperatures, there is less likelihood of steam being created which then condenses elsewhere.

Although gas defrost uses less energy than electric defrost, gas defrost requires valving that increases head pressure and consequently requires a higher refrigerant charge. The Pacific Gas and Electric Company (2011) assumed an increased charge size up to 10% for a system utilising hot gas defrosts. Gas defrost was also expected to increase the potential for leaks due to the need for additional piping and valves and the thermal shock caused by the rapid change in temperature. The The Pacific Gas and Electric Company (2011) assumed that prohibiting hot gas defrost would reduce refrigerant leak rates by 5%. In the climate zone of Sacramento, they estimated an annual refrigerant saving (mean of 6 store types) of 19 to 31 kg by removing hot gas defrosts, equating to a greenhouse gas saving of 74 to 121 $MTCO_{2e}$ per year (based on R404A/507 refrigerant). The greenhouse gas associated with the extra energy used by the electric defrost was much lower, equating to 11 $MTCO_{2e}$ per year, providing a net benefit in greenhouse emissions by removing hot gas defrosts. This benefit would obviously reduce with lower GWP gases. In terms of overall costs, the extra cost of the electrical energy of electric defrost was greater than the savings of reduced refrigerant leakage, meaning that hot gas defrosts were still financially better.

Compressor discharge pressure may not be high enough in the summer months to allow adequate defrost. This technology is therefore not compatible with floating head pressure technology.

The cool-gas defrost is essentially the same, except that the gas used for defrosting is obtained from the receiver, rather than from the compressor discharge. Cool-gas reduces thermal expansion that occurs when subjecting a cold suction line to elevated defrost temperatures. In addition, using saturated vapour will provide a quicker defrost cycle than when using superheated discharge vapour.

Warm liquid

Warm liquid defrosting (WLD) uses warm liquid from the system condenser to defrost the evaporator coils. Among the advantages is the potential for a simpler overall system design eliminating hot gas or saturated vapour lines and some of the associated valves.

There is a concern that not all the liquid used for coil defrosting and subsequently expanded into the suction line will be evaporated by the super-heated vapour from the operating display cases (not under defrost) under all conditions (Mei et al. 2002). This could cause liquid to return to the compressor. Another concern is that at very low liquid temperatures (below about 10-15 °C) there is not enough heat available in the condenser liquid to effectively defrost the evaporators. This could happen at low ambient temperatures, though it can be mitigated by increased condensing pressure. However, in this case there is an energy penalty. The system cannot be used in an R744 systems where the liquid is taken from an intermediate pressure at temperatures close to 0°C.

A refrigeration test rig with two open cases and two reach-in cases were tested using WLD at –34.4°C evaporating, 32.2°C condensing, and 4.4 K subcooling below the condensing temperature (Gage and Kazachki 2002). For the reach-in case, defrost time for the WLD was 1 hour compared to 35 minutes for electric defrost. As a result of the longer defrost time, the product temperature was higher by 1.7 K with WLD than with electric defrost. They noted that increasing the flow rate of the liquid would shorten the defrost time and improve the product conditions.

Hot liquid

Niu et al (2020) present a new type of defrost method named as Hot Liquid Defrosting System with Multiple Evaporators (HLME). When one of them needs to be defrosted, hot liquid refrigerant out of the condenser is first used to remove the frost layer of the fins whilst achieving liquid refrigerant sub-cooling at the same time. They showed that the compressor power did not increase during defrost.

The advantage of this system is that for WLD, if multiple display cases defrost, there may not enough heat available in the suction gas to evaporate the liquid, as discussed. With this system the liquid that passes through the evaporator coil that is being defrosted is then passed through the other "working" evaporator, rather than straight into the suction line.

Thermal heat store

Waste heat is always created during refrigeration. The problem is that this waste heat is created when the evaporator is cooling and is not available when the evaporator is defrosting. A heat bank can be used to capture the waste heat whilst the evaporator is cooling and then discharge it into the evaporator during defrost.

The Kramer-Trenton Company patented a heat bank defrost (Thermobank method), where the discharge of the compressor heats a water store (Dossat 1991). During a defrost the heat from the water bank is used to re-evaporate the refrigerant condensed in the defrosting evaporator.

A way to use a thermal heat store to defrost an evaporator was developed by FrigescoTM (Exeter, UK). This system used a phase change material (PCM) store that is heated by the cabinet liquid line (an added advantage is that it also subcools the liquid). When the PCM is melted a defrost can be initiated. During a defrost, valves are actuated such that the cold evaporator and the PCM store form a closed loop. The temperature gradient formed between the PCM heat store and the evaporator allows a thermosiphon to exchange heat between the two. Refrigerant boils in the heat exchanger, melts the ice on the evaporator and condenses before returning to the heat store to repeat the process until the heat store is exhausted.

Results from Foster et al. (2014) showed that it was possible to eliminate the use of the electrical defrost heaters during defrost; however, a heater mat was required to allow the water to drain from the cabinet without re-freezing. The electrical defrost power was reduced by approximately 80%. Subcooling of the liquid refrigerant reduced the refrigeration duty by approximately 10%. It was noted that methods needed to be employed to make sure all ice was removed from the cabinet between defrosts. The technology was still at a development stage and was never developed further.

Ultrasonic

Ultrasonic vibrations can be used to release frost crystals from evaporators. The technology is not suitable for removing the basic ice layer but frost crystals and branches on the ice layer can be removed. The frost falls off the evaporator and collects beneath it. As the basic ice layer cannot be removed the technology needs to be applied throughout the refrigeration cycle to be effective. In trials a vibration frequency of about 28.64 kHz was used with an average power of approximately 30 W (Wang, D. et al. 2012).

Tan et al (2014) found that by intermittently applying ultrasound to a finned-tube evaporator caused the frost crystals to fall off due to the ultrasound being at the resonant frequency of the frost crystals.

No practical information is available on the savings that can be achieved using the technology.

Electrohydrodynamic

This involves employing high voltage electric field to the airflow.

Joppolo et al (2012) have shown that a DC electric field reduces the frost mass and air-side pressure drop whereas it increases the cooling capacity by 3 to 10%. They also showed that with a superimposed electric field, the overall energy consumption (compressor + fan + defrosting cycle + high voltage generator) of the refrigerating unit reduces leading to significant energy saving of up to 11.5%.

Blanford et al. (1995) noted that enhancements were maximum in the laminar flow regime, at the lowest temperature difference between the air and the heat transfer surface, and at the highest applied electric field potential. A maximum enhancement factor of 3.3 in the overall heat transfer coefficient was obtained utilizing a barbed parallel electrode at a temperature difference of 20°C and at a Reynolds number of 1,000. Typical supermarket evaporators will operate in the turbulent regime, so real applications would not be as good.

The following table assumes default defrosts for medium and low temperature systems are off cycle (passive) and low temperature respectively.

Scope 1 emissions savings (% or another quantifiable metric)	Hot gas: 5% increase in refrigerant leakage. Reverse cycle: 5% increase in refrigerant leakage. Warm and hot liquid: 0%. Thermal heat store: 0%. Ultrasonic defrost: 0%. Electrohydrodynamic: 0%.
Quality of scope 1 emissions information	Medium
Scope 2 emissions savings (% or another quantifiable metric)	Hot gas (remote only): 100% reduction of electric defrost heat load. Reverse cycle (integral only): 75% reduction of electric defrost heat load. Warm and hot liquid: 100% reduction of electric defrost heat load. Thermal heat store: 80% of defrost power plus 10% of compressor power. Ultrasonic defrost: no information. Electrohydrodynamic: 11.5%.
Quality of scope 2 emissions information	Hot gas: M Reverse cycle: M Warm and hot liquid: M Thermal heat store: M Ultrasonic defrost: M Electrohydrodynamic: M
TRL level	Hot gas: TRL8-9 Reverse cycle: TRL8-9 Warm and hot liquid: TRL5-7 Thermal heat store: TRL1-4 Ultrasonic defrost: TRL1-4 Electrohydrodynamic: TRL1-4
Maintainability issues	Unknown
Legislative concerns	None.
Payback time (years)	Unable to fully quantify.

1.18.11. Distributed refrigeration system

Major retailers use a centralised refrigeration (otherwise known as parallel rack) plant for the majority of their retail display. Distributed systems consist of several smaller parallel compressor racks distributed throughout the store. These packs are located close to the display cabinets or cold stores. A typical store might have 5-6 units.

A centralised system distributes refrigerant through the entire refrigerated area and is often sited a long distance from the cabinets on the roof or in a dedicated plant room. As each of the distributed systems is smaller and quieter, they can be placed closer to the particular cabinets they serve. The reduction in pipe lengths reduces energy losses in the system.

Having shorter pipe runs, less refrigerant, being connected to fewer cabinets and using smaller and fewer compressors, can make maintenance simpler for each distributed system. A major advantage of a distributed system is that refrigerant leaks are confined to individual smaller systems rather than one centralised system. Therefore, leaks can be determined sooner and have more localised effects. Any system failure will be confined to a smaller number of cabinets.

In a centralised system the cabinets will generally run on only two evaporating temperatures, frozen and chilled. However, the chilled and frozen cabinets will not all operate at the same cabinet temperature. Chilled cabinets may be operated at 8 °C (produce), 3 °C (dairy), and 2 °C (dairy). Freezer cabinets may be operated at -21 °C (ice cream), and -18 °C (frozen but not ice cream). In a centralised system, the suction pressure will be the lowest of all the cabinets. A distributed system allows these cabinets to be grouped together and run at different evaporating temperatures, saving energy.

Modelling and analysis work was done on various supermarket refrigeration systems by Zhang (2006) showed 7 to 10% energy savings (compressor + condenser fans) over centralised systems at 3 different regions in the US. This is because the compressors of the distributed system are closer to the display cases causing lower parasitic losses, and the saturated suction temperature (SST) employed for each distributed unit can closely match the evaporator temperature of the display cases. Zhang (2006) also assumed the distributed system had half the refrigerant charge and 10% rather than 15% leakage rate.

Scope 1 emissions savings (% or another quantifiable metric)	67% of centralised refrigeration direct emissions
Quality of scope 1 emissions information	L
Scope 2 emissions savings (% or another quantifiable metric)	7 to 10% of compressor + condenser fan emissions.
Quality of scope 2 emissions information	L
TRL level	TRL8-9
Maintainability issues	Potentially more compressors, but shorter pipe runs and less failures effect less cabinets.
Legislative concerns	None currently.
Payback time (years)	Unknown.

1.18.12. Doors on cabinets

Supermarkets are among the most energy-intensive commercial buildings. A large amount of energy is used to store chilled and frozen food in product display cabinets. Energy consumption varies widely and depend on many factors such as store type/size, business practices and refrigeration control systems. In recent years, supermarket chains have increasingly opted to use refrigerated display cases with doors to display food products. The introduction of doors offered several advantages compared to standard open ones. It includes improved energy savings, more uniform temperatures, and better product quality with a correspondingly longer shelf life. The reported savings from installing doors in display cabinets vary. This is usually due to how cost savings are measured, how testing is done (e.g. real life or standard testing) and whether demand in the cabinet has increased (e.g. additional lighting, anti-sweat heaters).

Energy Saving Potential

Chaomuang et al. (2017) investigated the energy savings that could be achieved with display cases with doors. They compared studies in different countries at the laboratory and retail levels and reported potential energy savings ranging from 23% to 73% depending on the above factors.

Fricke and Becker (2010) compared two stores that received a new set of open or closed cabinets. They found that in the in-store trial, using open-fronted cases used 30 percent more energy than using closed cabinets, with no change in sales. It is important to maintain the doors and that their seals are effective. Heaters are often required to prevent condensation on glass surfaces but can be minimized with anti-sweat heater controls. It explains that the cooling capacity of an enclosed refrigerator is lower (about 50%) due to less entrainment of ambient air. They also calculated the average energy consumption of new-doored cabinets and new opened cases. They found that cabinets with doors reduced compressor power by 72% and fan power by 20%. However, lighting power increased by a factor of 2.3, and sweat heaters were required, consuming 37% of the open cabinet compressor power. Thus, a reduction of 18% of the total energy for doored cabinets.

Door manufacturers claim 35% to 45% energy savings (Delta Refrigeration Services Ltd.). The doors seek to reduce infiltration loads and it is dependent on the temperature and humidity difference between the cabinet and the ambient temperature. According to Faramarzi (1999), infiltration states for 73% of the refrigeration load in open cabinets display, while ASHRAE (2010) noted that meat and dairy products accounted for 81% and 78%, respectively.

Tassou (2011) claims that glass doors are expected to save 50% of the energy consumed by refrigerated chilled display cases. However, Van Der Sluis (2007) stated in his original report savings of 40% (or 56% for refrigeration compressors) in a study of installing glass doors on cabinets in Netherlands.

The additional energy consumed by HVAC offsets some of the savings from glass doors, but HVAC systems are typically a better way to remove heat from the store than the display cabinets due to the warmer evaporating temperature and its higher COP. However, if the cabinet's cooling load reduction is 68% and energy savings are 23% (Faramarzi and Sarhadian, 2002), the COP of the HVAC system should be three times that of the chiller. Cabinets with closed doors have less cold air flowing into the aisles, which increases net cooling demand in summer and decreases net heating demand in winter. In addition, cooling performance can be significantly reduced, which may require changes to the cooling system. The open-front refrigerated cabinets cool and dehumidify the store, so adding a door can make shopping more comfortable. However, this also reduces the cooling load in the summer which will need to be covered by the store's air conditioning system and may need to be reinforced.

Refrigeration load and temperature

Coburn and Sarhadian (2002) found that installing doors reduced refrigeration loads by 68%. Mathematical models by Markusson and Rolfsman (2013) predict that if all cabinets in supermarkets are fitted with doors, the refrigeration load would be reduced by 30%. They found that with the doors installed, they could increase the evaporating temperature by 6 to 7°C (from -8 to -1°C), and if the refrigeration system was reoptimized, a theoretical 60% refrigeration-system-related energy savings could be achieved. However, this may not be practical if elevated temperatures adversely affect other equipment connected to the same refrigeration system.

Rolfsman et al. (2014) confirmed previous theoretical investigations under real conditions in supermarkets. Frost-free operation also improves the temperature quality of the supply and, when the system is optimized, increases the COP of the plant. They showed that these doors reduced cooling requirements by 50%. By adapting cooling technology to lower cooling demands and part-load conditions, electricity demand can be reduced by more than 75%.

Given that anti-sweat heaters and supplemental lighting contribute to increased refrigeration loads, data from Faramarzi, Coburn, and Sarhadian (2002) show that in the tests conducted, infiltration was almost completely prevented (doors did not open); the data of Markusson and Rolfsman (2013) seem to be more suitable for normal use.

Costs

Costs vary importantly depending on the type of technology. Retrofit plastic doors are the cheapest and specifically designed, while double-glazed slide and hinged doors are the most expensive. Foster et al., (2018) propose the following costs for installing a door in a typical 8-foot cabinet. Low-cost glass doors (part cost 750 GPB = 898 € and installation cost 1012 GPB = 1212 €) and Quality of "top-end" doors (1500 GPB = 1797 € part cost and 2025 GPB = 2425 € installation cost). Cooperative Supermarket claims that installing doors in 100 stores can save 60 million € per year (The Guardian, 2012). Meanwhile, The Guardian (2012) claimed that Tesco found 4.8 million € savings per year by installing doors in 350 convenience stores with doored cabinets.

PECI (2011) modelled a supermarket to investigate the total cost of retrofitting glass doors. All labour and material costs, as well as total cooling system changes, were USD 566.17 per ft per case. (approx. 1343 €/m).

Ademe (2018) stated that there were two studies conducted in France, with a small supermarket (Biocoop Saint-Malo 2016) and a large supermarket (Super U - Erquy 2014) adopting the same cost of doors. For a glass door, it was 2500 € per linear meter. However, with a retrofit option, it was 300-400 € per linear meter.

Many of the above experiments were performed in a laboratory or on a limited number of cabinets. There are some limitations to using this data to estimate supermarket savings. A French study (PERIFEM and ADEME, 2008) estimated savings of 38-50% in supermarkets of various sizes in France. The expected savings of their study in terms of energy and costs were: [16]

Size of supermarket (m^2)	Annual savings by adding doors	
	kWh	EUR
18,000	4,500,000	300,000
5,500	800,000	60,000
2,500	700,000	50,000

Paybacks

According to a study conducted by the Swedish Ministry of Energy, the payback period for installing glass doors in open front cabinets was about 16 months. Evans (2014) estimates annual financial savings from installing doors depending on the size of the store (2,500-18,000 m^2 for approximately 50,000-300,000 €). It is not clear if they considered the optimization of the refrigeration system in their calculations. When calculating the cost of changing from an open door to a glass door cabinet, several factors are often not taken into account. According to PECI (2011), savings depend on the exact cabinet type, but estimated generally about 1.4-1.6 years of payback when including the savings from reduced refrigeration energy and reduced gas usage from less store heating. PECI's investigation did not consider continuous maintenance of the door. Cabinet doors inevitably require maintenance. It seems unlikely that the annual maintenance cost will exceed the installation cost (estimated to be around 196 GBP =

235 € / m according to PECI). Even if the door is re-installed each year, it is only about 25% of the savings achieved by the cabinet itself and the reduction in energy used for air conditioning.

A study conducted by Carbon Trust & IOR (2012) found a payback of 3.7 years including all costs.

Optimisations

A cabinet designed as a glass door cabinet features a smaller evaporator and air circulation system, reducing the overall cost. However, the most cost-effective option in supermarkets that already have open cabinets is usually a retrofit option that involves adding glass doors to an existing open cabinet. During the retrofit work, there is also an opportunity to make further energy-saving adjustments to the cabinet (Navigant Consulting, 2013). For example, you can incorporate LED lighting (probably using occupancy sensors). Furthermore, when the cabinet is closed, the fan power can be reduced and switched to an EC motor (electronically commutated). However, care must be taken so that adjustment does not adversely affect the temperature of the food. To save electrical energy and costs of retrofitted doors, the refrigeration system needs to be optimized according to the new conditions. No direct emissions savings are expected. However, reduced refrigeration duty may give the opportunity to reduce the size of the heat exchanger.

According to Foster et al. (2018), the air curtain behind the door improves the efficiency when opening it and so improves cabinet performance when the door is open. Some cabinets with glass doors are also fitted with air curtains that can be activated or accelerated as a result of door opening, especially if frequent door opening is expected. Trim heater requirements depend on a store's ambient conditions and the temperature of the glass door. Trim heaters are common in frozen cabinets but are not always used on chilled cabinets.

Doors are obstacles and ease of use is important. Shoppers need to be able to hold the basket at the same time as they open the door, shop workers need to be able to refill the cabinets, and if the shopper forgets to do so, the door must close automatically, fire protection regulations must be present to prevent restrictions and hinges, or runners must be strong enough to withstand frequent use. Various hinge designs and slide assemblies are proposed by the manufacturer. Perspex doors offer cheaper solutions but are of lower quality and less reliable than glass doors. You can use either single glazing or double glazing. Opening frequency or payback cost are usually the decisive factors between glass and plastic doors. For best results, the door should seal the front of the cabinet, which can be difficult to achieve, especially in a retrofit case. If the door is sealed, suction can cause the door to be too tight to open, as the cold air that enters when the door is opened cools. We also have other savings from optimising controls, repairing refrigerant leaks, optimising pipe work and implementation of expansion valves.

Case study

Symonds et al. (2017) stated that WWF-Hong Kong performed an open display refrigeration study that measures energy consumption and temperature performance over 10 hours in three scenarios: when the fridge has sliding glass doors, transparent plastic curtains, and no doors or curtains. From an energy consumption perspective, this study found that fridges with sliding glass doors and fridges with plastic curtains use 50% and 35% less electricity than fridges without doors, respectively. This is equivalent to savings of 5,000 kWh or HKD $ 5,700 per year (666 €). According to the International Institute of Refrigeration (2014), these results are similar to the studies conducted in the United Kingdom, the United States and Sweden. Retrofitting doors is mainly the most effective energy-saving measure for grocery retailers. The results of the study also led to the conclusion that open display case fridges and fridges with plastic curtains could not keep the temperature cool and the products could not be kept safe. They stated that the maximum temperature for storing perishable food is 4 ° C. In comparison, fridges with doors were able to maintain lower storage temperatures.

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)	128.7 ton / year savings of CO_2e (Carbon Trust & IOR 2012) (min 60-148 max ton/year) (Foster et al. 2018) 18-51% total energy savings (Foster et al. 2018) (Fricke & Becker 2010) 23-73% total energy savings (Chaomuang et al. 2017) 40-50% total energy savings in the case of double glazed glass doors (Ademe 2018) Depending on usage and factors
Quality of scope 2 emissions information	Lots of publications show potential to reduce CO_2 and save energy but the percentage differ based on the factors discussed above
TRL level	TRL8-9
Maintainability issues	Adjust runners and hinges to withstand frequent use Regular cleaning of the doors Long-term care: washing and polishing…
Legislative concerns	L No impact
Payback time (years)	3.7 years (Carbon Trust & IOR 2012): including all costs 1.4-1.6 years (Swedish Energy Ministry & PECI 2011): without costs of maintenance of the door, financial costs and including the savings from reduced refrigeration energy and reduced gas usage from less store heating. 3-8 years (Ademe 2018): from adding doors to full replacement of cabinets

The baseline store used to fill a part of this table is a typical supermarket of 5,000 m² sales area which is equivalent to a large supermarket or a small hypermarket (Carbon Trust & IOR (2012) values). However, Carbon Trust & IOR

(2012) affirmed that this information can be applied to any supermarket above 2,000 m^2 (as above this size energy usage is relatively linear with the size of the store). However, an ASDA store at Weston-Super-Mare was also used as a baseline store. The store refrigeration load was split between low temperature (LT) and medium temperature (MT) packs and condensing units. The size of the store was 6290 m^2 (74 x 85 m) (total store). (Foster & Al (2018) values).

1.18.13. Dynamic demand

Dolman et al. (2012) estimated that non-domestic buildings (excluding industry) contribute approximately 15 GW (c.30%) to winter peak demands on Great Britain's national grid. The retail sector contributes most to peak demands (33%), the majority of which comes from lighting. The initial assessment of the potential for DSR to reduce peak demands includes assumed flexibility in hot water, HVAC, other (mainly refrigeration) and lighting loads. This leads to an estimated technical potential of 1.2 to 4.4 GW, i.e. between 8–30% of demands during the peak hour. According to feedback from one organisation with experience in this area, 30 minutes of load interruption is possible in theory (but would be considered extreme). Cold stores and freezers offer further flexibility as they can be "charged up" (super-cooled) and then switched off for 30– 60 minutes, possibly more if not opened.

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

Dynamic demand is where the demand for electricity is reduced when the frequency of the electrical supply drops. When frequency drops, it means that energy generation is struggling to keep up with demand, so dynamic demand helps by effectively shedding load. This should not be confused with demand response. 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.

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.

Pedersen et al., 2014 investigated aggregation and control of supermarket refrigeration systems in a smart grid. The supermarkets were able to shift the power consumption in time by pre-cooling the contained foodstuff.

Coccia et al. (2019) investigated demand side management analysis of a supermarket integrated HVAC, refrigeration and water loop heat pump system. The demand response was based on real-time pricing rule-based controls. They predicted annual cost savings of between 4.1 and 4.7% depending on the extent of the control.

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. Cortella et al (2022) used ice thermal energy storage to shave the peak in electrical power use of an HVAC plant of a supermarket. The thermal storage was charged at night-time by the CO_2 refrigeration system, which was part-loaded during the shop closing time.

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%.

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.

Smaller users (approximate minimum of 100 kW per site) will tend to use an aggregator to manage their demand. Larger uses (upwards of 1 MW per site) can deal directly with the UK National Grid. Businesses signing up to provide Frequency Response services typically achieve around a two-year payback on equipment (McManan-Smith 2015).

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	0.12% of electrical energy assuming 0.5-hour energy shift to next or previous half hour, assuming perfect prediction of demand period in advance.
Quality of scope 2 emissions information	M
TRL level	TRL8-9
Maintainability issues	None
Legislative concerns	Unknown
Payback time (years)	Frequency response 2 years.

1.18.14. Economisers

As the pressure ratio of a refrigeration cycle increases, the efficiency of single stage cycles reduce, hence why two stage systems are employed for high pressure ratio cycles. An economiser is a type of sub-cooler that uses part of the total refrigerant flow from the condenser which is expanded to an intermediate pressure, to sub-cool the liquid from the condenser.

For two stage systems the intermediate pressure gas is returned between the two compressor stages. However, low temperature scroll and screw compressors in the size ranges typically employed in supermarkets commonly have an intermediate pressure port that allows economisers to be used on single stage systems.

Traditionally single stage economisers have been used on screw compressors but they can also be used on scroll or centrifugal compressors. It is not possible on reciprocating compressors. These machines act like a two-stage booster compression system. However, they only use one compressor with two inputs (the main suction and an economiser port at an intermediate pressure). This allows the benefits of a booster system with only one compressor.

There are two types of economiser setups; one uses a heat exchanger and the other a flash vessel.

In a heat exchanger system, part of the refrigerant, typically 10-20%, is expanded to an intermediate pressure and passed through a heat exchanger where it sub-cools the liquid from the condenser. This increases the capacity of the system by around 10% and reduces flashing. There is consequently a small increase in the power input caused by the transport of an additional mass flow; the increase in the system efficiency can be explained by considering that the additional compression work is taking place at a higher suction pressure, therefore with a higher efficiency.

With a flash economiser, all the liquid from the condenser goes through an expansion valve and into a flash vessel at an intermediate pressure (the pressure of the economiser port on the compressor). The flash gas is taken into the economiser port, whereas the saturated liquid is passed through another expansion valve into the evaporator.

The benefit of an economiser to the COP of the system is dependent on the thermal effectiveness of the sub-cooler heat exchanger or flash tank.

According to Bellstedt (2015), for a system with parallel screw compressors at an evaporating temperature of -25°C, COP improvement was between 7 and 9% between a condensing temperature of 25 to 35°C. At an evaporating temperature of -5°C, COP improvement was between 4 and 5% between a condensing temperature of 25 to 35°C.

Llopis et al (2018) investigated sub-cooling methods for CO_2 refrigeration cycles. They determined that sub-cooling at transcritical conditions had greater benefits than at subcritical conditions. This was because, for the former, sub-cooling has the added benefit of reducing the optimal working pressure. They found that economisation of CO_2 cycles, generally used with double-stage compression systems, showed COP improvements up to 15.2%.

Economizer systems require extra components, such as extra piping and either a sub-cooler or flash vessel. The additional capital expense makes this system solution viable only for large refrigeration systems. Pacific Gas and Electric Company (2011) showed that mechanical sub-cooling for low temperature parallel compressor systems was cost effective in all US climate zones. The benefit to cost ratio varied between 1.8 and 20.9 for the different climate zones and supermarket types over a 15 year life cycle. A typical cost benefit of 7.5, amounting to a 2 year payback was shown.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H

Scope 2 emissions savings (% or another quantifiable metric)	Depends greatly on system. For single stage at low condensing temperature and high evaporating temperature, benefit in COP can be as low as 4% For CO_2 systems with double stage compression improvement of 15.2% has been reported.
Quality of scope 2 emissions information	M
TRL level	TRL8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Depends greatly on circumstances. Typical 2 years.

1.18.15. Ejectors

Two-phase ejectors for the purpose of expansion work recovery can theoretically be used with any refrigerant. However, their main use has been in CO_2 systems. This is due to the large pressure differences and transcritical nature of CO_2 refrigeration systems and the resulting throttling losses, which are particularly high. Using an ejector enables kinetic energy to be recovered during the expansion process, which can then be used in a variety of different forms to increase the system COP. Refrigerant ejectors are inexpensive and reliable devices with no moving parts and just 3 connections which need to be made.

Ejectors have been used in different parts of the system. The most common ejector cycle is to use the ejector as a fluid driven compressor to increase the refrigerant pressure at the compressor inlet to a level above the evaporation pressure.

Other uses include utilisation of the ejector as a pump to provide liquid overfeed of the evaporator of the system, which increases the COP compared to superheated evaporators. Using and ejector avoids issues with cavitation that has been seen using pumps for this purpose.

The idea of an ejector cycle dates back to a patent by Gay (1931). More complex versions of this cycle have been proposed and investigated. Hafner, Försterling and Banasiak (2014) created simulation models of a one-stage and multi-ejector system representing a supermarket test facility. Compared to the investigated reference system a COP increase between 10% at 15 °C and 20% at 45°C ambient temperature can be determined.. Typical COP increase of 17% in Athens, 16% in Frankfurt and 5% in Trondheim can be achieved during the summer.

Pottker (2012) also showed that the COP of the ejector system increased between 8.2% and 14.8% when compared to a conventional expansion valve system operating with R410A. The two major mechanisms of improvement of the ejector system were quantified separately: COP gains of between 1.9% and 8.4% were solely due to the work recovery, while liquid-feeding the evaporator alone was responsible for 4.9% to 9.0% of COP gain. Overall ejector efficiencies from 12.2% to 19.2% were achieved.

Ersoy and Sag (2014) compared a conventional and ejector R134a system experimentally under the same external conditions. Depending on the operating conditions, it was found that the work recovery in the ejector was between 14% and 17% lower. It was also found that the refrigeration system with an ejector as the expander exhibited a COP that was 6.2 to 14.5% higher than that of the conventional system.

A CO_2 ejector cycle was installed in a supermarket (Migros) in Bulle, Switzerland, by Frigo Consulting Ltd in July 2013 (Frigo-Consulting Ltd, 2014). The system was a transcritical booster system. One of the MT compressors was shifted to become a parallel compressor and a low pressure receiver was added. They claimed a 15% increase in efficiency.

According to Pisano (2018) there are nowadays more than 200 installations using parallel compression in conjunction with ejector models, making it possible to consider these fully mature and available technologies, and leading carbon dioxide based refrigeration plants to outperform HFCs systems at any European latitude with reasonable return. He showed a return of investment of only 2 years for a booster system with parallel compression, liquid and vapour ejector compared to a simple CO_2 booster system.

Girotto (2017) states that an ejector with efficiency 8% can improve the overall annual performance as high as 15% if used for overfeeding evaporators, while the effect of an ejector with peak efficiency 30% used to pre-compress vapor can be only 5% on the overall yearly performance, depending on the outdoor temperature profile.

According to Gullo, Hafner, and Banasiak (2018) the addition of vapor ejectors with high pressure lift to units relying on parallel compression is economically acceptable for supermarkets with cooling capacities over 75 kW and located in cities having an average annual temperature above 15°C. A range in paybacks between 0.4 and 21.5 years was calculated. The best payback for a large (300 kW) liquid ejector at an annual average temperature of 30°C and the worst for a small (40 kW) low pressure lift vapour ejector at an annual average temperature of 0°C.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	Depends on many factors Typically for R744 with liquid overfeed 10 to 20% for cold to warm climates.
Quality of scope 2 emissions information	H
TRL level	TRL8-9
Maintainability issues	There are some issues with control at part-load; in some plants ejectors are by-passed when the technician meets control issues
Legislative concerns	None
Payback time (years)	Depends greatly on circumstances. Typical 2 years for multi ejector in Italian climate. Payback becomes much longer for pressure lift vapour ejectors and cold climates.

1.18.16. Electronic expansion valves

Electronic expansion valves (EEVs) are typically used to replace thermostatic expansion valves (TEVs). There are two main designs of EEV; those which vary their orifice opening in an analogue manner to continuously regulate refrigerant flow (modulating), and those which adopt a pulse width modulation strategy (PWM) to deliver refrigerant to the evaporator in short bursts over an orifice of a fixed size.

According to (Carel 2011), modulating valves offer more stable superheat control, thus allowing potential higher evaporating temperatures and lower energy consumption. They measured a 10% reduction in energy consumption compared to a PWM valve during laboratory testing on a Carter Retail Equipment a medium temperature upright showcase.

The sudden surge of refrigerant with the PWM EEV can cause reduced life expectancy with some types of evaporators and flashing in the liquid line in some systems. PWM valves also have high energy consumption as they are using energy all the time. The advantage of a PWM valve is that a liquid line solenoid valve will not be required.

There are two common control strategies; temperature-only based on temperature probes at the evaporator inlet and outlet; and temperature/ pressure which measures both pressure and temperature at the evaporator exit to more accurately determine the actual superheat.

EEVs are easier to commission than TEVs although it is important that the correct control parameters are used. They can also be used with different refrigerants by just altering the controller parameters. Maintenance and commissioning benefits of the electronic valves can also be valuable to the end user in practice. With an electronic valve, the settings can be controlled and altered automatically and remotely from the valve. The valve parameters can even be monitored and used to generate early warnings of service or maintenance issues with the cabinet or plant.

The cost of EEVs is still much higher than for the simple and mechanical TEV (SWEP 2019). EEVs are therefore mostly found on very large systems and systems with a high demand for precise regulation and can handle large variations in operating conditions.

The major benefit of EEVs in reducing energy consumption is their ability to enable systems to operate with floating head pressures. TEVs require high head pressure to make them operate correctly. EEVs do not, which allows them to run at reduced pressure as ambient conditions allow, reducing the energy consumption of the compressor. The majority of system operators in North America keep their head pressures near a saturation temperature of 105°F, which is considered acceptable because it works within the limitations of mechanical TXVs (Patenaude 2014). EEVs enable them to float their system pressures down to a saturation temperature of 70°F (or lower) condensing temperature, thereby achieving significant energy savings. According to Patenaude (2014) depending on the compressor type and make, a typical system can achieve 15%–20% energy-efficiency ratio (EER) improvements on the compressor for every 10°F of saturation temperature decrease in head pressures.

A water-loop self-contained (integral) refrigeration system with modulating compressors supermarket located in Italy was considered and its annual performances compared with those of both a simulated multiplex benchmark solution with thermostatic expansion valve (TEV) and fixed evaporation pressure and with those of a simulated multiplex solution with electronic expansion valve (EEV) and floating evaporation pressure (Bagarella, Lazzarin, and Noro 2014). The comparison between the two systems points out that the EEV with floating suction pressure leads to an 8.1% electric energy savings over the benchmark TEV fixed suction pressure system. The saving is due to a lower average condensation and higher average evaporation pressures.

A Danfoss Smart case controller and electronic expansion valves were installed at Tops Market 22 in Niagara Falls, New York (Hy-Save). The energy savings achieved averaged 9% with increasing savings in warmer months.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	8-9%, this assumes it allows floating head pressure.
Quality of scope 2 emissions information	H
TRL level	TRL8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Unknown

1.18.17. Expanders

Expanders are widely used in the refrigeration of gases in industrial processes such as natural gas and the liquefaction of gases for example cryogenic gases. The work created in the expansion process can be usefully used, e.g. to power a generator or to provide work directly to the compressor. Furthermore, the isentropic expansion in the expander drastically lowers the temperature of the gas in comparison to an isenthalpic throttling process, such as an expansion valve. However, the expansion is on a single phase gas. The expansion on a typical DX refrigeration system is from a liquid to a gas and therefore the expander needs to be able to handle two-phase flow that is generated when the high pressure liquid partially flashes into a gas during the pressure reduction. A two-phase expander is thus required to replace the isenthalpic expansion process of a throttling expansion valve with an isentropic expansion process.

Since trans-critical carbon dioxide refrigeration cycles have a large throttling loss, recovering the throttling loss by an expander is effective for improvement of the cycle performance (Fukuta et al. 2006). In theory, recovery of energy lost in the expansion process of a vapour compression cycle is of interest for any refrigerant.

See (Murthy et al. 2019) for a review of this technology. They report the highest COP improvement in a transcritical CO_2 refrigeration system was 30% and in a conventional refrigeration system was 10%.

There are a number of different types of expanders, these are reciprocating piston, rolling piston, rotary vane, scroll, screw and turbine.

The reciprocating piston is one of the oldest types. Baek, Groll and Lawless (2002) experimented with a piston-cylinder expansion device in a transcritical CO_2 refrigeration cycle. The design was based on a commercially available two-piston engine. The experiment showed that the expander increased the system's COP by up to 10%.

A three-stage reciprocating piston expander was developed and tested by Nickl et al. (2005) in a CO2 refrigeration system. The developed prototype was tested to directly power the second stage compressor. The study found that there was a 40% COP improvement compared to a similar cycle with throttling valve.

Kohsokabe et al. (2006) studied a transcritical CO_2 refrigeration cycle for a small capacity air-cooled chiller with a scroll type expander and a rolling-piston type rotary sub-compressor connected with a shaft. In experiments, the expander-compressor unit was shown to be stable and to improve the COP of the CO_2 chiller cycle. The test results indicated that the COP improvement of the cycle was more than 30%, while the total efficiency of the expander-compressor unit was 57%.

According to (Riha, Quack, and Nickl 2006) the cost of the expander/compressor is estimated to be less than 30% of the associated main compressor. The power saving, which is possible with this addition to the plant, will easily pay for the extra cost, especially when one considers the permanently rising cost of power.

Turbolgor offer a tubocharger expansion device (Turboalgor | Cold Energy Saving) which they claim offer up to 23% energy savings, and 56% increase in cooling power. PX G1300 for CO2 Systems - Energy Recovery offer an expansion system using "pressure exchanger technology" which uses rotating ducts to transfer energy from the high to the low-pressure side. This has been used in other technologies (e.g. de-salination and waste-water treatment) but they offer a model for commercial R744 systems.

Issues relating to the application of expanders such as internal leakage and irreversibility have started to be studied, but more research is required (Murthy et al. 2019). Control strategies that allow expanders to react dynamically to changes in the operating conditions of a refrigeration system are required for commercialization of the technology. Further development and optimization of expander designs and integration with compressors are crucial aspects for future progress of the technology.

There is no published information on commercial implementation of this technology.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	30% improvement in COP for CO_2 transcritical system and 10% for a conventional system.
Quality of scope 2 emissions information	M
TRL level	TRL1-4
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Not yet commercialised.

1.18.18. Fan motor outside of cabinet

Evaporator fan motors are normally mounted within the cold space of the cabinet; therefore, all of the energy of the motor is a heat gain on the cabinet. Mounting the electric motor outside of the cabinet but the fan inside the cabinet, by means of a shaft passing through the insulation of the cabinet allows the heat to be dissipated outside of the cabinet. Servicing of external motors may also be simpler. However, a shaft going through the insulation could cause air and moisture ingress problems.

In most cabinets the heat load from the fans will be approximately 5% of the total heat load (ASHRAE, 2001). According to Foster et al. (2018) the evaporator fan motor powers were 60 W per 2.5 m of frozen cabinet and 38 W per 2.5 m of chilled cabinet. Therefore, mounting the motors outside of the cabinet would reduce the refrigeration energy consumption by this amount.

The direct energy used by the motors may however be higher when mounted outside the cabinet as the warmer air passing over the fan motor may reduce the efficiency of operation.

The author is not aware of any publications where this has been carried out.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	Potentially up to about 5% of compressor power.
Quality of scope 2 emissions information	M
TRL level	TRL1-4
Maintainability issues	Easier to change motors and motors will be in a dryer environment, however, shaft sealing is likely to cause issues.
Legislative concerns	None
Payback time (years)	No product available.

1.18.19. Flooded (overfeed) evaporators (added to R744)

To get the maximum efficiency of an evaporator, it can be operated with a liquid overfeed (flooded). Unlike in a direct expansion system, the fluid at the exit of the evaporator is not superheated, it is a two-phase mixture with a small volume of liquid mixed in with the gas. The main advantage of operating an evaporator in a flooded state is that the temperature difference between the air temperature and the evaporating temperature can be greatly reduced since there is no requirement to heat the suction gas above its evaporating temperature. The main disadvantages of flooded systems are that a method of separating the liquid overfeed from the suction gas is required before it reaches the compressor, and the return of lubricating oil from the evaporators to the compressor, which is usually easy in a DX system, may require some additional equipment or maintenance routines. Nowadays ejectors are being used instead of a pump to transfer liquid to the evaporators.

Gullo et al (2016), reported that in comparison with a conventional booster system, overfed evaporators consumed at least 7.2% less energy in the selected locations (Rome, Valencia, Seville).

Singh et al (2018) studied the use of a liquid ejector to eliminate superheating of an R744 evaporator at high ambient temperature conditions (46°C). It was observed that the increment in evaporator pressure and decrement in compressor power consumption were 4.5% and 5.5% respectively.

Pardiñas et al. (2021) modelled a CO_2-based integrated refrigeration system for supermarkets. The combined effect of the high-pressure ejector and the 5 K evaporation temperature increase (with a liquid ejector) on system COP was 13% compared to the high-pressure control valve only system layout during the week used for validation.

The increase in evaporation temperature for a chilled cabinet can potentially reduce or even eliminate the requirements for defrosting.

Scope 1 emissions savings (% or another quantifiable metric)	None

Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	Potentially up to about 5.5% to 13%.
Quality of scope 2 emissions information	H
TRL level	TRL8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	No information available.

1.18.20. Heat from light outside cabinet

If lights are within the cold space of the cabinet, the heat generated by the light will be a heat gain on the cabinet. Open fronted cabinet lights are often mounted outside of the cold space for this reason and also because fluorescent lights do not work well at cold temperatures. However, it is difficult to position glass doored cabinet lights outside of the cabinet as light will reflect off the glass and therefore not illuminate the inside of the cabinet. Two solutions present themselves**:**

- To mount the light outside and shine the light inside using some type of reflective duct. The authors are not aware of any work in this area;
- To mount the light inside and remove the heat.

ASHRAE (2001) reports that depending on the cabinet type, the heat load from lighting can be between 2 and 10%. Olivewood Chil-LED (OliveWood, 2018) offers the second of the solutions for LED lights in cold storage. They use a heat pipe to transfer the heat from the LED through the insulation and outside of a cold room. This system is ready to use in cold rooms. However, extra development would be required to adapt it to display cabinets.

Energy savings of 23% with Chil-LED™ 90 compared with a well-designed 90W LED equivalent is reported by OliveWood (2018) and hence this value is assumed.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence.
Scope 2 emissions savings (% or another quantifiable metric)	23% savings for a cold store.
Quality of scope 2 emissions information	Information only from manufacture and only for a cold store.
TRL level	TRL5-7
Maintainability issues	Unknown.
Legislative concerns	None.
Payback time (years)	No information available.

1.18.21. Heat pipes

In supermarket cabinets, temperatures of products vary according to their position within the cabinet, with the warmest packs normally at the front of the cabinet, as they are more exposed to the ambient environment. Cabinets must be run to keep the warmest product within microbially safe levels. This means that other products are often over-cooled, increasing the energy consumption of the cabinet. Heat pipes offer a potential way to move cooling to warmer areas. Thus, the temperature difference in the cabinet could be reduced, allowing mean cabinet temperatures to be raised to save energy.

Heat pipes have been theoretically shown to improve the performance of display cases both in terms of maintaining temperatures within a narrower band and saving energy. Practical demonstrations of this by different authors have provided very different results.

(Wu et al. 2017) experimentally investigated the performance of a cool storage shelf for vertical open refrigerated display cabinet. The new composite shelf was based on heat pipe and PCMs. They showed that heat pipe was favourable in improving the performance of heat transfer in composite shelf.

Foster, Orlandi, and Evans (2014) showed a reduction of only 0.2 K at the centre of a Tylose test pack in a glass door cabinet using a heat pipe directly underneath the pack. This gave a predicted reduction in energy consumption of 1% based on an increased set-point of 0.2 K. A computer model was used to predict the benefit for a poorly performing open fronted cabinet. This showed a reduction in temperature of 0.7 K and a predicted reduction in energy consumption of 3.5%. The heat pipes were hand-made to order at a cost of £82.60 each for 10 units. The number of heat pipes required is dependent on where warm spots may exist on the shelves. However, if it is assumed that heat pipes are only used where "m" packs are located on shelves (not the base/well) in an EN23953:2005 standard test (this allows the cabinet to perform better in a test, but not necessarily in a real environment), this would lead to 9 heat pipes at a cost of GBP 743.40. As this is a significant additional cost for the cabinet, this would only be cost-effective if the price of the heat pipe was reduced dramatically due to mass production.

Jouhara et al. (2017) used flat heat pipe technology to produce a heat pipe shelf. The outcome of their tests showed that the heat pipe homogenised the temperature profile of the products and reduced the electrical energy consumption of the cabinet by approximately 12%.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	1% measured, potentially up to 3.5%. When incorporated with PCM, 12%.
Quality of scope 2 emissions information	M
TRL level	TRL1-4
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Prohibitively high unless mass produced.

1.18.22. Hydrophilic and hydrophobic coating on evaporators

Aluminium and copper (which are used in the construction of heat exchangers) tend to retain water in application, which can degrade performance. When the amount of water condensed on fin surface increases, some water droplets drain from the fins due to the gravity or airflow forces while some adhere to its surface due to the surface tension. Those water droplets that remain on fins can lead to unwanted conditions, e.g., (i) bridging between fins which increases the air-side pressure drop; (ii) reduction in the air-side heat transfer coefficient; (iii) degrading of the cooling capacity. Frost layers develop on fin surfaces resulting in an increase of the heat transfer resistance between the fin and air, the blockage of the airflow passages (Ganesan et al. 2016).

Evaporators used in HVAC systems mostly have hydrophilic coatings. Modifying the surface however to be can help to spread out the condensate, reduce the air-side pressure drop (reducing fan power consumption), and facilitate drainage (Edalatpour et al. 2018). However, although the hydrophilic treatment decreases fan power consumption, it adds to thermal resistance (Ganesan et al. 2016).

Hydrophobic coatings cause water to form droplets on the surface. These droplets are less likely to adhere to the surface reducing the wettability of the surface, however, they can bridge the gap between fins.

(Ganesan et al. 2016) conducted a review of air-side heat transfer characteristics of hydrophobic and super-hydrophobic fin surfaces in heat exchangers. They found:

- Under dry conditions the coatings had no effect.
- The hydrophobic surface retains the largest amount of condensate water; in some cases the amount can be similar to that of uncoated surface. Less condensate water retains on hydrophilic surface.
- The hydrophobic surface forms a very low-density frost but hydrophilic surface develops a high-density frost in comparison to that of uncoated surface.
- The super-hydrophobic surface has the best anti-frosting capability followed by hydrophobic surface.
- The pressure drop is found to be lowest for super-hydrophobic surface, but the highest is recorded for uncoated surface.
- The highest heat transfer occurs for super-hydrophobic surface, but the least is for uncoated surface.
- The rate of the drained water is the highest for hydrophilic surface and this is followed by the hydrophobic surface.
- In terms of melting time, the least duration is found for super-hydrophobic surface followed by hydrophilic surface. The longest duration is for uncoated surface.
- The least water retains on super-hydrophobic surface and this is followed by hydrophilic surface.

Jhee, Lee and Kim (2002) found that the frost development (density) is found to be the highest for hydrophilic surface during the early stage of frosting. For practical use hydrophobic surface treatments were more effective in view of the defrosting efficiency and time. The defrosting efficiencies of hydrophobic heat exchangers were enhanced by about 10.8% whereas hydrophilic surface-treated heat exchangers were enhanced by about 3.5%.

Liu and Jacobi (2006) found that hydrophilic coatings reduce the wet pressure drop (pressure drop through the coil when it is coated in water) significantly without decreasing the wet sensible heat transfer coefficient.

Truster et al. (2014) also studied the surface frost properties and defrosting effectiveness of a metallic heat transfer surface. They showed that non-coated surfaces accumulated 60-90% more frost mass than the hydrophobic surface during the same allotted time period. They also showed that the hydrophobic surface consistently removed more water than the non-coated surface during defrosting.

Min et al. (2011) studied the performance of hydrophilic treatments on copper finned tube evaporators. They showed that the hydrophilically treated evaporator tended to yield a greater cooling capacity than an untreated evaporator, but the increment was small. This may be partially attributed to the limited amount of condensate retained on the fin surface of the evaporator.

(Wang, F. et al. 2015) studied the effects of surface characteristic on frosting and defrosting behaviours of fin-tube heat exchangers. They found the frost thickness and mass of the superhydrophobic heat exchanger were 17.1% and 28.8% less than those of the bare heat exchanger. The energy consumptions for defrosting were 258.8, 301.7 and 244.7 kJ for the hydrophilic, bare and superhydrophobic heat exchangers, respectively. The frost layer on the superhydrophobic fins was thinner than those on the other two fins, so the heat capacity for melting was also less. The results indicated that the superhydrophobic heat exchanger can reduce the energy consumption and time for melting.

Research has been focussed on air conditioning and heat pumps, where frosting/defrosting is less of an issue as it with commercial refrigeration.

Scope 1 emissions savings (% or another quantifiable metric)	None.
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	Hydrophobic 11 to 19% lower defrost energy..
Quality of scope 2 emissions information	M
TRL level	TRL1-4
Maintainability issues	Less icing issues.
Legislative concerns	None.
Payback time (years)	Not at commercialisation stage.

1.18.23. Improved axial fans

Almost all refrigerated display cabinets are with evaporator axial fans.

Airflow across the plane of the fan blade is not uniform varying from positive at the tip to negative at the centre of the fan. Blade shape and twist of the aerofoil along the blade affects the shape of the velocity profile. The advantages of a tapered, well designed blade with even airflow across the fan result in higher efficiencies and thus lower power (Hudson Products Corp. 2000)

Yang and Zhao-Hui 2007) optimised the design of a low-pressure axial fan with skewed blades. The blade was optimised such that the circumferential skewed angle of the optimised blade was 6.1

degrees. The total pressure efficiency was increased by 1.27%, and total pressure rise was increased by 3.56%. The stable operating range of the optimised impeller was extended to more than 30%. Aerodynamic noise was also reduced.

Parker et al. 2005) designed, fabricated and tested improvements to an air conditioner outdoor unit fan system. An improved high efficiency fan design and advanced exhaust diffuser section reduced fan motor power requirements by approximately 49 W (26%) while providing superior air flow.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	Up to 26% of fan energy. For a supermarket remote refrigeration system with evaporators fans being 4% of total refrigeration consumption (Foster et al, 2018. Technological Options for Retail Refrigeration) this would provide a total refrigeration saving of up to1%.
Quality of scope 2 emissions information	L
TRL level	TRL5-7
Maintainability issues	None
Legislative concerns	None
Payback time (years)	<2 years

1.18.24. Improved cabinet loading

Cabinet loading has a significant effect on air infiltration in open cabinets. In supermarkets, shelves are sometimes partially filled or overfilled. This allows more air to enter the cabinet. Therefore, fully loaded shelves may improve the efficiency of the cabinet, and any method ensuring that the shelves remain fully stacked should bring energy efficiency benefits. Improving cabinet loading is a relatively simple energy-saving solution that needs training of supermarket staff. Through better loading methods, a baseline supermarket can achieve about 1% of energy savings. Overloaded cabinets can reduce a product's quality and increase energy consumption by up to 10 to 20% (Carbon Trust & IOR (2012)).

According to Foster et al. (2018), correct loading of refrigerated cabinets and multi-decks not only ensures that the goods are at the right temperature, but also saves energy. Faramarzi (2004) states that overfilled open refrigerated cabinets require up to 6% more energy. Thus, an increase of 6 K in the temperature of the warmest products. The air channels are to be kept free and maximum stack heights should be complied with.

Under controlled test room conditions, authors Foster et al. (2018) found that by changing the cabinet from 6 shelves to 4, the refrigeration load can be increased by up to 60%, with a corresponding increase of 2°C in the warmest temperature. Similar data from integrated multi-deck cabinets shows a 39% increase in direct energy usage when going from 5 shelf to 3 shelf layouts, while 8-foot (2.5 m) remote cabinets show an increase in total energy consumption when going from an empty cabinet to a fully loaded cabinet, except for M packs (500g test package with a temperature sensor). As a result, cabinet energy consumption and temperature control are greatly influenced by shelf layout choices and product loading (during normal use, these factors can change significantly as customers remove products).

The volume of product loaded into a typical multi-deck cabinet affects not only energy consumption, but also the temperature of the product being stored. Again, under test room conditions, the authors see cabinets that are optimized for minimum loading fail to hold the temperature of the products when fully loaded, which requires a more intelligent and advanced control of cooling. In addition, the energy consumption of an 8' cabinet under test room conditions showed a 30% increase in energy consumption when the load was increased from 20% to 75% and the control settings were adjusted to ensure similar product temperatures for both cabinet loadings. The most effective loading in a cabinet is likely to be a function of air circulation (volume of airflow and ratio of back panel flow to supply grill airflow) and will require changing control setpoints to match any combination (Foster et al. (2018)).

In fact, customers use cabinets, which have an impact on airflows and temperatures in the cabinets. Cabinet's loading is variable in real life, and warm products may be loaded into the cabinet. When performing a test, loading is defined as a solid block of test packs. Unlike in a store, where products tend to be contained in packages with a high proportion of air surrounding them, the thermal inertia of these packs is high.

According to Lindberg (2018), two common types of open vertical cabinets were included in a study, type 1: roll in and back loaded cabinets, and type 2: front loaded cabinets. Dairy goods, which are kept warmer than meat, are commonly stored in cabinet of the type 1. Cabinet 2 was a traditional cabinet with a rear wall that permits loading from the front only. Depending on the design, the vertical cabinets can be loaded with groceries from the front and/or from the back. So, for a better loading, it is recommended to use vertical designs that can be loaded from both sides.

Loading, in any supermarket, is in the hands of shoppers as well as the supermarket. The cabinet needs to be both fully loaded and almost empty, but as the load affects the flow of the back panel, which in turn affects the support of the air curtain, energy consumption is inevitably affected.

Efficiency

Foster et al. (2018) stated that up to 60% variation in refrigeration duty has been observed with shelf positioning and cabinet loading alone; In order to maintain product temperature under all conditions, it would be beneficial to redesign the cabinet to withstand variable loadings. Efficiency savings are difficult to quantify because each change needs to ensure that the lowest energy state is achieved as often as possible. Consideration should be given to the representativeness of each energy test condition in normal use; it can be noted that the lowest energy-shelving configuration is usually the one used for testing. Most cabinets would need to change their control parameters as the cabinet loading changes.

Energy savings

According to Faramarzi (2004) and Foster et al. (2018), there is no information on the load of the cabinet under store conditions. Compressor power savings of 60% were achieved under test chamber conditions. However, whether these translate into store conditions is unclear and appears to be too high to apply across whole supermarkets. There is insufficient evidence to quantify potential savings in baseline supermarkets.

United Nations Environment Programme (2018) stated that there are many examples of RACHP (refrigeration, air-conditioning and heat Pump) devices cooling unnecessary loads in cabinets. The first step in any system design should be to review cooling loads to try to determine which loads can be eliminated or reduced. A lot of strategies can be used to reduce cooling load. A common method is to use "free cooling" to pre-cool hot products before refrigeration. For example, cooked food at almost 100°C in a food factory is usually cooled by refrigeration. By pre-cooling the product with ambient air or water cooled in a cooling tower, cooling loads can be reduced by more than 50%. This illustrates a 50% energy savings with no additional capital investment required to minimize cooling loads through the use of doors on point-of-sale displays.

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)	17.4 ton / year savings of CO_2e (Carbon Trust & IOR 2012) No Information is available on energy savings (Foster et al. 2018) Depending on usage and factors
Quality of scope 2 emissions information	3 independent peer review papers in general agreement (Foster et al. 2018) Not enough information
TRL level	TRL8-9
Maintainability issues	L : No issues (Carbon Trust & IOR 2012) L/M : Depending on technology used (Foster et al. 2018)
Legislative concerns	L : No impact (Carbon Trust & IOR 2012) (Foster et al. 2018)
Payback time (years)	1.3 years (Carbon Trust & IOR 2012) Unable to quantify (Foster et al. 2018)

The baseline store used to fill a part of this table is a typical supermarket of 5,000 m^2 sales area which is equivalent to a large supermarket or a small hypermarket (Carbon Trust & IOR (2012) values). However, Carbon Trust & IOR (2012) affirmed that this information can be applied to any supermarket above 2,000 m^2 (as above this size energy usage is relatively linear with the size of the store). However, an ASDA store at Weston-Super-Mare was also used as a baseline store. The store refrigeration load was split between low temperature (LT) and medium temperature (MT) packs and condensing units. The size of the store was 6290 m^2 (74 x 85 m) (total store). (Foster et al. (2018) values).

1.18.25. Improved cabinet location

In a supermarket, display cabinets tend to be shaded from direct sunlight and the effect of radiation from ambient lighting is likely to be lower than that from the cabinet lights. Thermal fluctuation in open display cabinets is mostly caused by air penetration.

Locating display cabinets in a cool, draught free and shaded position will keep energy consumption low. Draughts have a significant effect on open fronted cabinets as they disrupt the air curtain. It is therefore important to keep them away from doors and ventilation systems. Chen and Yuan, (2005) investigated the performance of a refrigerated display cabinet through experiments to determine the effects of a number of critical variables, including ambient air temperature, relative humidity, and velocity. The heat load as well as the internal temperature distribution was investigated. The effect of different air speeds parallel to the length of the display cabinet, ranging from 0.2 to 0.5 m.s^{-1} were investigated. The results showed that an increase in longitudinal velocities caused the inside temperature to rise slightly but the impact was very limited. The variations of heat load were also small. D'Agaro et al., (2006) used a CFD model to compare the effect of the parallel air flow defined in EN23953 (0.1 to 0.2 m.s^{-1}) with that of no air flow and predicted that ambient air movement affected the cabinet return air temperature and consequently the refrigerating power, which was estimated to increase by about 30% when parallel airflow was applied.

Due to changes in the ambient air conditions, the vertical open refrigerated display cabinets experience changes in their thermal performance and energy efficiency. The thermal entrainment factor calculation or the computation of all sensible and latent thermal loads can be used to evaluate the aerothermodynamic insulation effect that the air curtain provides (Gaspar et al., 2011). The equipment ends walls encourage air curtain instability, which in turn leads to thermal entrainment. From the side where the incoming ambient air enters, the air curtain instabilities are more noticeable (Gaspar et al., 2010). Gaspar et al., (2011) shows how the thermal entrainment factor and heat transfer rate fluctuate depending on the ambient air conditions, including changes in air temperature, relative humidity, velocity, and direction in relation to the display cabinet frontal aperture. The authors concluded that due to disruption of the aerothermodynamics system of the air curtain, a rise in air velocity with direction parallel to the frontal opening plane enhances thermal and mass interaction, increasing total heat transfer and thermal entrainment factor. The results also indicated that the total heat transfer rate increased by 5% when the air movement (0.2 m.s^{-1}) direction moved from parallel to oblique and increased by an additional 1% when it changed from oblique to perpendicular. Hence it was concluded that latent and sensible heat transfers are significantly increased when the direction of ambient air velocity is changed from parallel to perpendicular. They also showed that when the magnitude of ambient air velocity was increased from 0.2 m.s^{-1} to 0.4 m.s^{-1} with constant ambient air temperature, relative humidity, and direction of velocity, the total heat transfer rate increased by 53% because of increase in air infiltration load across the air curtain.

Open vertical refrigerated display cabinets in the centre of aisles facing other refrigerated cabinets will generally work much more efficiently than cabinets at ends of aisles or outside of the refrigerated areas. This is because display cabinets cool and dry the ambient air around them, such that they gain less sensible and latent heat from their surroundings compared to a cabinet outside of the refrigerated aisle. According to Ligthart, (2007) the temperature in the chilled aisle is on average 15.5 °C as opposed to 21 °C elsewhere in the store and RH can drop to 20% when it is 70% in the rest of the store and that falls short of the standard thermal comfort requirements. Foster and Quarini, (2001) measured air temperatures in the aisles of 3 different ventilation type supermarkets. At six locations—two from each of the three supermarket chains—temperature and velocity measurements were taken overnight, when the stores were closed. Average temperatures varied between 12.5 °C and 16.1 °C. No information is available on the effect of cabinet location in store conditions. No solid evidence exists to make an accurate assessment of how many cabinets in the baseline store could be moved to a more appropriate location and quantify the energy savings. The above information for energy savings reported were based on test room conditions which are quite different from the real supermarket situation.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	No evidence

Quality of scope 2 emissions information	Poor information
TRL level	n/a. Not a technology
Maintainability issues	No issues
Legislative concerns	No impact
Payback time (years)	Lack of quantified evidence.

1.18.26. Improved glazing

Refrigerated display cabinets with doors use glass to restrict heat transfer from infiltration, and radiation. Glass doors can be made of single, double or triple glazing with or without a low emissivity coating. Chilled cabinets tend to have single glazing and frozen cabinets double glazing. The thermal conductivity of the glass, door frame and spacers used to separate double and triple glazed panels as well as the emissivity of the glass all impact on the heat transfer through the glass, represented as the U value. Low emittance (low-E) glass contains a thin, virtually invisible layer on the surface of the glass which reduces the heat transfer by reflecting radiant heat.

Reducing the conductivity of the gas between the layers of glazing will reduce the heat transfer through it. Traditionally dry air (desiccant inside glazing) or nitrogen has been used as the filler gas. Argon (34% lower thermal conductivity than air) is typically used today, and costs are 5% more than for air filled units (Brinda and Prasanna, 2015). Krypton (65% lower thermal conductivity than air) is even more expensive and therefore rarely used. Double glazing also exists with a vacuum between the panes, and this allows a smaller gap between the panes. In the case of Pilkington Spacia™ glazing, the overall thickness of the double-glazed panel is 6.5 mm compared to a typical pane of 24 mm (Pilkington, 2022).

The layers of double-glazed panels must be held apart to provide the cavity. Aluminium is commonly used because of its good structural properties; however, it has a high thermal conductivity. Aluminium has a thermal conductivity of 160 W/m.K, compared to other frame materials, e.g. steel (50 W/m.K), Rigid PVC (0.17 W/m.K) and Hardwood (0.18 W/m.K). This causes a lot of heat transfer at the edges of the glazing. Thermally efficient spacers (warm frame/edge) can reduce overall U values by about 25% (U.S. Department of Energy, 1997). Improving the efficiency of the spacers reduces condensation, which reduces the need for door frame heaters. Warm spacers can be flexible, made from thermoplastic or silicone-based materials, plastic/metal hybrid or stainless steel.

The heat loss associated with a thermal bridge is called linear thermal transmittance or psi-value. This is the rate of heat flow per degree per unit length of the thermal bridge that is not accounted for in the U-value of the plain elements. Psi values for different spacers and their effect on a windows U value is given in Table 11 (Fenzi, 2017).

*Table 11. Frame with U=1.2 W/m2.K and Insulating Glass Unit with U= 1.1 W/m2.K (940*1048 mm).*

Spacer Type	Psi (W/m.K)	Overall U value (W/m^2.K)
Aluminium	0.085	1.368
Stainless steel	0.05	1.27
Extruded PP with ferritic steel foil	0.044	1.254
Extruded PC hybrid spacer with austenitic steel foil	0.041	1.245
Flexible silicone	0.035	1.229

The heat conducted through the glazing will be proportional to the U value (combination of conductivity and surface heat transfer coefficient). SCHOTT (2022) provide double glazed doors for refrigerated cabinets with U values of 1.1 (swing door) and 1.6 $W/m^2.K$ (sliding door). REMIS quote a U value of 1.2 W/ $m^2.K$ for their hinged doors on refrigerated cabinets (REMIS, 2022).

It is assumed that the glazing improvements are additional to current glazing of cabinet doors. A single, double, and triple glazing's respective U values are typically 5 $W/m^2.K$, 3 $W/m^2.K$, and 0.8-1.6 $W/m^2.K$ (Abbey glass, 2022). This indicates that moving from single to double glazing on chillers would reduce thermal transmittance through the glass by 40%. For freezers, moving from double to triple glazing would result in reducing thermal transmittance in the range of 73- 46% depending on the U value of the triple glazing.

Based on calculation results the heat transfer through chilled cabinet glazing is 125 W/m^2 for single and 75 W/m^2 for double glazing. Hence moving from single to double glazing on a chiller would reduce the heat load on the cabinet by 50 W/ m^2 (assuming a 25 °C temperature difference between the cabinet and ambient conditions). If a chilled cabinet has a heat load of 500 W/m^2 display area assumed, this then could reduce the overall compressor load by 10%.

Assuming a 45 °C temperature difference between the cabinet and ambient air/environment which results in 135 W/m^2 for double and 36- 72 W/m^2 for triple glazing (with the respective U value of 0.8 and 1.6), moving from double to triple glazing on a freezer would reduce the heat load on the cabinet by 99 -63 W/m^2 (If a frozen cabinet has a heat load of 1000 W/m^2, this then reduces the overall compressor load by 9.9-6.3%.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	10% of chiller, 6 to 10% of freezer compressor power
Quality of scope 2 emissions information	Poor information in the literature and is based on authors calculations
TRL level	TRL8-9
Maintainability issues	Some problems
Legislative concerns	No impact
Payback time (years)	1-2

1.18.27. Increased cabinet set point

Cabinet temperatures are either controlled by individual controllers on each cabinet, or for larger retailers via a central controller. The primary control parameter is the temperature set-point, and this is set with the aim of keeping all the food within a safe temperature range.

As product within the cabinet will be at a range of temperatures, the set-point temperature will be only an indication of the product temperature. This indication is often based on a weighted average of temperatures measured in air at the exit and entry to the evaporator, or a probe placed within the refrigerated space.

For frozen cabinets the set-point is low enough to maintain quality of the frozen product but not so low as to use excessive energy. For chilled meat and dairy cabinets, the set-point is low enough to maintain safety and quality for the shelf life of the product, but high enough to avoid freezing. For produce cabinets the set-point is somewhat of a compromise as different fruits and vegetables require different temperatures.

A tool is available (FRISBEE Tool - download) which allows the user to look at the impact of temperature on the shelf life of a product. According to the tool, increasing the display temperature of cooked ham from 4 to 5 °C would reduce the shelf life by 20 hours, based on predicted growth of Listeria monocytogenes. The consequence on energy consumption is to reduce the heat load on the cabinet by approximately 5% (based on a store temperature of 25 °C).

According to Lindberg and Jensen (2014),green salad (ready to eat in a bag) has a shelf life of 12 to 13 days at 4 °C; this reduces to 8 to 9 days at a storage temperature of 6 °C The subsequent reduction in heat load would be 10% (based on a store temperature of 25 °C).

Other food quality tools and experimental data are available to allow a more considered assessment of ideal display temperatures of each of the products displayed in supermarkets. The benefits of increased set-point should be weighed against the effect of reduced shelf life.

Derens-Bertheau et al. (2015) conducted a survey in 2012 which measured temperatures in retail display cabinets in supermarkets in France. This showed mean temperatures (standard deviation) of 2.4 °C, 2.6 °C, 1.8 °C and 1.2 °C for yoghurt, prepared meals, meat and sliced cooked ham respectively.

Kou et al. (2015) showed that a relatively large temperature variation between samples located on the front rows and those at the back rows of retails display cabinets appear to be the major technical challenges hindering the compliance of FDA Food Code (<5°C) without freezing the products.

A study (Baldera Zubeldia et al. 2016) was conducted in all self-service refrigerating equipment's from every food retail store (11 supermarkets representing different national chain-store groups) located in various municipalities from Southern Spain. Statistically significant breaches in the cold chain were recorded in the case of products located at the top shelf for all kinds of foodstuffs during the summer period, and also during wintertime in the cases of top shelf of dairy products and refrigerated vegetables.

There is often little flexibility in raising set point temperature without causing food at the front and top of the shelves to be too warm. Doored cabinets should offer more opportunity to raise set point, due to a smaller temperature difference within the cabinet. However, no evidence has been found to show that cabinets are maintained too cold. Although some products at the rear of the cabinet are too cold, products at the front are often too warm and therefore raising set point, will make this problem worse.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	None identified.
Quality of scope 2 emissions information	High

TRL level	n/a. Not a technology.
Maintainability issues	None.
Legislative concerns	Important to maintain product temperature of all products below a specified value. Therefore, more appropriate for frozen foods than chilled.
Payback time (years)	No evidence to suggest real life savings can currently be achieved. Savings might be possible, if for example, temperature of frozen food was increased.

1.18.28. Internet shopping

Grocery shopping from home has been offered in various forms for many years, originally based on telephone, fax and postal ordering. Motivations behind early and often small-scale schemes included increasing sales and profits, supporting local communities or producers, providing a social service and reducing car traffic (Cairns, 1996). The introduction of computer-based internet ordering accelerated and expanded many schemes, to the extent that online ordering and home delivery are now commonly offered nationwide by most of the major supermarket chains.

Although home delivery can offer the potential for reducing customer car journeys, the overall environmental impact is not easy to gauge, with various contributory factors such as distances travelled by customers and delivery vans, type of vehicles, delivery failures and returns, type of goods and whether they are selected in store or at a warehouse (Cullinane, 2009). The aim of the study was to provide some insight into how online shopping affects the environment. It comes to the conclusion that, as things stand, it is impossible to say with any degree of certainty whether clicks are more environmentally friendly than bricks. Post pandemic study of Rai, 2021 on the online shopping reported the process complexity and claims on both side. In particular, assertions have been made on both sides regarding the environmental effects of online retail, crediting the effectiveness of home delivery vs individual shopping excursions on the one hand and pointing out complex consumer behaviour on the other. The complexity of most of these factors and their interactivity makes generalisation of likely benefits difficult to predict (for example see Visser et al., 2014 and Wiese et al., 2012, which look at complex factors which influence the impact on urban transport). The methodologies used to estimate or model environmental impact also vary and the differences in the results they give interact with differences due to "real" factors such as geographical location and consumer behaviour (see for example Matthews et al., 2002, who studied the energy implications of online book retailing). Although concentrating on the delivery of small, non-food items purchased online, Edwards, et al., (2011) assessed such methodological differences. For the same types of products, these authors also assessed the significant impact of failed deliveries, returns and residual consumer trips, e.g., for browsing before online purchase (Edwards, et al., 2010).

Potential environmental benefits were included in a model of a single dual channel retailer, i.e. simultaneous store and online, retailing products such as electronics, books and groceries (Carrillo et al., 2014). The effect on the overall environmental impact of operating the online retail channel was found to be more favourable as the proportion of online sales increased. However, differences between the goods studied were evident, with grocery deliveries being more energy intensive (and potentially somewhat less beneficial) due to the need for refrigeration.

Greenhouse gas (GHG) emissions for apples, tomatoes and yogurt sold in the UK, France and Belgium via hyper and supermarkets, corner shops, open air markets, producer’s basket direct sale, farm shops and e-commerce were studied by Rizet et al., 2010. The emissions were split between those resulting from road or sea transport, energy use in buildings (such as cold stores and the retail premises themselves) and from the consumer's journey home. For the first of these, not surprisingly, the emissions depended on distance and type of transport in combination with quantities transported. This meant that although emissions were high for items such as apples from New Zealand, there were examples where small quantities were distributed within the sale country, and emissions for these could also be high. Emissions from buildings varied considerably by country due to the different energy sources (France being the lowest due to the high proportion of nuclear power and the UK being the highest due to the low proportion of nuclear power). The journey home was found to assume varying importance depending primarily on whether the shopping journey was dedicated to just the product studied or to a combined shop for multiple products. In assessing emissions related to e-commerce, the authors assumed selection of goods at a regional distribution centre (RDC) followed by home delivery or collection at a central collection point but did not include in-store selection. The emissions for refrigerated yoghurt retailing in the Paris area were given as an example, which showed that e-commerce was more efficient than the traditional "physical" stores (Table 12).

Table 12. Emissions for refrigerated yoghurt.

Type of retail operation	**GHG emitted (g CO_2-eq/kg)**
Hypermarket	170
Supermarket	160
Minimarket	160
E-commerce	110

This was because of several factors; the reduced road transport to the RDC, because physical stores require considerable energy input for refrigeration, heating, lighting etc. which e-commerce does not, and significantly that the "last mile" emissions in grouped delivery rather than multiple consumer trips home were lower. It should be noted, however, that many of these figures are highly dependent on the assumptions used in the study, on the type of product and the location of the retailing operation.

Factors which impact on GHG emissions associated specifically with grocery retailing in Finland were described in detail by Siikavirta et al., 2002. The potential to reduce emissions associated with transport was highlighted, as was the reduced energy required to operate warehouses rather than physical retail stores. An additional benefit was also described – the possibility of reducing waste due to avoidance of over-production, better temperature control and use of technologies such as RFID tracking to assist and speed up distribution, sorting etc.

Considering the case of retailing in Austria, Seebauer et al., 2016 came to different conclusions – that promotion of online retailing is unlikely to have significant impact on carbon emissions and that a more fundamental shift in consumer attitudes is required to move towards lower personal consumption of groceries and other goods.

If the potential environmental benefits of e-commerce are to be realised, reducing consumer car travel is essential and the importance of consumer behaviour must also be included in any analysis as e-commerce does not necessarily fully substitute a home delivery for a consumer shopping trip. A Life Cycle Analysis (LCA) model of various shopping fulfilment methods was developed to include such factors (van Loon et al., 2014). This found that impacts varied depending on whether full substitution of consumer trips was assumed or whether some trips were retained for shopping and related purposes. Impacts also varied between types of supply, e.g. from the retailer to the consumer by van or parcel, retailer sold but shipped directly from the producer, online orders fulfilled by selection in RDCs, dedicated warehouses or stores, collection in store or elsewhere, and through traditional "bricks and mortar" stores. In the full substitution scenario, the key contributors to emissions were found (where present) to be consumer transport, parcel based delivery networks, the physical store, and transport between the producer and the distribution centre. The carbon footprints of van home deliveries and consumer pick-up methods were found to be the least, with the others up to 4 times worse. When some (up to 90%) of the consumer trips were retained, the relative impact of the different types of supply shifted, with van delivery from local shops becoming worse than consumer collection from local stores and the same as visiting traditional stores.

Current technology

As mentioned above, online grocery retailing is increasingly based on internet ordering. The goods ordered can be held in a dedicated home delivery warehouse (the so-called "dark store" option), they can be selected at RDCs, or they can be selected in-store from goods on display or held in in-store cold rooms. In the UK, home delivery by multi-compartment vans is common, with the option of collection by the customer at the store or at a specified collection point. Each of these types of operation has different transport and refrigeration needs, and all could benefit from further study.

Cost

A comparison of the financial performance of UK online grocery retailing operations during their set-up and early operation was presented by Hackney, et al. (2006). One of the aspects considered was the choice of warehouse or store fulfilment of orders. Store models were stated to achieve break-even earlier and incur lower losses before break-even, but to be less profitable than warehouse models beyond break-even. This is evidenced by the most successful UK operation in terms of lowest initial losses and time to break-even at the time, which was Tesco's store-based model.

The impact of internet shopping on the product quality, particularly for perishable foods (meat, fish, fruit and vegetable etc.), should be taken into consideration. However, few studies have been carried out.

The information given in the sections above is mainly concerned with the emissions of transportation related to e-commerce compared to buying directly from a supermarket. There is no available data for the difference in emissions from refrigeration for internet shopping compared with supermarket shopping. If the food is removed directly from the stores' retail cabinets for the internet shopping, there would be no difference, except for the refrigerated delivery vehicle. However, if the food is taken from a cold store and does not enter the retail cabinets, significant emissions benefits would be expected. It has been assumed that minimum savings are associated with food removal from stores (i.e., no savings) and maximum savings are associated with the store being replaced by a cold store and the supermarket no longer being necessary.

Scope 1 emissions savings (% or another quantifiable metric)	0-100%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	0-100%
Quality of scope 2 emissions information	High confidence.

TRL level	TRL5-7
Maintainability issues	No information.
Legislative concerns	There are some legislative concerns with internet shopping like the enhanced IT security is needed with the online services.
Payback time (years)	Varied depending on assumptions made and technology used.

1.18.29. Lighting (cabinets) - efficiency

Refrigerated display cabinets are fitted with lights to illuminate the food on display. Lighting has both a direct load from the electrical power of the lights as well as an indirect load from the increased compressor power to remove the heat load created by the lights. Orlandi et al. (2013) found through numerical simulations that the heat produced by lights accounts for 25% of the total thermal load in closed refrigerated display cases when the lighting in the cabinets is on. Fluorescent lighting was frequently used in refrigerated display cases, both closed and open, however, LED lighting is the normal for new cabinets. The efficiency of a lamp to produce light is called its luminous efficacy (lm/W). It is the ratio of luminous flux, to input power.

Fluorescent lamps

Linear Fluorescent tubes are only found in old cabinets within stores which have not had a refit. These lamps are due to be phased out in August 2023 with no new production or import into the EU.

LED lamps

LED lights are fitted to new cabinets and have been retrofitted to older cabinets during supermarket re-fits. LED lights operate with a direct current (DC) at about 12 V, therefore require a transformer (driver) to convert the mains (230 V AC) voltage to 12 or 24 V DC. Some lamps have this built in and some require a transformer. Enhanced safety is a prime feature of LED lighting due to the low voltage. Another advantage of LEDs is that they allow the use of motion sensors because they can turn on and off rapidly with no damage, unlike fluorescents.

The US DoE (US Department of Energy, 2022) established the efficacy of warm white colour mixed (CM)-LEDs to be 138 lm/W in 2020. They have a target of 336 lm/W by 2050. They also presented the efficiency of the driver as 88% in 2020, with a 2050 target of 95%.

Philips has a number of case studies where their lights have been installed in supermarket cabinets. They are detailed below.

- Edeka – Philips installed LED lights in their freezer cabinets. They state a 70% reduction in energy and a 2.7-year payback (Philips LED lighting for refrigeration, 2011).
- A project was conducted in a participating supermarket in northern California to demonstrate the performance of LED lighting for refrigerated display cases under real world conditions (Diebel et al., 2013). Energy savings of 46.3% were reported when changing from fluorescent to LED lights (with greater savings if motion sensors were used).
- Heidinger et al. (2014) developed experimental tests in a glass door multideck display case with different types of lighting setup: fluorescent lamps and LEDs, both tested in horizontal (under the shelves) positioning and LEDs in vertical positioning (next to the doors). Experimental results show that LED illumination under the shelves reduces the direct energy consumption by 41% and LEDs in vertical position result in 74% of energy economy. The LED illumination in vertical positioning is the best alternative to save energy and highlight the products exhibited.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	46-70% of lighting power if replacing T8 with LEDs
Quality of scope 2 emissions information	High confidence.
Availability barriers	No barriers
TRL level	TRL8-9
Maintainability issues	No issues
Legislative concerns	No impact
Payback time (years)	2.7 years reported in 2011. Rising energy costs and lower cost of LEDs may have reduced this payback period.

1.18.30. Lighting (store) - efficiency

Supermarket store lighting directly affects the overall energy consumption of the store, through the electricity consumed by the lights. However, it also indirectly affects the overall energy consumption by increasing the radiation heat load on the refrigerated display cabinets, resulting in increased electrical input to the compressor in order to maintain the set temperature. Electricity consumption by the lights in conventionally lit stores is generally the second highest after the refrigeration system. For example, Timma et al (2016) reported that lighting used 29% of the total energy in a supermarket store in Latvia, while a study by Foster et al (2018) reported that 14% of the electrical load was due to lighting in 565 UK stores. During this study it was noticed that many of the UK stores were undergoing or had undergone changes in store lighting to more efficient (LED) lighting, so the proportion of the electricity load due to lighting was likely to be falling.

Generally, supermarkets use high lighting levels e.g., up to 1000 lux, as bright lights are considered to make products more appealing to customers (Tassou et al, 2011).

For the retail industry (brc.org.uk) have a climate action road map for the retail industry that has a milestone of 100% LEDs in all new buildings by 2025. They state that LEDs consume approximately 15% of the energy of halogen bulbs for the same light output.

Sainsbury's plans to install hundreds of thousands of LED fixtures in more than 450 stores by the end of 2020 and has committed to lighting all stores entirely with LEDs by the end of 2022. The retailer expects the adoption of all-LED lighting to reduce lighting energy consumption by 58% and reduce emissions by 3.4% annually. Sainsbury's ambition is to become the first grocery chain in the UK to use exclusively LED lighting – in new builds, as well as by retrofitting all existing stores.

Sarhadian et al (2004) reported that 8% of the total heat load for a vertical, open, chilled, display cabinet was due to lighting (both store and cabinet lighting) with fluorescent tubes. In a more recent study, Chaomuang (2019) investigated the thermal load for products in a vertical, closed, chilled display cabinet, utilising low emissivity coated glass doors, also using fluorescent lighting for both the store and cabinet. It was estimated that visible light radiation transmission through the glass doors comprised approximately 7% of the total transmission contributing to the cabinet heat load, which was mainly due to conduction and convection through the glass doors and side walls, for room (i.e., store) lighting with fluorescent tubes (~600 lux). This visible light transmission and heating occurred despite the reduction in thermal radiation (between the surrounding walls and the food products in the cabinet) due to the glass doors, expected to be in the range 87-94% (Faramarzi et al 2002; Heidinger et al, 2019).

The above findings show that both stores and display cabinet lighting contribute to the cabinet heat load for both open and closed cabinets. No independent studies have been identified where the effect of using LED store lighting on cabinet heat load has been investigated, although Chaomuang (2019) did model a vertical, closed, chilled, display cabinet with LED cabinet lights. Within the model, the LED lights contributed directly to visible light radiation heating of the products, with a 13 W LED cabinet light located inside the glass door at the top, which was assumed to contribute 75% of its power to heating of the front load for the top shelf of the cabinet i.e., 9.75 W. This compared to a contribution from the external (store) lighting power of 1 W m^{-2} (equivalent to 650 lux) across a front load area of 0.25 m^2, contributing a heat load of 0.25 W. The total lighting load for the front of the top shelf of the cabinet was therefore calculated to be 10 W. In fact, a similar lighting power density at the front of the cabinet was used in modelling a vertical, open, chilled, display cabinet by Laguerre et al (2012). In this case, a lighting power density of 1.2 W m^{-2} (equivalent to 800 lux) was used for products at the top of the cabinet, and a value of 0.9 W m^{-2} (equivalent to 600 lux) for products at the bottom of the cabinet. For this model, the lighting power density was attributed to both the store and cabinet lighting.

Commercial availability

Installation of LED lighting presents the main opportunity at present for improving store lighting efficiency (and as noted earlier, has already been adopted for many supermarkets in the UK). However, its primary energy saving benefit appears to be by directly reducing the stores' energy use, and it is unclear whether it provides additional indirect energy savings by reducing the heating load for the display cabinet. Lower maintenance costs and longer life for LED lighting is also claimed by manufacturers,

Technology: Lighting (store), impact on cabinet performance

Scope 1 emissions savings (% or another quantifiable metric)	Up to 30% direct energy and emissions saving on store lighting reported, however, no direct effect on cabinet emissions,
Quality of scope 1 emissions information	M
Scope 2 emissions savings (% or another quantifiable metric)	No data on cabinet emissions saving
Quality of scope 2 emissions information	M
TRL level	TRL8-9
Maintainability issues	L – LED lamps have longer life and less maintenance than fluorescent lights is needed
Legislative concerns	L
Payback time (years)	No data on payback times relative to cabinet performance

1.18.31. Liquid pressure amplification (LPA)

Compressors in refrigeration plants tend to operate at a higher delivery pressure than is needed. With liquid pressure amplification (LPA), compressors can run at a lower pressure and save energy.

As stated in the section "Reducing head pressure", reducing head pressure will allow the refrigeration system to run more efficiently (higher COP). However, reducing the head pressure too far can cause too small a pressure difference across the expansion valve, causing it not to work effectively.

LPA consists of a pump at the outlet of the condenser after the liquid receiver. The pump provides an elevated stable pressure before the expansion device, allowing the compressor to float as low as ambient conditions will allow. The pump needs to be able to operate within a refrigeration circuit without leaking. The energy consumed by the pump and that caused by the extra condenser fan flow rate (to reduce head pressure) is far lower than that saved at the compressor.

As the pressure at the outlet of the pump is higher than at the exit of the compressor, this allows a percentage of the liquid after the pump to be injected into the superheated gas after the compressor. This allows the superheated gas entering the condenser to be brought to saturation, accelerating condensing and increasing subcooling.

Hadawey et al. (2010) have shown that it is possible to achieve more than 10% in energy savings over and above those that can be attained with floating head pressure by adopting the use of LPA in conjunction with liquid injection. The level of energy savings that can be achieved with LPA, however, is system specific and each application will require careful consideration of the savings against the capital cost of the technology.

In trials of the HY-SAVE® Liquid Pressure Amplification (LPA) system at a Tesco store in Ireland (Hy-Save, 2009), independent energy consultants saw the amount of energy consumed by the refrigeration plant reduce by 24%. Previously at the store, condensing temperatures had to be kept unnecessarily high at around 32 °C to combat system flash gas and to keep the stores evaporators operating efficiently. Since LPA® pumps were installed in the system's liquid line, condensing temperatures have been reduced to 20 °C (68 °F) whilst delivering vapour-free refrigerant to the store's display cabinets and cold rooms, maintaining peak efficiency. Flash gas at the evaporators may be a consequence of undersized and poorly insulated liquid lines and can also be overcome with liquid subcooling.

Information provided by a refrigeration contractor who trialled several types of liquid pumps has not shown these delivered energy savings. The type of pump is important due to cavitation which can limit the operating conditions (head pressure), reducing the potential savings.

No new information has been published on this technology since the last Road map document was produced.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	24% of compressor energy
Quality of scope 2 emissions information	L
TRL level	TRL5-7

Maintainability issues	None.
Legislative concerns	None
Payback time (years)	Unknown

1.18.32. Liquid-suction heat exchangers

Liquid-suction heat exchangers (LSHEs), also known as suction-liquid heat exchangers (SLHEs) or internal heat exchangers (IHX), exchange heat between the suction line at the exit of the evaporator and liquid line at the exit of the condenser. They increase refrigeration capacity by subcooling the liquid supplied and prevent flash gas at the expansion valve. In addition, they help to ensure that all refrigerant is evaporated before returning to the compressor. Since most supermarket systems have a substantial amount of non-productive heat gain between the load and the compressor (due to long pipe runs), the LSHE essentially recovers capacity that would otherwise be lost.

The beneficial effects of a LSHE are offset by the increase in temperature and reduction in pressure (caused by pressure drop though the heat exchanger) of the suction gas causing a decrease in the refrigerant density and compressor volumetric efficiency. Therefore, their installation is not an energy efficient option for all refrigerants. LSHEs will increase the temperature to the compressor, which reduces motor cooling and increases discharge temperatures.

Klein, Reindl, and Brownell (2000) state that LSHEs with a minimal pressure loss on the low pressure side are useful for systems using R134a, R290 and R600. Navarro-Esbrí. Molés and Barragán-Cervera (2013) showed that when a R134a system is converted to R1234yf a LSHE can help lessen the reduction in COP between 2 and 6%.

Torrella et al (2011) investigated the effect of a SLHE operating in a CO2 transcritical refrigeration plant. They showed a maximum increase in refrigeration capacity and efficiency of 12%. However, discharge temperature increased by 10 K at an evaporating temperature of -10°C.

Mastrullo et al. (2007) state that a LSHE is always beneficial for refrigerants R290, R134a, R600 and R600a. They showed that for R134a the COP could increase by up to 20% (condensing temp of 50 °C and evaporating temp of -40 °C). At an evaporating temperature of -10 °C and condensing temperature of 35 °C, the COP increase will be nearer 5%.

Mota-Babiloni et al (2015) showed SLHE had a positive influence on the energy efficiency of R134a, R1234ze(E) and R450A. They showed benefits in COP for R134a of 0 to 6%, R1234ze of 2 to 7% and R450A of 1 to 6%. COP increased as pressure ratio of compressor increased.

Nuriyadia et al. (2015) showed a maximum benefit in capacity/COP of 20% for a freezer using R404A at -20 °C cabin temperature with a HE effectiveness of about 0.5. However, for a refrigerator at 0 °C there was a 5% reduction in capacity/COP.

Pacific Gas and Electric Company (2011) carried out a feasibility and cost- effectiveness study of high-performance LSHEs on display cases and walk-ins. The results show that the benefit/cost ratio for all system configurations and in all climate zones (in California) for all LSHE types is greater than 1 with the exception of certain MT walk-in LSHEs in small stores. For sizes less than approximately 150 square feet (14 m^2), LSHEs were generally not cost-effective for MT walk-ins. Stakeholders noted that with certain refrigerants (notably R407A), compressors were sensitive to return gas temperatures and that an increase in this as a result of adding LSHEs could potentially cause excessively high compressor temperatures and premature compressor failure for low-temperature suction systems.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	CO_2 transcritical: 12%. R134a: 0 to 5% (chiller) to 20% (freezer at high condensing temperature). R1234ze: 2 to 7% R450A: 1 to 6%.
Quality of scope 2 emissions information	M
TRL level	TRL8-9
Maintainability issues	None.
Legislative concerns	None
Payback time (years)	Unknown

1.18.33. Loading (food) – reducing heat load

Refrigerated display cases are used to keep food cold; they are not created to remove a lot of heat from overly warm products. Therefore, products should be loaded at the cabinet display temperature. According to Foster et al. (2018), this may not happen:

- When the product arrives in the cold store too warm, with no time to cool down.
- If the temperature of the cold store from which the product is put into the cabinet is higher than the temperature of the cabinet.
- If the product has been exposed to ambient conditions for too long, waiting to be charged.

The first one should not happen if the refrigerated product is carried out with a correct temperature checking at delivery. The second should not happen if the temperature of the cold store is set correctly, is not malfunctioning, and is used effectively with a good door management strategy. The third should not occur if appropriate procedures are in place to ensure that the product is not left unattended and uninsulated for longer than recommended.

The main consequence of loading a warm product is that the product will be above safe storage temperature until it cools, reducing in this way its shelf life. Another important consequence is that if the heat load from a product is higher than what the cabinet can extract, then the cabinet will heat up and possibly raise other products above their storage temperature. Products that are left out on humid days may also experience condensation, which can adversely affect the appearance of the product and may also affect the defrosting process of the cabinet.

Even if cabinets are capable of removing all the heat, refrigerated cabinets are not the most efficient system to accomplish this task. Refrigerated cabinets operate at a lower COP than cold stores and are therefore inefficient to cooling products. Effective policies and procedures should limit the temperature of products loaded into cabinets. These policies and procedures should include employee training.

The amount of time it takes to load food into a cabinet affects the amount of air that gets into it. This is more important in closed cabinets, but also affects open cabinets where the air curtain is disturbed during loading. This increases energy consumption while the refrigeration system removes the additional heat and also requires additional defrosting heat to remove moisture. Staff training can clearly illustrate the importance of keeping the door open for as short a time as possible during loading.

ASHRAE (2006) stated an increase in maximum product temperatures by 6.3°C, 2.6°C, 1.2°C, and 0.5°C due to blocked return air, overloading, cavities, and air curtain interference, respectively.

According to Carbon Trust and IOR (2012), reducing loading time minimizes infiltration and reduces food heat gain, thus saving energy. The time it takes to load food into a cabinet with doors affects the amount of air entering the cabinet and the amount of heat the food gets at ambient temperature. Extended door openings can also increase the number of defrost cycles, as well as the use of a cabinet heater to prevent condensation from forming on the door. Loading time can be minimized by pre-merchandising groceries so that large quantities of food can be put into the cabinet quickly. Staff training can also help reduce the time it takes to load cabinets. The temperature at which food is loaded into the cabinet can affect the performance and energy consumption of the equipment. Thermal gain during loading can be minimized by reducing loading time and transferring food from cold storage rooms to cabinets in insulated containers. Eliminating the temperature rise during loading can reduce the energy consumption of basic supermarkets by around 1%. Most groceries in supermarkets are pre-cooled prior to loading, but there are some cases where items such as beverages are loaded at ambient temperature. In these cases, the beverage can be cooled more efficiently in a cold room or similar location before being loaded into the cabinet.

Tsamos et al. (2019) conducted an experimental study of the heat transfer and airflow behaviour in an open front vertical multi-deck refrigerated display cabinet. In their project, cold shelf technology was tested, where air is circulated in each individual shelf. They showed a temperature distribution of all M-Packs (test packages with a temperature sensor) measured during the 48-hour test. The average temperature was determined to be 2.1 °C. During the 48-hour test, the temperature of all products was recorded between -1 °C and +5 °C. This indicates that the cabinet can meet the requirements of ISO 23953-2015. The energy consumption of the tested cabinet was 25.38kWh/24h on the first day and 25.31kWh/24h on the second day, showing the consistency of the energy consumption. Compared to the same test cabinet, but without cold shelf technology, the determined energy was 42 kWh/24 hours. As a result, significant energy savings can be achieved when using cold shelf technology along with air guiding strips. The technology has been integrated into the airflow guiding strips and shows even greater energy savings, from 42kWh/24h to 25.3kWh/24h (Refrigerated Display Cabinets (2015)).

According to Derens et al. (2014), a previous cold chain survey was conducted in France in 2002 (Derens et al., 2006) with the French Association of Food Industries (Ania study). Three types of refrigerated chilled products were monitored along the cold chain: prepacked meat, ready-to-eat or to cook products, and yogurt. At the end of the production line, a small temperature logger was placed inside the food packaging and was sent through the supply chain. In the end, the consumer who found the logger was asked to return it to the lab. 480 recorders were sent back, with a return rate of 66%, to create time and temperature reports of 314 product locations. The results show that temperature control is crucial in the last 3 steps of the cold chain. The average product temperature was 2°C higher than the recommended value for 7.3% of products in display cases, 59.7% in transport after purchase, and 40.3% were in household domestic refrigerators. Another field study on smoked salmon was conducted for 200 products by Morelli and Derens (2009). This study confirms the results presented by Derens et al. in 2006 which is the temperature abuse in the last 3 steps of the chain. The authors reported that 45% of the product (smoked salmon) was consumed within 2 days of purchase and 75%

within 7 days. However, the product shelf life was 4 weeks, and the recommended preservation temperature was 4°C. Since most of the products are consumed within a few days, the safety risk is low despite the high temperature of household domestic refrigerators.

According to Gougou et al. (2015), a cold chain field European study (2013) in France named Frisbee investigated products distributed in supermarkets and hypermarkets. Two field tests were conducted in Greece and France to update the cold chain database. According to Derens et al. (2014), the analysis of the information provided by consumers gave 89.1% of the products were sold in hypermarkets and 8.9% in supermarkets. Data processing for the 83 returned temperature loggers was performed as follows: average product temperature from production to consumption was calculated for each logger representing 83 cold chains. The average of 83 chains was then calculated. The average temperature of sliced ham in the French cold chain was 3.8°C. Analysis of the temperature distribution showed that, throughout the cold chain, 58% of the products were kept at or below 4°C and 90% were kept at or below 6°C. The lowest temperature observed in the entire chain was -1.9°C and the highest was 21.5°C. The average duration of a product in the entire chain was 14 days, with 67% of duration being less than 15 days. This shows that 67% of consumers have used their ham before the 'halfway use date', as the product has a 30-day shelf life. Frisbee field testing confirmed other studies highlighting the most sensitive link: post-purchase transportation by consumer and especially the domestic refrigerator.

Zubeldia et al. (2016) performed a temperature and duration study between mid-day and 2pm to ensure that stores were opened before many hours. Measures were performed on packed products situated inside the refrigerating equipment at the most unfavourable places as close to load limit as possible. They found that the official procedures adopted for controlling the cold chain are not appropriate to ensure compliance with safety regulations for perishable foods in self-service retail. Such procedures need to be modified, especially in regions like Andalusia, where temperatures vary continuously throughout the year. The procedure should take into account lower temperature-controlled foods, the season and the position of the product in the refrigerator, measuring regularly the surface temperature of the stored product as per previous specifications. Such changes should not only be adopted by economic operators but should also be revised by official controls when examining food stores.

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)	16.7 ton / year savings of CO_2e (Carbon Trust & IOR 2012) Insufficient evidence exists to quantify savings. (Foster et al. 2018)
Quality of scope 2 emissions information	There is no doubt that this technology can save energy. However, there is not enough information in the articles to quantify the savings in terms of energy and CO_2 emissions.
TRL level	TRL8-9
Maintainability issues	L : No issues (Carbon Trust & IOR 2012) (Foster et al. 2018)
Legislative concerns	L : No impact (Carbon Trust & IOR 2012) (Foster et al. 2018)
Payback time (years)	2.8 years (Carbon Trust & IOR 2012) 1.4 years (Foster et al. 2018)

The baseline store used to fill a part of this table is a typical supermarket of 5,000 m^2 sales area which is equivalent to a large supermarket or a small hypermarket (Carbon Trust & IOR (2012) values). However, Carbon Trust & IOR (2012) affirmed that this information can be applied to any supermarket above 2,000 m^2 (as above this size energy usage is relatively linear with the size of the store). However, an ASDA store at Weston-Super-Mare was also used as a baseline store. The store refrigeration load was split between low temperature (LT) and medium temperature (MT) packs and condensing units. The size of the store was 6290 m^2 (74 x 85 m) (total store). (Foster et al. (2018) values). Insufficient evidence exists to quantify savings.

1.18.34. Magnetic refrigeration

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 megnetocaloric effect. Magnetic refrigeration has the prospect of efficient, environmentally friendly and compact cooling for a wide field of applications.

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

Back in 2008 Gschneidner and Pecharsky 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 and the authors do not know of any commercially available systems to date (2023).

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 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. Cooltech Applications declared bankruptcy in 2018. Ubiblue was formed by some of the old Cooltech Application's team members, this later became Magnoric. Magnoric is still at the prototype stage.

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

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
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	1-4
Maintainability issues	Unknown
Legislative concerns	None
Payback time (years)	Not known

1.18.35. Motor Efficiency Controllers (MECs)

Unlike inverter drives, motor efficiency controllers do not influence the operating speed of the motor; they simply aim to improve the efficiency of the motor by reducing the losses in the motor windings. Because an MEC does not affect the running speed of the motor it will not provide any means of capacity control. However, it can provide energy savings without altering the fine balance of a well optimised and well sized refrigeration system and can be used on systems where variable speed units cannot be employed.

MECs reduce the power supplied to an induction motor by monitoring the current and voltage waveforms for slip as the voltage waveform is trimmed by the MEC. The more the voltage can be trimmed, the greater the savings; hence savings are usually only appreciable on motors running at 75% load or less for a significant amount of the time. Peak to peak voltage and frequency are maintained as shown in Figure 37, to ensure that peak torque and operational speed are unaffected by the MEC.

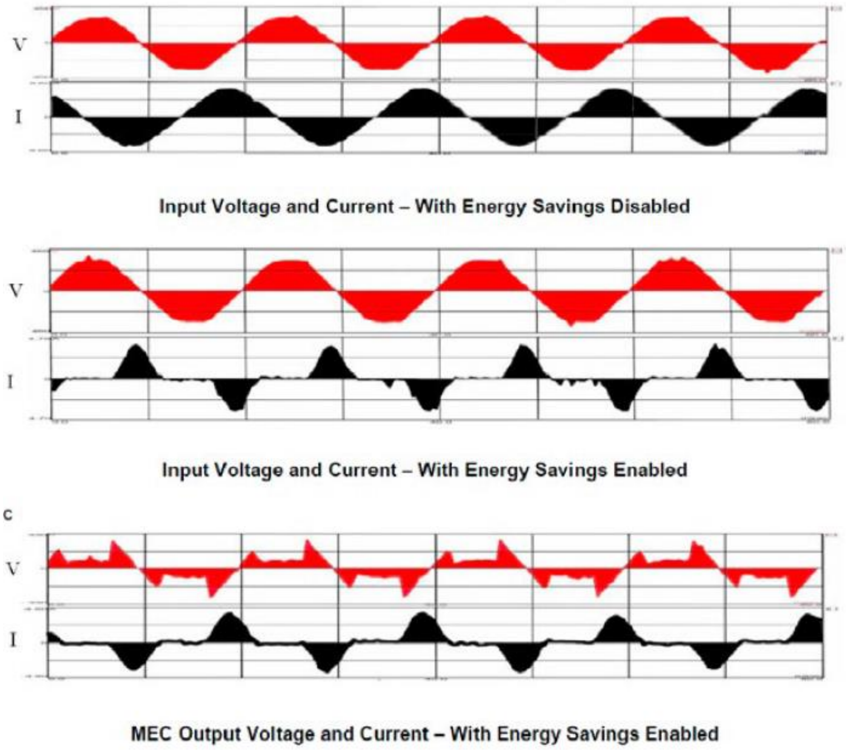


Figure 37. Current & voltage waveforms on single-phase motor both with and without energy savings (Envirostart).

The energy used and paid for is equal to the integral of the area under the input voltage waveform multiplied by the integral of the area under the input current waveform multiplied by the power factor.

Savings from MECs are limited by the magnitude of the losses within the motor being controlled and are generally greatest in motors which are part-loaded. Case studies by Envirostart (2022), a manufacturer of MECs, have found that savings of up to 40% are likely on single-phase applications and savings of 15% are likely on three phase applications.

A case study in retail refrigeration in Scotland reported energy savings for a single-phase chest freezer and three-phase walk in freezer estimated to be 25% and 17%, respectively (Grant, 2008). The estimated payback periods for the single-phase and three-phase units, based solely on the capital cost of the MEC units, are 2.44 years and 0.6 years, respectively.

A supermarket case study in France (Hughes and Hollis, 2004) reported average energy savings on the refrigeration pack of 10.46% for two weeks (1 week energy saving mode on and the other energy saving mode off), with a payback period of 1.7 years including unit installation costs.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	10.5% on display cabinet compressor pack 25% on integral chest freezer

	17% on 3-p walk-in freezer
Quality of scope 2 emissions information	Manufacturer information
TRL level	TRL8-9
Maintainability issues	No problem
Legislative concerns	No impact
Payback time (years)	1.7 y on display cabinet compressor pack 2.4 y on integral chest freezer 0.6 y on 3-p walk-in freezer

1.18.36. Nanoparticles in refrigerant

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, mainly based on copper and aluminium nanoparticles of above 20 nm size (Eastman et al., 1996). Theoretically, these nanoparticles have a high thermal conductivity and hence should improve the heat transfer near the laminar sublayer (Jana et al., 2007; Lee et al., 2007; Ko et al., 2007). Experimental work at NIST (Bello, 2008) with varying concentrations of nanoparticle additives indicates 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 polyester lubricant and combining it with R134a improved heat transfer by between 50 and 275%. 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.

Energy savings of between 9.6 and 26% have been reported for a domestic refrigerator (Bi et al., 2008, Bi et al., 2011). The 26% reduction in energy was for R134a/mineral oil with nanoparticles compared to R134a/POE oil. The ability to use mineral instead of POE (polyolester) oil was the main reason for the energy savings. The 9.6% in savings were with R600a refrigerant.

Jaiswal (2015) evaluated nanoparticles suspended in R404A. They calculated COP enhancement between 3 and 15% depending on the nanoparticles and their concentration. Higher concentrations gave the highest COPs and copper oxide was the best nanoparticle.

Fedele et al (2015) studied several nanolubricants, formed by polyolester or mineral oil as a base fluid, and titanium oxide (TiO_2) or single-wall carbon nano-horns as nanoparticles in a heat pump test rig. In contrast with some published data, no improvement was detected with 0.05 to 0.5 wt% of TiO2 or 0.1 wt% of single-wall carbon nano-horns in tested commercial oils.

An updated review on the application of nanorefrigerant showed that R134a and R600a with nanoparticles had been used in earlier studies with the main issues of reliability and stability (Kasaeian et al., 2018). Hence a suitable method of nanoparticles production and dispersion needs to be adapted for nanoparticles, and refrigerant pair.

According to Saidur et al (2011) several literatures have indicated that there is significant increase of pressure drop with nanofluids. For example, Peng et al (2009) presented experimental results which showed that the frictional pressured drop of refrigerant-based nanofluid increased with the increase of the mass fraction of nanoparticles, and the maximum enhancement of frictional pressure drop was 20.8% under the test conditions.

A recent review study on the challenges with the nanorefrigerant for the refrigeration system in terms of performance and stability reported that long term stability could be achieved by moving away from the isoelectric point (pH at which an equal number of positive and negative charges) (Gokhan, et al.,2021).

Currently there has been little work on the safety of nanoparticles in refrigeration systems. Although nanoparticle "kits" are sold, there are serious concerns over their safety and their impact on the compressor and expansion valve. Majgaonkar (2016) reviewed the use of nanoparticles in refrigeration system and proposed the investigation of the possibility of utilization of non-toxic or biodegradable nanoparticles.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	Up to 26 % is reported, depending on the nanoparticles type and its concentrations. However, many studies also raise issues and show minimal benefit.
Quality of scope 2 emissions information	No robust information is available for supermarkets and the values are based on assumptions that the domestic and supermarkets refrigerators have the same savings
TRL level	TRL1-4
Maintainability issues	Major issues of reliability and stability with toxic effect, poor stabilization, erosion effect, high viscosity, clogging issues and environmental impact when dealing with leakages
Legislative concerns	Lack of legislation with potential health issues
Payback time (years)	<6 months

1.18.37. Night blinds and covers

Night blinds (or curtains) are a well-established energy saving technology for open refrigerated display cabinets (both chilled and frozen). They act as a physical barrier reducing air entrainment into cabinets and reducing radiation heat transfer to products, especially when reflective blinds are used. This results in reduced heat gain by the cabinet, and hence reduces the cooling load and energy input for the cabinet refrigeration system. Although they save significant energy when used, they are generally only applied outside of store trading hours i.e., overnight or during holiday periods. Night blinds are most commonly used with multi-deck refrigerated display cabinets.

Covers

Covers are often used for well-type open cabinets e.g., freezers. They are typically solid plastic or glass and may be used outside of trading hours only (as for night blinds), or they may also be used during trading hours as well, in which case they are usually transparent and typically of the sliding door type, to provide visibility and access to products.

Effectiveness of night blinds and covers

Hawkins et al (1973) investigated the use of reflective night blinds during non-trading periods for freezer cabinets, and reported energy savings of 27-29%, when the night blinds were in use.

Faramarzi and Woodworth-Szleper (1999) investigated the use of low emissivity (i.e., reflective) aluminium shields in open chilled display cases during non-trading hours. They found that for standard operation i.e., 18 hours of trading, and 6 hours of non-trading with the shields in place, the refrigeration load was reduced by 8.5%. However, during holiday periods, where non-trading was extended to 24 hours, with the shields remaining in place, the refrigeration load was reduced by 42.4%.

In another study, Axell and Fahlen (2000) reported energy savings of between 25 and 40% when using night curtains for a chilled open display cabinet, with the curtains in place for a period of 12 hours (out of 24). However, it was also noted that for poorly fitting curtains, air infiltration could result in unacceptably warm food at the edges of the cabinet during night hours. However, an investigation by Datta et al (2004) into the effect of night blinds in open integral chilled display cabinets, also with the blinds lowered for 12 hours out of 24 found energy savings were between 10 and 22%.

Acha et al (2016) reported that the use of night blinds in open refrigerated display cabinets during non-trading hours of 10 hours (out of 24), provided an energy saving of 10%. However, it was noted that staff in stores may not pull-down night blinds when the store closes, as replenishing of refrigerated items inside cabinets usually takes place during non-trading hours. However, motor-driven blinds are often installed, to close cabinets automatically during set periods of shop closure. In a second case study by Acha and Shah (2016), the energy benefit of using night blinds for non-trading periods (10 hours (out of 24), was determined to be 31-32%, when the night blinds were in use.

Commercial availability

Night blinds for refrigerated open display cabinets are available commercially and widely used. They can generally be provided as an option from the manufacturer when installing a new cabinet, however, they can also be retrofitted to an existing cabinet. Claimed energy savings when using commercial night blinds for chiller cabinets include: (i) a reduction in energy costs of 50% (based on cabinet and ambient efficiency) (Chiller Blinds, 2022); and (ii) a reduction in total energy consumption (for the cabinet and associated plant combined) of 20-30% with the night blinds lowered for 12 hours (out of 24) and 48% when the night blinds were lowered for 24 hours (Thermasolutions, 2022).

Technology: Night blinds and covers

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	27-29% when night blinds in use applied to freezer cabinets 8.5-40%, depends on room temperature, and hours (in 24) of blinds use
Quality of scope 2 emissions information	M
TRL level	TRL 8-9

Maintainability issues	Need to ensure good fit of blinds to cabinet to minimise air entrainment at edges; and need to ensure staff apply blinds promptly during non-trading hours
Legislative concerns	None
Payback time (years)	2 years new installation; 4 years retrofit (Datta et al, 2004)

1.18.38. Novel heat exchanger designs

The majority of evaporators and condensers in supermarkets are fin and tube heat exchangers. Evaporators are a significant part of the overall cost of refrigerated cabinets and therefore less efficient evaporators are often used to keep the cost of the cabinet low. The same is the case for condensers on integral cabinets. Space is also an issue for refrigerated cabinets. Display area and loading volume are at a premium, and smaller heat exchangers are often used (Chandrasekharan and Bullard, 2004a).

The heat flow to or from the evaporator or condenser is governed by the overall heat transfer coefficient, the surface area of the heat exchanger and the temperature difference between the refrigerant and the heat exchange fluid.

Evaporator optimisation

Optimising the design of display cabinet evaporators has been demonstrated to achieve compressor energy savings of 28% (Chandrasekharan and Bullard, 2004b). The main reasons for the better performance were the better frost distribution, higher air-side area due to the larger depth of the coil and higher fin density.

Sarhadian et al. (2004) carried out an experimental evaluation of a number of viable and near-term energy-efficiency solutions to an open vertical refrigerated display case. They improved the evaporator effectiveness as a function of the product of overall heat transfer coefficient and surface area (UA) by 68% over a baseline evaporator by increasing the number of circuits, increasing the number of fins, reducing the tube diameter and enhancing the internal tube surface. The evaporator had an 18% increase in refrigerating effect, measured as cooling effect, per mass of refrigerant (mainly due to the increase in UA, but also partly due to improved suction-liquid heat exchange due to a better liquid suction heat exchanger). Incorporating these technologies improved the refrigeration effect by 19% and reduced the refrigeration system's electric power consumption by 11% (excluding condenser).

It is worth considering that the optimum evaporator for a horizontal open and a vertical glass door refrigerator maybe different. Getu and Bansal (2007) used a mathematical model of evaporators of low-temperature supermarket display cabinets based on various empirical correlations of heat transfer coefficients and frost properties in a fin-tube heat exchanger in order to predict the performance of the display cabinets under frosted conditions. They showed that the frost thickness and the frost thermal resistance on the horizontal open evaporators were higher than that of vertical glass door evaporators for the measured store relative humidity (33 to 41%) and temperature (24.1 to 26.7 °C). However, the air pressure drop was far higher for vertical glass-door than horizontal open cabinets. This higher pressure drop in the vertical glass door cabinets was mainly due to higher mass flow rate of the air (14.66 kg/s) and smaller dry free-flow area of the evaporators (3.1 m^2), as compared to 1.84 kg/s and 4.4 m^2 for the horizontal open cabinets.

Micro-channel heat exchangers

The use and understanding of transport phenomena in micro-channel heat exchangers is still developing and is currently a topic of much research effort (Shiferaw et al., 2009; Xiong et al., 2022).

Micro-channel heat exchangers have small channels between plates, giving them better rates of heat transfer (effectiveness). As these heat exchangers are often less deep in the air flow direction, they offer less resistance to air flow and therefore can reduce fan power. These heat exchangers have been used for some time in the automotive industry for air conditioning due to their compact nature and low weight. In addition to enhanced heat exchange, micro-channel heat exchangers weigh less and by being smaller than conventional heat exchangers can aid reduction in refrigerant charge. Reducing refrigerant charge can potentially enable less safe, more environmentally friendly or more efficient refrigerants to be applied.

According to Danfoss (2015) micro-channel heat exchangers improve COP by around 10% and require 30% less refrigerant. However, this percentage of increment in COP is linked to the particular design of the unit and can be lower for an enhanced design of the classical “round-tube-and-fin” coil. Furthermore, the charge reduction can be lower; it mostly depends on the design of the manifold.

Frost formation can block evaporators (especially in freezers) and so gaps between pipes and fins need to be larger on evaporators than on condensers and air conditioning evaporators. This limits the effectiveness of the evaporator. For this reason, micro-channel heat exchangers tend to be more suited to condensers and evaporators which do not generate frost. With careful design microchannel evaporators can be used under frosting conditions. However, defrosting issues must be considered (Carlson, Hrnjak and Bullard, 2001). Another issue with micro-channel heat exchangers is refrigerant maldistribution which to date has been an issue preventing their use as evaporators (Kulkarni and Bullard, 2013). In this regard Shao et al. (2010) compared fin and tube heat exchanger with microchannel heat exchanger under frost conditions and it was reported that the performance of the microchannel heat pump system is significantly impacted by the refrigerant-side maldistribution in the presence of ice. A recent work by Hu et al., 2020 conducted an experimental investigation of a micro-channel evaporator's performance and icing characteristics in an air source heat pump unit and it was emphasized that there are still some important aspects that needs attention. For example, refrigerant maldistribution may not only be among flat tubes, but also exists among the micro-channels of the same flat tube. In addition, flow resistance characteristics of microchannel is very important and may affect refrigerant distribution and the heat transfer performance greatly, and relevant study should be strengthened in future.

Currently micro-channel heat exchangers are costly to fabricate. The cost of extruding and brazing tubes to the header is higher than that of manufacturing louvered fins (Kulkarni & Bullard, 2013). There is no evidence of utilising this as a case study in supermarkets.

Heat exchange with different groove types

Rifled tube

Rifled-tube heat exchangers were introduced in the early 1980’s. Rifling can be used in both condensers and evaporators. Rifling increases the wetted surface area and increases the surface heat transfer coefficient by inducing turbulence (ACHR, 2000).

Rifled tube has a more beneficial effect on evaporators than condensers - the reason for this is two-fold:

The increase in evaporator performance has a larger effect on the system performance than the same increase in condenser performance.

An evaporator coil has a higher percentage of its internal surface area in two-phase flow than a condenser does.

Celik and Nsofor, 2014 conducted the performance analysis of 3.6% higher COP. Despite the fact that the pressure drop for the grooved-tube evaporator was marginally higher (364.5 pascal for grooved type compared to 41.7 pascal in case of regular tube evaporator for liquid and 439.5 for grooved type to 50.9 in case of regular type for two phase) than that for the standard tube evaporator, the additional compressor demand was not very substantial. Rifled tube is more expensive to produce than plain tube; however, the heat exchanger could be smaller and use less material. Due to a lower overall effect on system performance and the better applicability of micro-channel heat exchangers, condensers are not as likely to justify rifled tubing.

Internal finning type

Internal finning can aid evaporation and condensation inside the tubes. One approach is to use small spiral fins (micro-fins). The benefits of this are increased heat transfer, with a consequential increase in pressure drop.

Ponchner (1995) showed average condensation enhancement factors ranging from 2.0 at a low mass flux to 1.4 at a high mass flux for R134a in an 18° helix angle, 0.375" o.d. micro-finned tube. The micro-fins increased pressure drop by a factor of 1.19 to 1.26. Jiang et al. (2016) showed for the micro-fin tube, the average heat transfer coefficients of R22, R134a, R407C and R410A are 1.86, 1.80, 1.69 and 1.78 times higher than those of the smooth tube. The average pressure drop of R22, R134a, R407C and R410A for the micro-fin tube is 1.42, 1.30, 1.45 and 1.40 times higher when compared with that for the smooth one. The benefits of increased heat transfer in reducing temperature difference between refrigerant and air needs to be compensated with the negative effect of the pressure drop on compressor power.

Energy savings assumed

Evaporator optimisation: As it is not clear what an un-optimised and optimised evaporator are and that results have been reported that include other technologies, we are unable to evaluate a savings value.

Micro-channel heat exchangers: according to Danfoss (2014) micro-channel heat exchangers improve COP by around 10% (based on fin and tube coils of the same size). It is unknown from the reference if this includes the evaporator as well as the condenser. It is assumed that compressor power will reduce by this amount.

Groove types: 3.6 % increase in the COP value with the grooved tube evaporator in comparison to regular tube evaporator (Celik and Nsofor, 2014).

Refrigerant emission savings assumed

According to Danfoss (2014 micro-channel heat exchangers require 30% less refrigerant. It is therefore assumed that the direct emissions are reduced by this amount.

No direct emission savings are assumed for each of the other technologies. Any improvement in the effectiveness of heat exchangers should make them smaller, reducing the overall refrigerant charge.

Scope 1 emissions savings (% or another quantifiable metric)	Micro-channel heat exchangers: 30% All other technologies 0%
Quality of scope 1 emissions information	Lower confidence for Micro channel heat exchanger savings Medium confidence for all other types

Scope 2 emissions savings (% or another quantifiable metric)	**Evaporator optimisation**: unknown **Micro-channel heat exchangers**: 10% reduction of compressor power **Heat exchange rifling**: 3.6% **Enhanced internal heat transfer (micro-fins):** no information
Quality of scope 2 emissions information	Low to medium confidence depending on the technology
TRL level	TRL 1-4 for microchannel TRL5-9 for other types
Maintainability issues	Frosting issues with micro-channel.
Legislative concerns	No concern
Payback time (years)	Unknown

1.18.39. Peltier cooling

Peltier or thermoelectric (TE) devices are lightweight, small, and inexpensive and do not utilise refrigerants. TE devices are limited by their low efficiencies (approximately one third those of a vapour compression system) but do have some advantages in terms of direct emissions, reliability, quiet operation and also may be useful for spot cooling.

There is no published information on the use of Peltier coolers in real life retail display cabinets. It would appear likely that the most suitable application would be to spot cool an area of high temperature within a cabinet. However, good design and optimisation could potentially overcome such issues without the use of a more complex additional technology such as Peltier cooling.

Information presented by Min and Rowe (2000) indicated that the COP of current Peltier coolers is less than 0.5 when operating over a 20 K temperature span. With optimisation, COPs of between 1 and 1.2 were thought possible by the authors. The COP of direct expansion integral systems was presented by Grace et al., (2000). They suggested that, depending on optimisation of the system, a chilled cabinet would have a COP of around 2.5. Therefore, it is assumed that if Peltier cooling were used as a replacement for the current baseline store chilled integral cabinets, the energy usage would be 2.5 times higher (compressor energy only).

The COP value for the TE module is low and therefore is unlikely to replace the traditional vapor compression system. However, the utilization of TE as a subcooler is easy to control and suitable for medium and small capacity plants and its utilization with CO_2 transcritical system were widely investigated in contrast to other refrigerants but mainly theoretically (Wantha, 2020). Aranguren et al., (2021) performed experimental research by testing an actual transcritical CO2 vapor compression system including a TE subcooler at the exit of the gas-cooler of the refrigeration system. The results indicated an enhancement of COP of 11.3% with increase in cooling capacity of 15.3% at optimum operating point when the discharge pressure was 83.3 bar and voltage supplied to TE modules were 2 V and 9 V for the fans. The experimental study investigating the impact of thermoelectric subcooler integration to a R134a refrigeration system, while looking into system performance, total power consumption, and cooling capacity was conducted by Wantha (2020). The study reported an improvement of the system overall COP 27.3% with increase of 50.7% cooling capacity at a maximum subcooling of 8K. The cooling capacity of the system was around 300 W, with a subcooler COP around 2 at 7 K subcooling.

Scope 1 emissions savings (% or another quantifiable metric)	100%
Quality of scope 1 emissions information	Assumptions based
Scope 2 emissions savings (% or another quantifiable metric)	2.5 times higher energy consumption
Quality of scope 2 emissions information	High confidence
TRL level	TRL5-7
Maintainability issues	No issues
Legislative concerns	No impact
Payback time (years)	None

1.18.40. Pipe insulation

Tubing should be insulated on the low-pressure side between the evaporator and compressor to minimise condensation (on chiller circuits) or ice build (freezer circuits). Liquid lines on CO_2 plant may also require insulation as it may run at an intermediate pressure leading to a below ambient temperature. There is likely to be some potential benefit in energy consumption due to good insulation as colder, denser gas will enter the suction of the compressor. However, this is likely to be small.
Liquid lines on economised systems should also be insulated as they may form condensation and the benefits of the economiser could be somewhat reduced if un-insulated. Liquid lines which run through hot ceiling voids could also gain heat and lead to flashing so should also be insulated.
It is standard practise to insulate pipework and so there is minimal opportunity for energy savings unless the refrigeration plant insulation has been damaged or compromised.

Abujab and Abusafa (2022) investigated the economic and environmental impacts due to optimum thickness selection for thermal piping insulation in building air conditioning system piping network with different diameters for the common insulation types (rock wool, extruded polystyrene, and flexible foam). The research was based on the current thermal insulation cost over its life cycle and was calculated as 15 years. The thermal power savings of 1.2% of the system overall capacity were obtained with optimal thermal insulation. However, the study concludes that the physical parameters of the refrigerant, such as quality and flow rate, do not affect the optimal insulation thickness for all insulation types. These results are for a building air conditioning system and therefore will not be the same as for a supermarket refrigeration system. However, it is reasonable to expect that energy savings would be of a similar magnitude as the thermodynamic effect of the heat losses through the cold long pipe runs are similar.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	1.2% of the system overall thermal capacity

Quality of scope 2 emissions information	Low
TRL level	TRL8- 9
Maintainability issues	No issues
Legislative concerns	No impact
Payback time (years)	15

1.18.41. Pipe pressure drops minimisation

Reducing the pressure drops between the compressor and condenser and compressor and evaporator will reduce the pressure ratio of the compressor, reducing its energy consumption. A saturated temperature difference in the suction line or liquid line of about 1 K (between compressor and heat exchanger) would account for an energy penalty of about 3% for a chiller system.

However, it is not practical to significantly minimise suction and discharge line pressure drops, since sufficient oil return velocity of between 6-10 m/s should be maintained for all operating conditions and this inevitably imposes a significant pressure drop, especially in systems with long suction line runs such as pack supermarket systems. The competing requirements of maintaining oil return velocity and reducing pressure drop will always lead to a significant pressure drop.

Pressure drops can be reduced by reducing pipe runs, and this gives an obvious benefit to integral systems over remote systems. However, it is essential to consider the energy efficiency of the integral system being used in comparison with a pack system. A simple integral system without capacity control for example may be intrinsically less efficient than a pack system with capacity control. There is no evidence to suggest that energy could be saved in a typical supermarket store. Refrigeration systems should already be designed for low pressure drops and therefore, there should not be any savings available for this measure.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	No quantified value with emission savings reported in the literature
Quality of scope 2 emissions information	High confidence
TRL level	TRL8-9
Maintainability issues	No issues
Legislative concerns	No impact
Payback time (years)	None

1.18.42. Recommissioning

The aim of commissioning new buildings is to ensure that they deliver, if not exceed, the performance and energy savings promised by their design. When applied to existing buildings, commissioning identifies the almost inevitable "drift" from where things should be and puts the building back on course (Mills, 2009).

It has often been found that significant amounts of energy are wasted through poor commissioning (Evans et al., 2013) and it is widely known in the industry that recommissioning (commissioning again) can help (Gaved, 2013). A recommissioning effort will detect and correct any major systemic problems that develop over time.

There is a crossover between service and maintenance and recommissioning. A very thorough servicing programme may incorporate many aspects which are considered under recommissioning. Aspects of recommissioning which are not likely to be included in servicing are optimizing control logic and establishing the most appropriate equipment set points. It is possible that these have been modified inappropriately at some point or it may be that things have changed, and new values are considered more appropriate.

Recommissioning maybe done at different frequencies, either periodically to ensure systems are operating at their designed set-points or after performing significant maintenance, replacement, or upgrades to a store which fundamentally change how a store will perform. The U.S. Department of Energy (2012) recommends recommissioning every three to five years. Recommissioning may be triggered by other things, e.g., energy consumption or higher-than-normal maintenance costs. Monitoring of plants and cabinets provides an early warning of equipment losing efficiency and it may be more prudent to recommission when monitoring indicates there are problems.

A number of refrigeration recommissioning measures are given below:

- Check refrigerated cases set points. It is possible they have been set lower than needed.
- Clean and calibrate humidity sensors that control anti-sweat heaters.
- Repair or replace gaskets and seals on refrigerated cases (should be covered under maintenance).
- Verify correct charge in refrigeration systems and repair any refrigerant leaks. Leaks should be covered under f-gas maintenance. However, it is possible that systems have been improperly charged.
- Verify optimal head and suction pressures.
- Verify or establish an effective maintenance protocol.
- Ensure that airflows in refrigerated cases are not blocked by improperly stocked shelves. If they are, adequate measures, e.g., Training, monitoring or a physical mechanism to stop this happening, should be put in place.
- Check temperature probe locations. For refrigerant temperatures, they should be in proper contact with the refrigerant pipe and for air probes they need to be in a sensible position for measuring the air temperature.
- Training of service contractors is a vital part of ensuring that the plant continues to operate at the best possible efficiency, much of the blame for poor performance being laid at the door of under-skilled, time-poor service staff.

Retro- and recommissioning yield average whole-building energy savings of 16% (not specific to retailing) and a simple payback of 1.1 years, according to Mills (2009).

Some companies offer a recommissioning service paid for as a commission on energy saved and forecast energy savings of 5 to 10% as a result of recommissioning (Xcel Energy, 2010). Energy savings for display cabinets was reported up to 10% (Carbon trust, 2019). A payback period of less than 2 years was also reported for the recommissioning in supermarket refrigeration system (Klemick et al., 2015).

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)	Up to 10%
Quality of scope 2 emissions information	Low confidence
TRL level	TRL8-9
Maintainability issues	No problems
Legislative concerns	No impact
Payback time (years)	less than 2 years

1.18.43. Reducing/floating head pressure

Condensing temperatures (as determined by head pressures) need to be higher than the temperature of their surroundings e.g., air or water, in order to reject heat from the refrigeration system to the outside environment. Most supermarket refrigeration systems operate with a minimum condenser head pressure (and temperature), selected to be high enough to allow consistent operation under all expected operating conditions, ensuring that the thermostatic expansion valves (TXVs) can operate effectively, and allow the use of refrigerant gas to defrost the evaporators, when required. However, in many cases, particularly for air cooled systems (which is the most common cooling method used), there is scope to reduce the condenser head pressure. The benefits of reducing head pressure and methods that can be used for achieving this are discussed below.

For R744 refrigeration the pressure drop across an expansion valve is greater than with other refrigerants, so the minimum setting for head pressure control will be a lower condensing temperature. Therefore, the opportunity for reducing the head pressure is at best reduced and possibly eliminated.

Effect of head pressure on refrigeration system efficiency

Using a set minimum head pressure means that when outside temperatures fall, the temperature difference between the condenser and ambient air increase. However, if head pressures are allowed to float down as ambient air temperatures decrease e.g., in winter, while the temperature difference between the condenser and ambient air is maintained (allowing heat to continue to be rejected at the same rate), significant energy savings can be achieved. The savings in energy result from improved coefficient of performance (COP) of the refrigeration system, which depends on the pressure ratio i.e. the ratio of condenser to suction pressure. The suction pressure relates to the refrigeration temperature, so is effectively fixed for a selected operating temperature, however, if the condenser pressure floats down with the ambient temperature, the compressor work input energy needed is reduced, and the COP will correspondingly increase. Reducing the head pressure will result in energy saving of between 2 and 4% for every 1°C reduction in condenser temperature (Carbon Trust, 2011).

Methods of controlling head pressure

There are a number of methods used for controlling the head pressure for air cooled refrigeration condensers (Parker and Hannifin, 2021), namely: (1) Air side control. For example: (a) fan cycling i.e. switching fans on and off to control the air flow rate across the condenser, which will affect its temperature. However, this can cause step changes in temperatures, unstable refrigerant flow and stress on the fan motors; or (b) a variable speed drive (VSD) can be used for the fans, which provides better control and less stress on the fan motors but is more expensive; (2) Refrigerant side control. This involves reducing the condenser surface area. This can be done by: (a) partially flooding the condenser with liquid refrigerant, in order to maintain a constant head pressure during periods of low ambient temperatures. However, this requires the use of additional refrigerant, which would be an issue with charge restrictions, and also a large reservoir that is able to hold all of the refrigerant, when needed; or (b) splitting the condenser into two circuits, one for summer/winter use and one for summer only use. The summer condenser is not used during periods of low ambient temperature. This method requires the installation of a condenser splitting valve in the discharge line.

Issues to consider when floating head pressures

Possible issues that can arise when floating head pressures, at low ambient temperatures are: (A) underfeeding of TXVs, leading to refrigerant starving of evaporators, reducing their capacity; (B) oil logging may occur if the load is low e.g. during defrost of the evaporators, resulting accumulation of oil in the evaporator, which can then cause damage to the compressor when normal refrigerant flow rates resume; (C) a reduction in compressor efficiency and higher discharge temperatures can also result from reduced load and underfeeding of TXVs, as a result of high superheats (Demma, 2004).

Strategies to avoid low head pressure issues

Improved and more stable control of refrigerant circulation at low head pressures can be achieved by using electronic expansion valves (EXVs) instead of TXVs. EEVs are more expensive but can help to minimise fluctuations in capacity and liquid quality, and better control superheat. Using this approach 15-20% improvements in compressor efficiency were reported, for every 6°C reduction in head pressure for supermarket refrigeration systems, enabling stable operation while at condenser temperatures of 21°C and lower (Emerson, 2022). Another way of avoiding low head pressure issues is to use a liquid pump to maintain refrigerant (see section on liquid pressure amplification (LPA)) circulation and reduce flash gas. When using this approach, energy savings of between 19 and 43% were reported for two supermarket installations, in the USA (Wheeler and Smith, 1988).

Benefits of reducing head pressure

The Carbon Trust (2011) stated that for a typical refrigeration system with a condenser temperature set point of 40°C, allowing the head pressure to float down to 20°C, (when the ambient temperature permits), would typically reduce compressor energy by 25-35% for a chilled temperature system. Mathematical modelling of supermarket refrigeration systems by Ge and Tassou (2000) found that by reducing the head pressure set point from 15.1 bar to 12 bar on an existing supermarket system, could provide substantial energy savings of over 22% for a 24-hour period in summer. They also noted that variable-speed control of the compressor provided better control of the suction pressure, and reduced power consumption by 10% compared to an on-off strategy.

In other studies Wang et al (2017) reported energy savings for compressors and condenser fans, when floating head pressure, of between 4.2 and 28.3% for a range of locations and ambient temperature conditions, across the US. Yu and Chan (2004) investigated the effect of reducing head pressure using condenser temperature control for air cooled building chillers. They reported savings in chiller power consumption of 18.4% across the annual cooling load profile for the building. A study by Yu et al (2006) investigating the constraints of TEVs on air cooled chillers reported that by using EEVs, differential pressure requirements could be met while reducing the condenser temperature from 45°C to 22°C, providing a 28.7% increase in chiller COP. They concluded that the potential savings in chiller power could help decide the economic viability of replacing a TXV with an EXV to facilitate the floating of head pressures.

Commercial availability

All equipment needed to allow floating of head pressure is readily available. Simplest method of controlling head pressure is on-off switching of condenser fans. However, variable speed drive for the fans reduces stress on fans and avoids sudden changes in refrigerant flow. Also, stability of flow through expansion device improved by replacing TEV with EEV, but at additional cost. Liquid line pump can also be used to maintain refrigerant pressure at expansion device, but at additional cost.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	5-40% compressor energy, depending on scope for reducing head pressure e.g., variation in ambient temperatures. This is for HFC systems. For R744 systems there is no evidence that head pressure is maintained higher than required.
Quality of scope 2 emissions information	M
TRL level	TRL8-9
Maintainability issues	M – need to avoid low head pressure problems e.g., due to unstable TXV operation
Legislative concerns	L
Payback time (years)	Depends on whether additional equipment e.g., EEV expansion device or variable speed drive fans are installed

1.18.44. Reducing thermal radiation

Refrigerated retail cabinets gain heat by infiltration and by convective, conductive and radiative heat transfer. The rate of heat gain and proportions of the different heat transfer modes depend on the design of the refrigerated cabinet (e.g., vertical or horizontal) and the temperature difference between the inside of the cabinet and its surroundings. Radiative heat gain is greatest where temperature differences are highest. Faramarzi et al (2000) reported a radiation heat load of 8-10% for a medium temperature (i.e., chilled) open vertical cabinet, but a radiation heat load of 43% for a low temperature (i.e., frozen) coffin (or well) type cabinet. A study by Sarhadian et al (2004) showed that radiation accounted for 12% of the heat load for an open multi-deck (vertical) medium temperature display cabinet. In a further study, Faramarzi et al (2002) found a radiation heat load of 7.5% (of the total) for a medium temperature open vertical cabinet, in contrast to a radiation heat load of 1.3%, for a medium temperature closed (i.e., glass door) vertical cabinet, with a total reduction in heat load (from all heat transfer modes) of 68%. Radiative heat load for refrigerated retail display cabinets or the products within these cabinets, depends on the emissivity of their surfaces. Emissivity values (between 0 and 1.0) represent the fraction of the incident radiation that is absorbed or reflected. For example, matt black paint surfaces may have an emissivity of 0.95, indicating that 95% of the heat is absorbed and 5% reflected, whereas aluminium foil may have an emissivity of 0.04, indicating that 4% of the heat is absorbed and 96% reflected. Standard glass typically has an emissivity between 0.85 and 0.95. Consequently, by using different materials, the radiative heat load for refrigerated display cabinets can be modified.

Radiant reflectors

Aluminium foil or infrared reflectors provide low emissivity surfaces and are used in some open display refrigerated cabinets, both for aesthetic reasons and to reduce radiation heat transfer. They have greatest impact on freezer cabinets, although open freezer cabinets are less popular nowadays (only horizontal freezer cabinets are available, not vertical), with glass door freezer cabinets most common. Radiant heat reflectors are less effective for vertical display cabinets due to the orientation of the exposed surfaces, which tend to face cooler surfaces within the supermarket room, than horizontal cabinets which face a warm ceiling. The use of radiant heat reflectors in open well-type freezer cabinets was reported by Hawkins et al (1973), who found 2 K reductions (in the highest temperature locations) for products stored within the cabinets, by using simple reflectors, and reductions of up to 5 K, using corner cube type reflectors. This would represent energy savings of between 5 and 8%, if the evaporator temperature for these cabinets was increased by between 2 and 5 K.

Afonso and Matos (2006) investigated the effect of radiant shields (i.e., aluminium foil reflectors) placed around the air condenser and compressor components of the refrigeration system for a domestic refrigerator-freezer. They found a decrease in the internal temperatures of the refrigerator-freezer of 2 K. No difference in the energy consumption of the refrigeration system with or without the radiant shields was found in these tests, however, if the evaporator temperature was increased by 2 K, when using the radiant shield, it is estimated that an energy and carbon saving of 5% could be achieved. These results could be applicable to integral refrigerated retail display cabinets; however, this type of shielding would not improve the performance of remote display cabinets.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	5-8% (for low temperature, open well-type display cabinets)
Quality of scope 2 emissions information	M
TRL level	TRL 8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	No information available.

Low emissivity glass

An experimental study comparing the use of TEC15 low emissivity (0.2) glass with high emissivity (0.9) glass, in a medium temperature (i.e., chilled) horizontal delicatessen cabinet was reported by Paurine et al (2018). The comparison involved measuring the surface temperatures of food products placed within the cabinets, with the tests carried out under controlled environmental and operating conditions. It was found that lower food surface temperatures (of the order of 2 K, on average) were obtained when using the low emissivity TEC15 glass, and it was estimated that energy (and carbon emissions) savings of approximately 13.5% could be obtained.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	Up to 13.5% (for medium temperature, horizontal, delicatessen cabinet)
Quality of scope 2 emissions information	M
TRL level	TRL 8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Not available

Low emissivity packaging

An alternative approach to reducing radiative heat transfer to food products placed in refrigerated retail display cabinets is to use low emissivity packaging for the food products. Cortella (2008) noted that frozen food is often wrapped in aluminium bags, with emissivities of typically 0.2 to 0.3, which is much lower than that for paper (emissivity 0.9 to 0.95). In open refrigerated display cabinets, the use of low emissivity packaging can provide reductions in food temperatures of 4 to 5 K for food placed at the front or top of the cabinet. This would imply that the evaporator for these refrigerated cabinets could be increased by 4 to 5 K, which could provide energy and carbon emission savings of 12 to 15%. Davies et al. (2012) examined the potential to use new printing techniques to produce low emissivity packaging. In the work they measured packaging emissivities from 0.79 (waxed paper) to 0.01 (aluminium foil/plastic laminate). They showed food top surface temperatures were reduced by 10.6, 9.9, 9.4 and 6.0 K for packaging emissivities of 0.01, 0.07, 0.28 and 0.44 compared to the standard packaging emissivity of 0.79, when used in a low temperature open well-type display cabinet. This would enable refrigeration system efficiency improvements that could reduce energy consumption and carbon by up to 30%. Overall carbon savings were predicted based on energy and the use of packaging with low embodied carbon.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	None
Scope 2 emissions savings (% or another quantifiable metric)	Up to 30% (for low temperature open well-type display cabinet)
Quality of scope 2 emissions information	M

TRL level	TRL 3-4; or TRL 8-9
Maintainability issues	None
Legislative concerns	None identified to date
Payback time (years)	Not applicable. Any small additional cost of packaging recovered in product price

Commercial availability of these technologies

There are a number of manufacturers offering low-E (i.e., low emissivity) glass as an option for supermarket refrigerated display cabinets. These include: Oscartielle's Brione 2 and Dione refrigerated glass doored cabinets; Quisure's insulated glass door refrigerated display cabinets; and low emissivity glass manufacturers of low emissivity glass for refrigerated display cabinets e.g., Glacier Door Systems.

1.18.45. Refrigerants - general

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 was typical in supermarket refrigeration systems and 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, typical in supermarket refrigeration, 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. Supermarket remote systems are not hermitically sealed, however, refrigerated cabinets with integral refrigeration system are. This mainly affects the use of HFC 134a (GWP of 1430) and most non-flammable "drop-in" refrigerants.

F gases with global warming potentials of more than 150 will also be banned in central pack systems with a rated cooling capacity of 40 kW or more. This covers centralised refrigeration systems supplying many refrigerated cabinets.

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[42] per kilo of the GWP value.

At the time of writing (March 2023) the European Parliament supported an HFC phase out by 2050 and multiple bans on fluorinated greenhouse gases (f-gases, both HFCs and HFOs) in applications such as heat pumps and stationary refrigeration. The phase out of HFCs by 2050 takes the phase down of 80% to 85% between 2036 and 2047. The proposed revision would bind this legislation to the PFAS (per- and polyfluoroalkyl substances) restriction process.

1.1.1.4 Carbon dioxide (CO_2, R744)

Carbon dioxide (R744) is an alternative refrigerant for remote supermarket refrigeration systems and heat pump chillers. The major benefit 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.

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. Despite the issues with R744, many retailers are convinced that the benefits far outweigh the drawbacks.

R744 systems started to grow in 2001 in Scandinavian countries when Denmark introduced GWP based taxation of refrigerants. Later in 2007 a charge limitation of 10 kg was placed on HFC systems, ruling them out supermarket refrigerated cabinets (Matthiesen, Madsen, and Mikhailov 2010).

R744 has very different properties from other refrigerants at working temperatures. The saturated vapour pressure of R744 at -10 °C is 26 bar, as opposed to 4.3 bar for R404A, therefore, the transport properties are excellent, and pressure drop in long pipelines does not reduce the performance as in conventional unit. The pipework and joints need to be able to withstand a much higher pressure, however, the pipes itself are much smaller in size (diameter). When the saturated vapour temperature is below 31 °C the system will be operating sub-critically and therefore similar to a standard refrigeration system. However, when above this temperature, the discharge pressure is above 73 bar and the system will operate trans-critically. This means that heat at the high-pressure side of the cycle cannot be rejected by condensation in a condenser but instead must be rejected by gas cooling, i.e. at gliding temperatures. Whether the system is operating sub or trans-critically will depend on climatic conditions.

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

Sawalha et al. (2017) compared field measurement and modelling results of COP's for HFC and CO_2 systems, the new CO_2 systems had higher total COP than HFC systems for outdoor temperatures lower than about 24 °C. The modelling was used to calculate the annual energy use of HFC and new CO_2 system in an average size supermarket in Stockholm, new CO_2 systems use about 20% less energy than a typical HFC system.

In addition, according to Sawalha et al. (2017), "new" installations (i.e. booster-based architectures) are characterized by higher COPs at outdoor temperatures below 24 °C, as well as by an energy saving by 20% compared to HFC systems in an average-size supermarket in Stockholm

In theory, a transcritical refrigeration system is not efficient, however, in practice, most transcritical systems that have been installed are as efficient or more energy efficient than corresponding state of the art R404A systems (Matthiesen, Madsen, and Mikhailov 2010). There are several reasons for this, but most important is that the trans-critical systems are installed in areas where they actually operate sub-critically most of the year. Therefore, this has given rise to the so-called "CO_2 efficiency equator". By that time, this line approximately falls on the Northern border of Spain and Italy, making tran-scritical R744 systems in countries below this latitude less efficient than the typical subcritical R404A refrigerant. Additional technologies can make R744 systems more efficient than HFCs, these are heat reclaim, booster systems, parallel compression and ejectors, thereby eliminating the so-called "CO_2 efficiency equator".

According to EIA and Shecco (2018) adding an adiabatic gas cooler to a trans-critical system offers annual energy savings of 8-12%. Adding parallel compression delivers 6-8% savings and in combination with gas ejectors, savings can reach 8-10% compared to a trans-critical system without these enhancements. These additional technologies, recommend for new systems installed in warm climate regions to reduce the energy consumption also led to increased installation costs. Currently, initial costs of enhanced CO_2 trans-critical systems are higher than conventional HFC based systems; for example, the price of a system with ejector technology and parallel compression is up to 10% higher than a standard CO_2 booster system; however, this is expected to change as the technology becomes more widespread (as has occurred with the standard CO_2 booster system), and simplified ejector system configurations are implemented, as shown by SINTEF/NTNU (Pardiñas et al.). The cost of CO_2 compressors in Europe is now on par or even lower than the cost of HFC compressors; however, cost is still an issue for variable speed technology, especially for larger equipment.

From the end of 2011 up until October 2013 an additional 1,555 R744 TC supermarkets appeared on the European market, bringing the total number of CO_2 TC stores in Europe to 2,885 (Masson 2014). The adoption of R744 varies in Europe, mainly for climatic reasons, but also legislative. Only 21 installations were running in Southern Europe (i.e., Spain, Italy) over the same period of time. German retail group ALDI Süd reports that the discount food retail giant had 1,496 stores using CO_2 transcritical systems worldwide in 2017 (McLaughlin 2018). Plug-ins using CO_2 are also available and tests have shown 16 per cent energy usage reduction compared to HFC-404A units. The initial system cost however is eight per cent higher for the CO_2 unit, owing to the heat exchanger costs (Menghini 2016).

Case Study

Food retailers who participated in the Life-C4R (Carbon 4 Retail Refrigeration) project reported energy savings and other benefits associated with installations of transcritical CO_2 (R744) equipment in warm ambient climates (McLaughlin, 2018). The first pilot project for the Life-C4R project, launched in October 2019, took place at a store in Carpenedolo, Italy, where summer temperatures frequently reach 35°C. The store saved 54,514kWh/year compared to standard solutions. At a store in Bologna, Italy, they saved 55,868 kWh/year. These systems used patented technology whereby a low-pressure liquid receiver is used to flood medium-temperature cabinets with liquid CO_2, eliminating superheat and allowing the evaporation temperature of the cabinets – and, ultimately, the efficiency of the system – to increase. Case Study II: See: https://www.ntnu.edu/multipack/virtual-tour-to-demo-sites

Cascade

The advantage of a cascade system is that the high-pressure side of the R744 circuit can be kept subcritical by using the low pressure side of another refrigerant to cool it.

R404A has been used for the high temperature circuit, as it is has been the predominant refrigerant used in supermarkets for many years. As the high temperature circuit is confined to the plant room, leakages of the higher GWP fluid can be kept to a minimum.

Da Silva et al. (2012) compared a R744/R404A cascade system to a conventional R404 system. They found that the cascade system presented a lower refrigerant charge, 47 kg of both fluids, which represents less than a half of the refrigerant charge of the other system. They found the cascade system to be 22-25% more efficient than the R404A system. The two racks that make up the cascade system using CO2 on low temperature and R404A on high temperature stage were found to be 18.5% (based on 2008 values) more expensive than single stage racks using R22 and R404A based on the same cooling capacity. CO_2 evaporators were physically smaller and less expensive due to the increased specific cooling capacity of the refrigerant. It was found that the R404A evaporators need approximately 20% more surface area to achieve the same thermal performance as the CO2 evaporators (based on the same temperature difference between evaporating and room temperature). Refrigerant charge in each of the three systems also has an influence on the total cost. The cascade system has 32 kg of CO_2 as well as an additional 15 kg of R404A, (32 + 15 = 47 kg). The R404A system had 125 kg.

However, with future F-gas legislation, another refrigerant is required. Cabello et al. (2017) conducted an experimental comparison of a cascade refrigeration facility working with the refrigerant pairs R134a/R744 and R152a/R744. They found that, apart from safety considerations, as R152a is included in the A2 group, the results of the wide range of tests conducted show that no special energy improvement or penalty is achieved. They also concluded that replacement of R134a with R152a is technically and energetically feasible.

Amaris et al (2019) found that an R744 cascade system had better performance than a R744 booster conventional system and R744 parallel-compressor booster system above ambient temperatures of 2 and 14°C respectively.

As the high side is outside the building, this allows the possibility of using flammable refrigerants. Felzer (2020) produce a R290/R744 cascade system for supermarkets, as a relevant and future proof alternative in warm climate regions.

The latest figures from Masson et al. (2014) reveal 1,639 stores using CO_2/HFC cascade systems in Europe. In addition, 19 stores use CO_2/NH_3 cascade systems. Germany has the highest number of these systems. A German retailer has shown 35% energy savings using R134a/R744 compared to the previously used R404A systems.

Booster systems

A booster system uses two compressors to run both LT and MT packs in the same cycle. The first prototype was developed in the framework of the EU Project "Life" at Danish Technological Institute in June 2006 and installed in a small Danish store in 2007.

Fricke et al. (2016) compared the coefficients of performance of a trans-critical CO_2 booster and an HFC-based refrigeration, and it was found that over the outdoor ambient temperature range of 15.6°C to 31.1°C, the COP of the trans-critical CO_2 booster system was on average 15% greater than that of the HFC system.

Carrier has installed a transcritical CO_2 booster system in a Carrefour supermarket in Valencia, Spain, where temperatures average 30 °C in summer (Cooling Post 2014). This system uses hydrocarbon subcoolers, economisers and parallel compression to allow the CO_2 system to operate efficiently at such high ambient temperatures. After 15 months of operation the system is showing a return on investment of 1.2 years with energy savings of 13% from the refrigeration system.

RDM controls have equipped New Zealand's first transcritical CO_2 refrigeration grocery store. The new plant has only been running for a relatively short period, yet early indications are that the system is delivering "a double digit percentage reduction in energy use" compared with conventional systems (Darby 2018).

Parallel compression

In a conventional R744 booster system, the amount of flash gas removed from the liquid receiver and thus compressed by the high stage (HS) compressors goes up significantly with rise in outdoor temperature (Gullo, Hafner, and Banasiak 2018). Gullo et al. (2016) estimated that in trans-critical running modes the flash gas mass flow rate is on average equal to 45% of the total mass flow rate. As a consequence, extremely poor performance can be ascribable to such a technology in high ambient temperature countries. A method, which leads to modest enhancements in COP, is that based on the compression of a part of or the total amount of the flash gas from IP to HP with the aid of one or more parallel (or auxiliary) compressor(s). As reported by Gullo and Hafner (2017) compared to a R404A direct expansion unit, the energy efficiency limit commonly experienced by conventional booster technology at outdoor temperatures above about 14°C can be pushed up to 27°C by adopting parallel compression.

Secondary system

With a secondary system, R744 is pumped as a volatile secondary fluid through the evaporators of the refrigerated appliances where it boils and provides the cooling effect. The return pipe to the receiver carries a mixture of liquid and gas. The high side will primarily use an HFC refrigerant in a conventional circuit. This does not appear to be a common system type and no references to systems in Europe were found.

Scope 1 emissions savings (% or another quantifiable metric)	GWP of refrigerant reduced to 1.
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Up to 20% quoted compared to HFC. This value depends on type of CO_2 system and where installed. High ambient temperatures in Southern Europe can still offer energy savings, but plant may need to be more complex.
Quality of scope 2 emissions information	High. A number of peer reviewed publications agreeing and lots of case studies.
TRL level	TRL8-9
Maintainability issues	Less staff trained for CO_2.

Legislative concerns	None.
Payback time (years)	Lack of published information. An efficient R744 supermarket may cost up to 10% more than an HFC equivalent but the energy savings achieved should balance the additional cost giving paybacks of <1 year.

1.18.46. Refrigerant - HFO refrigerants and blends

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.

R1234yf (GWP =<1, on a 100-year perspective) was developed for motor vehicle air conditioning and was used to replace R134a from 2011 to 2017. It is not suitable for supermarket refrigeration in its pure form. It is mildly flammable (A2L classification).

R1234ze (GWP = 7) is currently still allowed to be used for air-cooled and water-cooled chillers. It has a comparable energy efficiency, but slightly lower cooling performance compared to R134a. Although it is classed A2L, it is considered non-flammable at 20°C ambient temperature, however, forms a flammable mixture with air at temperatures above 30°C. PED fluid group 2.

R1234zd (GWP = 4.5) can be used in low pressure chillers where R-123 may have been used in the past or for organic Rankine cycle applications.

Blends

There are many refrigerant blends containing HFOs (Table 13).

Table 13. List of HFO based refrigerants suitable for supermarket 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

Oruç et al (2021) experimentally investigated blends R454A and R454C in a R404A refrigeration system. Three evaporation temperatures (−5, 0 and +5°C) were considered. The COP of R454A and R454C were greater than R404A by about 14% and 10%, respectively. The cooling capacity of R454A was higher than R404A by 11%. These refrigerants could be used directly in available R404A systems without any constructional modification requirement if safety concerns can be solved.

Makhnatch et al. (2017) carried out a retrofit of R449A into an existing R404A medium temperature indirect supermarket refrigeration system (secondary fluid temperature at the evaporator outlet between -9 and -4 °C). It was demonstrated that with a slight expansion device adjustment and 4% increase of refrigerant charge, R449A could be used in this refrigeration system designed for R404A because of its suitable thermodynamic properties and acceptable maximum discharge temperature. At a secondary fluid temperature at the condenser inlet of 30 °C, the COP of R449A nearly matches that of R404A (both were between 1.9 and 2.2), despite having approximately 13% lower cooling capacity.

Hart et al (2020) investigated investment strategies to reduce carbon intensive refrigerants in the food retail industry. The marginal abatement cost (MAC) curve, relating to CO_{2e} abatement for an average 30K ft^2 store in the estate, demonstrates the benefit of R449A retrofitting. Achieving 45% of the R-744 CO_{2e} savings at just 9% of the MAC, it is a useful stepping-stone towards the superior, but costly, R744 CO_{2e} savings available. The strong uptake of retrofitting with R449A may mean the industry becomes over reliant on this single refrigerant and, as regulatory phaseouts commence, and prices rise, companies could be left exposed. They also showed that although R449A is a better retrofit option, however, new stores should implement R744, as it is seen to be a future proof option, beside HC based systems.

Peterson et al, (2016) looked at fractionation of the blends during leakage due to their temperature glide during phase change. They showed that the composition shift of the blend components for a charge loss of 20% to 30% remained within typical refrigerant tolerances. The performance parameters for capacity and efficiency remained within ±5%.

Mendoza-Miranda et al. (2016) carried out a comparative evaluation of R1234yf, R1234ze and R450A as alternatives to R134a in a variable speed reciprocating compressors. Predictions showed a reduction in the cooling capacity obtained with R1234yf, R450A and R1234ze, in comparison with R134a. Also, COP values for R1234yf, R450A, and R1234ze were lower than those obtained from R134a.

Gullo and Cortella (2016) found R1234ze can be effectively used in indirect refrigerating plants along with R744 as the secondary fluid. Secondary loop systems using natural or HFO refrigerants as the primary working fluid and R744 as the secondary fluid could be considered as an efficient alternative to currently used technologies as long as a suitable trade-off among economic, environmental, and energetic aspects is found.

Gil et al (2021) theoretically tested new HFC/HFO blends. The analysis showed that it is extremely difficult to find a blend with a negligible impact on the greenhouse effect and at the same time good thermodynamic properties, which could be used as a replacement for R404A in low-temperature systems.

Prices of HFC refrigerants in Europe stabilised in the first quarter of 2020, but R1234yf declined in price for the first time https://www.coolingpost.com/world-news/hfc-refrigerant-prices-stabilise/. However, R1234yf was still more expensive than the HFC blends containing it. By comparing online prices (https://www.wolseley.co.uk/) of refrigerants, R407F was the most expensive, closely followed by R1234ze. R134a, R448A, R449A were about half the price of R407F. R452A was about 75% of the price of R407F and reclaimed R404A was 2/3 the price of R407F.

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 14).

Table 14. 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

Scope 1 emissions savings (% or another quantifiable metric)	In proportion to their GWP.
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	It is not possible to come up with an overall value as there are many blends and they perform differently under different conditions.
Quality of scope 2 emissions information	High. A number of peer reviewed publications agreeing and lots of case studies. However, the COP of the blends is almost always higher than for R404A. The worst case reported is R454C used at low temperatures where the COP can be reduced by up to 6%. The best case is the R448A at low temperatures where the COP can be increased by up to 21%. Although the COP is generally higher, the capacity of these refrigerants is general lower, by a similar degree. Therefore, components such as evaporators may need to increase.

TRL level	TRL8-9
Maintainability issues	Potentially some issues around flammability.
Legislative concerns	A2L refrigerants will require some safety. Blends above GWP of 150 will be subject to some restrictions due to f-gas regulations. Also, potential issues with new regulation and PFAS.
Payback time (years)	Systems becoming similar in price to conventional HRC systems (especially if the HFO used is A1 classification).

1.18.47. Refrigerant - HC refrigerants

Hydrocarbon (HC) refrigerants are natural, low toxicity refrigerants that have no ozone depleting properties and negligible global warming potential. There are 3 common HCs used in refrigeration. These are R290 (propane), R600a (isobutane) and R1270 (propylene). A number of other hydrocarbons, such as blends containing ethane, propane or butane, are also used as refrigerants.

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, such that they are unable to be used in distributed systems where refrigerant is transported from a central condensing unit to multiple evaporators through piping.

For distributed systems, secondary circuits must be used. They can, however, be used in integral cabinets as long as charge restrictions are observed. The limit for R290 is approximately 1 kg according to EN 378 standard.

R600a (GWP of 4) has a lower volumetric refrigerating effect (VRE) than R134a and therefore requires a specific compressor. R290 (GWP of 3) and R1270 (GWP of 2) have similar thermodynamic properties to and therefore can be used as a retrofit. However, flammability mitigation measures must be taken.

The world's biggest retailers and food and beverage manufacturers have been testing natural refrigerants since the early 2000s. Since approximately 2010 they have moved beyond pilot projects, undertaking mass rollouts of R290 propane-based standalone refrigeration cases (HRAI 2020).

Arslan et al. (2021) saw a 24% increase in COP of R290 compared to R449A.

Anthunes et al. (2016) experimentally investigated drop in alternatives refrigerants to R22. The behaviour of the refrigerants (with the same cooling capacity) showed that the system with the R1270 had the highest COP values for the same evaporation conditions. At an evaporating temperature of -10°C it had a 20% higher cooling capacity than R404A and 13% higher than R290. R1270 had a 29% higher COP than R404A and 5% higher than R290.

R290 can also be used to provide sub-cooling of a two stage transcritical R744 system. This can significantly increase the COP of the system (Liu et al. 2019). Hydrocarbons can also be used in cascade refrigeration systems with R744 in the low-temperature circuit (Bellos and Tzivanidis 2019)

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.

Arnemann et al. (2012) carried out experiments with a scroll compressor. They showed R290 and R1270 have a higher COP than R404A at higher pressure ratios. At low pressure ratios, R290 does not show such an advantage, while R1270 always has a better COP than R404A. At an evaporating temperature of -10 °C, R290 has a better COP than R404A, between 0 and 29% for a condensing temperature of 30 and 60 °C, respectively. At the same conditions, R1270 has a better COP of between 8 and 15%.

R290 is used with polyolester oil in compressors, meaning material compatibility is almost identical to R134a or R404A in terms of oil.

It is technically feasible to remove R404A or R134a from existing systems and replace them with R290, R1270 or blends containing HC, as appropriate. However, it is highly likely that the resultant system will not comply with safety rules related to the application of HC refrigerants because the refrigerant quantity is unlikely to comply with charge limits and the electrical equipment will not be suitably protected.

The safety of commercial applications with incorporated or remote condensing units in Europe is covered under EN 60335-2-89 and is currently limited to a refrigerant charge of 150 g. Above this charge is covered by EN 378. However, the IEC version was updated to allow charges of approximately 500 g of R290 and 1.2 kg of A2L refrigerants. This is not yet harmonised with the relevant EU Directives.

Scope 1 emissions savings (% or another quantifiable metric)	In proportion to their GWP.
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	-2 to +31%
Quality of scope 2 emissions information	High. A number of peer reviewed publications agreeing and lots of case studies. The COP of both R290 and R1270 is almost always quoted as higher than R404A.
TRL level	TRL8-9
Maintainability issues	None
Legislative concerns	Flammable so require compliance with relevant standard.
Payback time (years)	Generally, cost parity with HFC systems.

1.18.48. Secondary systems

The majority of medium and large supermarkets use multiplex refrigeration systems with direct expansion evaporators in each of the display cabinets, with refrigerant distributed by means of common suction and discharge lines to a centralised refrigeration system in a plant room (IIR, 2018). Consequently, they use a large refrigerant charge and are prone to leakage e.g., typically 15 to 17% per annum (Zhang, 2006 and Accurio, 2017). Secondary loop systems use a refrigeration system contained in a plant room to cool a secondary fluid which is then circulated to all the display cabinets in the supermarket. The secondary fluids are often termed brines, but are typically single-phase glycol based fluids, although two phase CO_2 or ice slurries can also be used. In supermarkets, secondary loop systems are most commonly used for cooling medium temperature display cabinets, although CO_2 or potassium formate can be used for low temperature i.e., freezer, cabinets.

The main advantage of secondary loop systems is that they use fluids with virtually zero (or 1 in the case of CO_2), so there are no emissions from any leakage. Also, the primary refrigerant which may have a higher GWP, is contained in the plant room and a lower refrigerant charge is needed and leakage rates are likely to be lower, so overall refrigerant leakage will be lower and direct emissions greatly reduced. The use of secondary loop systems has been claimed to reduce direct emissions by up to 90% compared to multiplex centralised refrigeration systems for supermarkets, where high GWP refrigerants e.g., R404A or R507A are used e.g., Wang et al (2010), Palm (2007).

Whether secondary systems are more or less expensive is disputed. Delventura et al (2007) state that there is a cost saving due to reduced halocarbon refrigerant (this would not necessarily be the case with R744) and the reduction in pipe length. They also state a field trial by the California Energy Commission conducted over a 9-month period resulting in energy savings of 4.9%. Another advantage suggested by Delventura et al (2007) were ease of maintenance due to simplified pipe layout, not requiring f-gas trained technicians, no need to adjust TEVs (this is not the case if EEVs are used) and reduced oil return issues. According to ACHR (2009) this can lead to up to 50% lower maintenance costs.

IIR (2018) state extra costs due to the introduction of an additional heat exchanger between the primary refrigerant and the brine, which reduces the performance (i.e., COP) of the cooling system compared with multiplex systems; the energy consumption of the brine circulation pumps are high, as secondary fluids are often viscous, particularly at low temperatures. Stignor (2007) reported that replacing propylene glycol (39%$_w$) with Temper -20 reduces total costs and using variable speed pumps can reduce energy consumption by almost 30%

The use of CO_2 as a secondary fluid can reduce the power consumption of the liquid circulation pumps (due to its low viscosity, thereby reducing the pressure drop in the secondary loop). It can also enhance heat transfer in the heat exchangers and improve the overall performance of the refrigeration system. It was concluded that although secondary loop systems are likely to be more expensive, in terms of capital cost, the potential reduction in operating costs could compensate for this, although this would need to be evaluated on a case-by-case basis.

Llopis et al (2018) note that secondary loop systems usually increase the energy consumption of the system. This results from the extra temperature difference due the additional heat exchanger between the primary and secondary fluids, and the energy consumption of the secondary fluid pump, although this can be minimised by appropriate design of the secondary loop system. Additional energy consumption for secondary loop systems ranges from -4.9% (i.e. an energy saving) (Delventura et al, 2007) to 22.8% for R134a and 32.8% for R507A (Llopis et al, 2018).

Sanchez et al (2017) evaluated the energy input of using a R134a/CO2 direct cascade system against a R134a – secondary loop/CO_2 indirect cascade system. They determined an energy increase for the indirect cascade system of between 7.6% and 14% when using the secondary loop system with propylene glycol, and between -0.3% and 11.1% when using a proprietary secondary fluid, Temper -20.

Sánchez et al (2018) conducted an energy assessment of an R134a refrigeration plant upgraded to an indirect system using R152a and R1234ze(E) as refrigerants. Experimental tests demonstrated that an indirect configuration results in an increase in the total energy consumption of the refrigerating plant regardless the refrigerant adopted. The average increase was 21.8% for R134a, 18.7% for R152a and finally 27.2% for R1234ze(E). The adoption of an indirect system also reduces the refrigerant mass charge of the facility from 42.5 up to 62.0% depending on the refrigerant used.

Nelson et al (2015) compared a secondary CO_2 system to a baseline DX system and found the energy consumption was 7 to 12% higher and the initial costs 17 to 32% higher.

In summary therefore, the use of secondary loop systems can provide significant savings in direct emissions e.g., up to 90%, compared to a multiplex centralised refrigeration system where a high GWP refrigerant e.g., R404A is used, although as the supermarket industry moves to low or zero GWP refrigerants, these savings will correspondingly reduce (to zero). By far the majority of cases show secondary loop systems increasing energy consumption.

Scope 1 emissions savings (% or another quantifiable metric)	Up to 90% (for high GWP refrigerants, e.g., R404A and R507A)
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	-32.8% to +4.9%. By far the majority of studies show energy increases.
Quality of scope 2 emissions information	H
TRL level	8-9
Maintainability issues	L (low maintenance requirements claimed)
Legislative concerns	L
Payback time (years)	Probably no payback.

1.18.49. Shelf risers and weir plates

Shelf risers are strips of (usually clear) plastic of approximately 50 mm height that are fitted to the front of refrigerated display cabinet shelves. They have two functions, firstly to retain products on the shelves, but secondly to reduce outside air entrainment for open cabinets.

Weir plates are used similarly, although they are typically around 100 mm in height. They can be made of either plastic or glass, and are fitted at the front of the shelf, helping to separate the chilled air curtain air from the outside air. This creates a shallow well of cold air across each shelf, providing a more uniform and lower temperature environment for the products on the shelf. This helps by reducing temperatures for the products at the front of the shelf. It also reduces the refrigeration system energy input needed to achieve the set cabinet temperature.

The main drawback of using shelf risers or weir plates is that customer access to the products on the shelves is slightly restricted, so they are sometimes removed (in which case the benefits are obviously lost). They may also become damaged or detached, and if not replaced their benefits are again lost.

Shelf risers and weir plates are a simple, well-established technology, and are easily manufactured, at low cost. It is estimated that they are already fitted to 50% of display cabinets (Foster et al, 2018).

Energy savings

It has been suggested by the Carbon Trust (2019) that energy savings of 1-2% can be achieved by fitting shelf risers or weir plates to refrigerated display cabinets. However, Foster et al (2018) reported that in experimental tests with refrigerated display cabinets, the use of risers and weir plates produced much larger energy savings of between 8 and 16%. With these higher energy savings, payback times will be reduced.

Commercial availability

Shelf risers and weir plates for use in display cabinets are available from a range of manufacturers and are already widely used.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	1-2% energy and cost savings suggested by Carbon Trust (2019) 8-16% energy and cost savings measured by Foster et al (2018)
Quality of scope 2 emissions information	M
TRL level	TRL 8-9
Maintainability issues	Need to clean risers and weir plates regularly for hygiene and visibility reasons. Need to replace damaged or detached risers or weir plates
Legislative concerns	Need to use food grade plastic for risers
Payback time (years)	1 -1.5 years with higher cost savings

1.18.50. Short air curtains

Conventional open vertical refrigerated display cabinets have a full length, down flowing, refrigerated air curtain in front of the cabinet shelves, supporting the refrigerated air used to maintain the temperature of the food products on each shelf, which is generally introduced through the back panel. The aim of using the front air curtain is to minimise entrainment of the room air and protect the temperature of the products at the front of the shelves. One problem, however, is that as the distance the air flows from the top of the cabinet increases it is subject to turbulent mixing and the temperature of the food products is less well controlled (Stribling, 1997). Another drawback of full-length air curtains is that the high flow rates needed result in increased entrainment, causing chilled air to build up in the walkway/aisle, reducing the thermal comfort of store customers as well as being inefficient i.e., wasteful of cooling energy.

Hayes and Stoecker (1969) suggested that short air curtains, with no back panel flow, could remain stable throughout their height, and that slower discharge velocities could be used than for taller curtains, and would have a lower entrainment rate. Studies by Stribling et al (1995), Axell (2002) and Schuster and Krieger (2007) also suggested that shorter air curtains would be more efficient and less subject to turbulent mixing. This was supported by findings from CFD modelling work and practical measurements on air curtains undertaken by Hammond et al (2011).

Hammond et al (2016) investigated the use of short air curtains with the air issuing from the front of each shelf, protecting and enclosing the products on the shelf immediately beneath within a cell (of air). This provides a stable air curtain for each cell and enables the use of the back panel flow to be eliminated. This results in less pressure on the air curtain for each cell and a reduction in cold air spillage from the case, providing improved energy efficiency. In tests, a reduction in heat gain by the cabinet of 28.3% was achieved, and a 35.9% reduction in refrigeration energy consumption, compared to a conventional cabinet with a full-length curtain and back panel flow. Temperature control was also improved, with the range of product temperatures being reduced from 9.5 K to 3.1 K.

Short air curtains for open, vertical refrigerated display cabinets were also investigated by Pitchers et al (2018), who reported a 24.5 % reduction in total energy consumption compared to a conventional cabinet.

Commercial availability

Adande Refrigeration has developed a cabinet based on short air curtains called "Aircell" which is being proposed as a viable alternative to doors. Aircell works by dividing the case's merchandising envelope into separate air flow managed cells with short, low pressure air column (Aircell, 2022). Each cell has its own air curtain which is more effi-cient than the full height air curtain on a conventional multideck case. The net result is less pressure on the air curtain of each cell and a substantial reduction in cold air spillage from the case (Wood, 2013).

Efficiency

Aircell his claimed to provide similar energy savings (circa 30%) to fitting doors and tighter temperature control than conventional cabinets.

Costs

Aircell claims that the cost for fitting the technology (to a new cabinet) is not expected to be any more expensive than fitting glass doors to a cabinet, with payback times of the order of 2 years.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	24.5-35.9% energy savings and hence emissions savings reported in tests; 30% claimed by Adande
Quality of scope 2 emissions information	M
TRL level	TRL 8-9
Maintainability issues	Unknown at present
Legislative concerns	L
Payback time (years)	2 years claimed by Adande

1.18.51. Store dehumidification

Entrainment or infiltration of ambient air into an open display cabinet account for around 78-81% of the total heat load on the cabinet (ASHRAE, 2002). For ambient temperature of 25 °C and 60% relative humidity (RH) (class 3 BS EN ISO 23953 conditions) around half of the infiltration load is latent. The condensation and subsequent freezing of the moisture removed from the ambient air results in frosting of the evaporator coil. Frosting then reduces the performance of the cabinet by reducing the effectiveness of the evaporator (frost forms a thermally insulating layer) and by reducing the volume of the air circulation (due to increased pressure against fans) which weakens the air curtain and so increases the rate of infiltration of ambient air into the cabinet.

Dehumidification of the ambient air reduces the latent heat load portion of the infiltration load. Work by Howell (Howell, 1993a, Howell, 1993b and Howell et al., 1999) has shown that even after the energy required to dehumidify the ambient air is considered, the energy saving is around 5% for every 5%

reduction in store humidity (based on reduction in store humidity from 55 to 35% or 14 to 7 °C dew point temperature). In the UK dew point varies from about 1 °C in winter to 12 °C in summer. It is therefore applicable to dehumidify UK stores in the summer, but in winter the humidity is already quite low according to thermal comfort requirements.

When determining the ideal store conditions, the comfort of the shopper must be considered. It is likely that drier, warmer air will be more acceptable to shoppers than cooler air (Pursglove, 2013; Tassou and Xiang, 2003; Ndoye, Mousset, Carlier, and Arroyo, 2011). Low humidity can lead to dry skin, irritated sinuses and respiratory tract, and itchy eyes. Over time, low humidity can dry out and inflame the mucous membrane lining your respiratory tract, although it is unlikely that the time spent shopping in a supermarket store will lead to such severe effects. Reducing the dew point to below 2 °C can also result in eye irritation (ASHRAE, 2013).

Fricke and Sharma (2011) investigated the potential energy savings associated with reducing the relative humidity in the vicinity of refrigerated display cases in supermarkets, as compared to the widely accepted current practice of maintaining a relatively high and uniform humidity level throughout the entire supermarket. They showed that when the relative humidity is reduced from 55% to 35%, refrigeration system energy use decreases by 15% to 22 % for medium temperature and 0% to 17% for low temperature refrigeration systems. The defrost cycle could be reduced in the range of 25-50% in case of medium temperature open display cases. Additionally, the anti-sweat heaters could be deactivated at RH value of 35%. The energy savings depends on the temperature level of the refrigeration system and refrigerated case type. The performance improvement because of lower humidity with open display cases is likely to be lower with doored display cases. Adaptive defrosting (or at least a less frequent defrost regime) may be required for the display cabinets to fully realise the potential benefits of store dehumidification (Tassou and Datta, 1999). There are clearly benefits to the refrigeration system in dehumidification throughout the year. However, these benefits may only be practically possible in summer.

Howell (1993a and b) developed a method to relate the RH in supermarkets to the energy performance of open display cabinets. The results indicated that reducing the RH of the supermarket from 55% to 35% reduces the energy demand of open display cabinets by 30%, defrost energy by 60% and anti-sweat heater operation by 70%, but with an increase in HVAC energy consumption by 8%. According to Howell, 1993a, Howell, 1993b and Howell et al., 1999 there should be overall benefits in the UK in the summer months (UK dew point is above 7 °C for approximately 5 months of the year).

Orphelin et al., (1997, 1999) proposed the optimal RH level as 40% for the specific case studied in French context during the summer. Lower RH puts pressure on the HVAC system and is very ineffective in terms of cost, while high RH puts a burden on the refrigeration systems due to defrost. At 25°C ambient temperature a 10% reduction in RH will lead to a 6% reduction in compressor power, however, it becomes 4% at 15°C.

Kosar et at (2005) quantified the savings (in refrigeration) when dehumidification was applied (3–21 % reduction in compressor energy use with a 20 %relative humidity (RH) reduction in the space, a 4–6 % reduction in defrost energy, and a 15-25 % reduction in anti-sweat heater energy)

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence.

Scope 2 emissions savings (% or another quantifiable metric)	4 to 30% reduction in energy consumptions in open display cabinets but with increase of 8% increase in HVAC system.
Quality of scope 2 emissions information	Lack of agreement in literature but some level of quantification of savings achieved were reported.
TRL level	TRL8-9.
Maintainability issues	No issues.
Legislative concerns	No impact.
Payback time (years)	Variable depending on situation.

1.18.52. Store temperature control (increase/decrease set points)

Store temperature will usually be controlled between two values. When the minimum value is reached, heat will be put into the store and when the maximum temperature is reached cooling will be put into the store. The set points may change between night and day and winter and summer and trading and non-trading hours. Reducing the set point minimum value would allow some savings on the refrigeration system because of the lower temperature difference between the ambient and cabinet temperature. However, the thermal comfort of customers' needs to be considered while adjusting the set points values.

Thermal comfort is a human-experienced sensation that occurs as a consequence of a scenario of environmental and personal variables. The environmental variables such as air temperature, mean radiant temperature, relative air velocity and ambient water vapour pressure are within the control of the HVAC system of a store. However, personal variables such as activity level and clothing are not (ASHRAE, 2013). Literature review reported the human thermal comfort and interactions between the subsystems (HVAC and display cabinets set points temperature) in order to investigate the comfort challenge and possible energy savings. In this regard Alfano et al., (2019) investigated thermal global comfort, local discomfort, and cold stress in the supermarket refrigerated areas via surveys in central Italy. The result of the local microclimatic conditions shows air temperature vertical differences of up to 8-9°C between head and ankles for open display cabinets. Due to chilly air stratifications, it was found that local discomfort was one of the biggest challenges for females. Cold aisles near refrigerated cabinets are the most common complaint from shoppers but most remedies for this would result in increased energy consumption of the store. Fitting doors on cabinets does, however, allow both the energy consumption of the cabinets to be reduced and improve customer comfort.

Mylona et al., (2017) investigated the relationship between the building envelope, temperature set points and the subsystems in order to reduce energy consumptions with fitted doors display cabinets. An integrated building/HVAC/refrigeration system model was developed in EnergyPlus for a supermarket in the UK that was calibrated using operational data. Due to the usage of closed frozen food cabinets, the environment was kept at a level where workers and consumers could be comfortable. A significant interdependence between the subsystems smart operations and energy savings was found, with the biggest total store energy reduction of (4%) occurring when the HVAC is only working during trade hours. Further detailed investigation with the model was highly recommended to look into the interaction of subsystems in terms of energy performance, the provision of comfortable interior environments for staff and customers, and the impact on refrigeration system performance.

An updated review study by Lindberg (2020) summarized the complexity due to temperature constraints and interactions between the ambient environment and the display, cabinet and in-store layout design which places a heavy burden on supermarket refrigeration systems. There are reasons to assume that energy efficiency measurements, with regard to both energy efficiency in buildings and energy efficiency in operations, contain difference of opinions on how different barriers should be studied differ. It was concluded that it is necessary to do empirical research that makes use of real data, including field measurements, behavioural research involving lab experiments, and perceptions. A single study cannot give a comprehensive overview of all the connected factors in the topic of consumers' buying situations for chilled groceries because it is so broad and complex.

Assuming store temperature is reduced by 1 °C, the impact on compressor energy based on temperature difference between the cabinet and the ambient conditions (25 °C difference for chillers, 40 °C for freezers) would be 4% for chillers and 2% for freezers. This assumes that the reduction in set-point does not come from air conditioning.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	Effect of reducing store temperature by 1°C (assuming A/C not required) 4% of compressor energy for chiller 2% of compressor energy for freezers
Quality of scope 2 emissions information	Low confidence as it is based on a simplistic calculation.
TRL level	TRL8-9
Maintainability issues	No issues
Legislative concerns	No impact
Payback time (years)	If feasible, paybacks will be very short as only a setting change is required.

1.18.53. Strip curtains

Strip curtains consist of clear, plastic (usually PVC) strips hung over the front of supermarket refrigerated display cabinets, to provide a separation between the cold and warm air and prevent air infiltration. They are quicker and cheaper to install than glass doors, although they are less transparent, and require more maintenance e.g., regular cleaning for hygiene and visibility reasons, and inspection for damage and replacing strips if needed. The grade of PVC selected needs to be appropriate for the temperature at which they are used, and UV stabilisers are used to prevent loss of transparency over time. Condensation can also be problematic and affect visibility under some conditions.

By preventing air infiltration into refrigerated display cabinets, strip curtains can reduce the heat load on the refrigeration system, resulting in energy savings. In general, strip curtains are less effective than glass doors at preventing air infiltration, but more effective than air curtains.

Use of strip curtains in cold stores

Strip curtains are widely used for cold stores, where they maintain a barrier between the inside (cold) air and the warmer outside air, while allowing ready access for e.g., personnel and fork lifts. In studies by Chen et al (1999) and Cleland et al (2015), on the effectiveness of strip curtains in preventing air infiltration through the doors of cold stores it was found that reductions of 85-95% could typically be achieved.

Commercial availability

PVC strip curtains for use in refrigerated display cabinets are commercially available from a number of suppliers. For example, in the UK, these include Redwood PVC (Redwood, 2022), who claim energy and cost savings of 60% when using their strip curtains for a supermarket chiller cabinet at 3°C and suggest payback times of less than 1 year. The cost of a strip curtain of 2.5 m x 1.7 m for a typical size chilled multi-deck cabinet would be £205 in 2022.

Chiller Blinds (2022) also offer PVC strip curtains for supermarket chiller cabinets with claimed energy savings of 50%, while Rayflex Group (2022) also provide top fixing PVC strip chiller blinds for refrigerated cabinets with claimed energy savings of 40%.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	30%-60% energy and cost savings of open fronted display cabinets claimed by commercial suppliers.
Quality of scope 2 emissions information	M
TRL level	TRL 8-9
Maintainability issues	Need to clean strip curtains regularly for hygiene and visibility reasons. Need to renew damaged or aged strips
Legislative concerns	Need to use food grade PVC for the strip curtains
Payback time (years)	1 year suggested by commercial supplier

1.18.54. Suction pressure control

The required suction pressure is not a constant parameter; and will depend on the load demand of the display cabinets. Hence proper suction pressure control is very crucial for the effective operations of the refrigeration systems inside the supermarkets to achieve the balance between the demand and supply. The suction pressure value would normally be set to allow adequate cooling at peak load. During the winter and overnight a higher suction pressure may be acceptable due to lower cooling demand. Increasing the suction pressure will also increase duty time. Compressor power consumption is directly related to pressure ratio, so increasing suction pressure will reduce pressure ratio and therefore compressor power. The compressor operations at higher pressure ratio continuously may degrades its performance due to lubrication issues and hence negatively impact the compressor life. According to typical compressor data from Bitzer (compressor 4NES-14Y-40P with R404A as a refrigerant), raising the evaporating temperature by 4 to 5 °C (typical with suction pressure optimisation) will increase the COP by 11% in chiller and 13% for the freezer.

Approaches used

Various approaches have been adapted to control the suction pressure adequately based on the literature review. Altering the number of compressors in the pack in operations approach is more commonly used. The means by which suction pressure control operates to reduce energy use is by running fewer compressors for shorter periods of the day. This is best done by acting on the pack controller directly. The suction pressure prevailing is compared with the suction pressure set-point value to control the number of compressors in operation. It is possible to vary the set-point according to external factors, such as the external ambient temperature. This can save significant amounts of energy. Sometimes, for convenience, cabinets are connected to systems that are aimed at higher temperatures than that for which the system has been designed and set up. To enable this to be done, mechanical evaporator pressure regulators (EPRs) are used to maintain the higher set pressure to the refrigerated cabinets. However, the pressure drop across the EPR represents a cost. It will be understood that the suction pressure of the compressor needs to be below the pressure of the EPR. One way of implementing suction pressure control is to use an electronic EPR that varies the pressure by using a stepper motor. The suction pressure will be controlled to maintain cabinet temperature rather than fixed suction pressure. This varies the evaporator temperature in the individual cabinet. The different evaporator temperature feeds through to providing a different amount of cooling to the cargo in the cabinet. This type of suction pressure control means that the evaporating pressure (and, therefore temperature) varies independently for each cabinet. The suction pressure provided to the system as a whole (from the refrigeration pack) has to be lower than that required by the "most needy" cabinet. To ensure that this is so, it is done separately for each load (cabinet). Therefore, suction pressure will vary to maintain a constant cabinet temperature. It is necessary for the pack controller to be in communication with the cabinets and to adjust the suction set-point dynamically in operation. This lower pressure will mitigate against overall refrigeration system efficiency. Another way of implementing suction pressure control is to vary the pressure set-point at the compressor pack dynamically without altering valves on the cabinets. The input for the change in the pack pressure set-point can be ambient temperature in the shop or, better, information about the state (i.e. refrigerating, defrosting, recovering from defrost etc.) of and "hunger" of each of the cabinets. The temperatures for each of the cabinets is then controlled by a solenoid valve switching the refrigerant flow on/or off to the evaporator. The literature review reported varying information regarding the energy savings and hence the carbon emissions due to suction pressure control according to the system size, number of packs, low, medium and high temperature packs, locations, and optimization with other technologies. For example, Lawrence et al. (1998) analysed the potential savings of suction pressure optimisation for three climatic conditions, Barcelona (Spain), Birmingham (UK) and Bergen (Norway). They predicted savings from 8.6% for frozen packs in Bergen to 14.7% for chilled packs in Birmingham. Lawrence and Gibson (2009) state that typically suction pressure control saves 15% of pack energy. A study conducted by a supermarket chain (Parker Hannifin Corporation, 2010) showed an 11.4% reduction in energy for the low temperature pack and 1.5% reduction for the medium temperature pack when suction pressure was controlled. A study by California Utilities Statewide Codes and Standards Team, 2013 showed that floating suction pressure was considered cost-effective (based on a Life Cycle Costing Methodology and not just financial cost) for all system configurations and in all climate zones.

Acha et al. (2016) considered a UK supermarket located in south-east with sales area of 3,300 m^2 as a case study to estimate the energy savings with suction pressure control and night blinds optimizations. Other key features of the refrigeration system were a) Transcritical CO_2 refrigerant (R744) booster system utilization with multistage compressors; b) Fully functional night-blinds in all open sales floor cabinets (chilled and frozen); c) Pack suction optimisation enabled in the refrigeration control system. The study reported total energy savings of 17% of compressor over a year via suction pressure control in conjunction with night blinds optimization (7% with suction pressure alone) in contrast to business as usual (BAU). The study reported energy saved/total store electricity use as 7.9% for the blinds plus suction pressure control optimization. A payback period of 3 months was reported for the suction pressure optimization only. The yearly Carbon emission savings was 27.6 tonne per year due to pressure control with a total of 64.1 tonne per year for the Blinds +PO scenario.

The most recent study found, by Liu et al. (2021) was on the performance analysis of a modified dual-ejector and dual-evaporator transcritical CO_2 refrigeration cycle for supermarket application and its impact on the pressure ratios. The authors introduced two ejectors and a flash tank in contrast to the conventional dual evaporator transcritical CO_2 refrigeration cycle. The results showed that the compressor pressure ratio reduced by 19.1%, due to increase in suction pressure at a typical working condition and with the COP improvement in the range of 15.9 to 27.1%. at a range of working conditions.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence (No direct emission savings are assumed)
Scope 2 emissions savings (% or another quantifiable metric)	Limited information is available. One study reported 11.4% in energy for the low temperature pack and 1.5% for medium temperature pack when suction pressure was controlled. It is assumed these savings apply only to remote cabinets. Another study for the pressure control optimization with night blinds reported a total energy savings of 17% per total packs use per year in conjunction in contrast to business as usual (BAU).
Quality of scope 2 emissions information	Savings not robustly quantified with varying information based on the combination with other technologies, cycle and cabinet type used. Most supermarkets do control suction pressure.
TRL level	TRL8-9
Maintainability issues	The suction pressure control via electronic pressure regulators is more accurate in comparison to mechanical regulators, however the stepper motor needs to be checked and replaced regularly.
Legislative concerns	No impact
Payback time (years)	<1 year/3 months reported for optimization with night blinds

1.18.55. Tangential fans

Air flow in retail display cabinets is usually provided by axial fans interspersed across the length of the cabinet. The diameter of the fan is usually bigger than the height of the evaporator, so the fan is angled downwards to allow it to fit. This leads to a very uneven flow onto and through the evaporator.

The small ratio of impeller diameter (30 to 65 mm) to impeller length means that tangential fans are an easy fit within retail display cabinets. The impeller length can cover the full length of the cabinet e.g., 2.5 m and the impeller diameter the height of the evaporator. This leads to a very linear even flow onto the evaporator.

It is claimed that tangential fans can provide more even air flow in cabinets and have been shown to produce overall energy savings of 2% (Faramarzi et al., 2000). The savings are relatively small and are probably related to the slight increase in evaporating temperature that can be achieved if air flow is more uniform.

The use of tangential fans in place of axial fans could reduce the number of motors required and thereby reduce capital cost. A disadvantage of tangential fans may be that they are more difficult to clean in comparison to axial flow fans and the motor at the side can cause them to be difficult to fit in place without restricting the length of the impellers.

Scope 1 emissions savings (% or another quantifiable metric)	0%
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	2% of compressor energy on remotes and integrals
Quality of scope 2 emissions information	Savings not robustly quantified and based on assumptions
TRL level	TRL8-9
Maintainability issues	some problems with cleaning
Legislative concerns	none
Payback time (years)	No information

1.18.56. Thermal store

To cope with the challenges of peak power consumption in refrigeration processes, technology that can provide flexibility to these systems has gained significant interest over the last decade. Cold thermal energy storage (CTES) is a technology that relies on storing thermal energy at a time of low demand for refrigeration and then using this energy at peak hours to help reduce the electricity consumption of the refrigeration system. This could mean a significant reduction in investment costs for the plant owner, as well as reduced operating costs due to limiting the electricity consumption of the plant during the most expensive hours of the day. (Arteconi et al. (2017)).

According to Selvnes et al. (2022), there are two methods of storing thermal energy in a material: By changing the temperature of the material (sensible CTES) or by changing the phase of the material from liquid to solid (latent CTES). A common term for materials where the latent heat capacity is used for the purpose of storing thermal energy is phase change materials (PCM). PCMs are often divided into three groups: eutectic materials, inorganic materials, and organic materials (Mehling &Cabeza, 2008). Phase segregation or separation are the limitations/challenges that occurs in several PCMs, particularly inorganic salt hydrate PCMs (Farid et al., 2021). The primary selection criteria to meet when choosing a PCM for the refrigeration application is a high latent heat capacity and an acceptable phase change temperature (Li et al., 2013). To assess heat transfer and effectively design the heat exchanger (HEX) of the cold thermal energy storage system for improved performance, the thermal conductivity characterization of PCMs is required. The amount of published research integrating cold thermal energy storage in various food cold chain components employing water-salt solutions and paraffin PCM in both active and passive approaches has increased over the past ten years (Selvnes, et al., 2021).

Selvnes et al. (2022) stated that the main benefit of PCMs related to CTES for refrigeration systems is the possibility to store and release thermal energy at a constant temperature, which matches the process in the refrigeration system very well. PCMs have become an emerging product on the market, and PCMs with a phase change temperature down to -40 °C are available. Their paper presented the design and thorough experimental performance testing of a CTES unit based on a pillow plate heat exchanger with a low-temperature commercial PCM as the storage medium. The results from the experimental testing have demonstrated the feasibility of using the CTES unit with PCM for peak shifting of the refrigeration load. The charging time of the CTES unit was mainly affected by reducing the CO_2 evaporation temperature, effectively increasing the temperature difference between the CO_2 refrigerant and the phase change temperature of the PCM. Decreasing the $T_{CO_2,evap}$ from −13 ◦C to −15.5 ◦C yielded a reduction in the charging time by 44% for δo = 30 mm. Moreover, the flexible design of the CTES unit allows the designer to select a discharge characteristic of the CTES unit that matches the refrigeration load curve of the refrigeration plant by changing the plate pitch.

Ballot-Miguet et al. (2019) stated that one of the outcomes was the completion of several demonstration projects in the US, Canada and Japan where CTES technology was implemented in large chillers for air-conditioning systems. The principle was storing cold energy in large cold-water tanks or tanks filled with ice to serve the cooling demand during peak summer periods where extra refrigeration capacity was needed, and the supply of electricity was limited and expensive. A glycol solution was circulated in tubes inside the tanks to transfer the heat to and from the storage and the refrigeration system. They also reported the performance of a 500 kWh-capacity CTES unit integrated into a glycol circuit for medium temperature cooling purposes in a supermarket CO2 refrigeration system. The CTES unit was installed in a supermarket in France and operated as a subcooler for the refrigeration system during high ambient temperatures to improve its performance, reducing the annual electricity consumption by 6%.

According to Arteconi et al. (2017), as far as cold applications are concerned, a cold thermal energy storage (CTES) is typically coupled to a chiller for air conditioning. It can be a thermally stratified chilled water storage or an ice storage. The purpose of using a TES is to improve refrigeration equipment efficiency, reduce the installed capacity, increase the operational flexibility and reduce energy costs: cold is produced during off-peak periods and used during on-peak periods. Typical operational strategies of such systems are full storage and partial storage strategies. A full storage strategy shifts the entire peak cooling load to off-peak hours. In a partial storage strategy, the load is partially supplied by the thermal storage and partially by the refrigeration unit. The chiller can be designed to operate as load levelling or demand limiting. Partial storage is the most used configuration because of lower initial capital costs. It saves about 40-60% of peak cooling electricity demand. Full storage is interesting for short peak periods with very high costs for electricity production. The peak electricity demand can be reduced up to 80-90%.

Referring to Bush et al. (2018), Fidorra et al. (2016) provided an overview of four possible configurations. In Layout #1, a dedicated medium-temperature evaporator can be used to cool a storage medium, which may later be used for subcooling. This has the advantage of being internal to the cycle. A TRNSYS model of such a concept was explored by Polzot et al. (2015), who considered a water tank as the storage medium. Layout #2 shows storage integrated in the MT level load such as by a PCM inside display cabinets; a similar concept was explored by Waschull et al. (2014). In Layout #3, storage is used to cool the receiver liquid outlet to the evaporators, to reduce the required mass flow for a given cooling capacity. In Layout #4, a storage medium upstream of the receiver inlet can be charged or discharged by adjusting the refrigerant pressure passing through the storage medium. Lowering the pressure boils some refrigerant to charge the storage media; increasing the pressure to a point where the saturation temperature is warmer than the storage temperature in turn allows the refrigerant to be cooled by the storage medium.

Fidorra et al. identified the above storage approaches and evaluated them through steady state thermodynamic analysis. The researchers found Layout #1 to have high demand reduction potential, with relatively small hardware required; a large temperature difference leads to relatively low efficiency though. Layout #2 was also assessed to have high potential for peak reduction, but sizing and deployment of the storage material is challenging. In Layout #3, small temperature differences mean that large heat exchangers are needed, and the total reduction potential is comparatively small. In Layout #4, there are no new heat exchangers required other than the storage itself; however, the temperature difference between charging and discharging is small which may present heat transfer challenges. Research gaps in the areas of detailed simulation models and transient simulations were identified. In addition, the work of Fidorra does not examine the opportunity to use external sources (such as a dedicated cooling unit) for storage; there may be an opportunity for improved efficiency from dedicated cooling equipment.

According to Selvnes et al. (2022), CTES pilot installation are also currently being discussed for the dairy industry and in supermarket refrigeration systems. The experience gained from field tests will be important for the stakeholders in the industry to gain confidence in CTES technology, demonstrating the potential of the technology and ensuring further implementation across multiple sectors. The planned future studies on the technology are the development and validation of a dynamic numerical model to investigate the impact of integrating CTES technology into a complete refrigeration plant. Furthermore, it is relevant to investigate any performance degradation of the CTES unit over time, as well as partial charging and discharging cycles.

According to the studied literature, there are two ways to integrate PCM storage units into display cabinets: directly into the shelves of the cabinet, or by installing a PCM-HEX unit in the air circulation duct. A PCM-shelf-based design with heat pipes has been demonstrated to be an effective method for reducing product temperature fluctuations of up to 83.3% (Wu, et al., 2017). The drawbacks when PCM and heat pipes are added to the PCM shelf design are that the shelf become significantly heavier and may need the shelf support to be reinforced. Even with water acting as the PCM in the shelves, food may still be harmed in the event of a PCM leak. However, the more common application was the integration of a PCM-HEX unit in the cabinet's main duct for air circulation. This might be due to the fact that these PCM-HEX units are quicker to install, more technically feasible, and require fewer alterations to the display cabinet itself. An energy savings of up to 5% were obtained using water as a nucleating agent (with a melting temperature of -2°C and radiator- HEX), with a reduction of peak display cabinet temperature by 2K during defrosting period, and a 27% reduction of compressor ON/OFF cycling (Alzuwaid, et al., 2015; Alzuwaid, et al., 2016). Similarly, another study reported a reduction in maximum cabinet temperature of 1K using water/ice PCM with Fin tube -HEX configurations (Ben-Abdallah et al., 2019). New concepts for PCM-HEX unit designs are proposed and developed, allowing the display cabinet to be separated from the primary refrigeration system during the process of releasing the storage (Jokiel, et al., 2019; Manescu, et al., 2017). Each cabinet could work independently having the ability to meet its entire refrigeration demand during the discharge process with this type of PCM-HEX. To demonstrate the viability of these concepts, however, experimental validation must be done.

The second method for integrating thermal energy storage in supermarkets is centralised storage into the central refrigeration circuit. Despite the fact that extensive research was done in this area, with most of the reported work has only used analytical methods. Therefore, experimental studies are required to demonstrate the overall system performance and reliability. The integration of a coil-in-tank laten heat storage with ice serving as the storage medium with CO_2 refrigerated system between the high-pressure control valve and the liquid receiver was suggested by Heerup and Green, (2014). The storage integration's goal was to reduce energy use and costs utilizing the shift in refrigeration load from day to night, as well as the benefiting from the ambient temperature conditions and electricity cost. A total energy reduction of 14.4 % with a peak compressor power reduction of 50% was reported. The payback period was found to be greater than five years. Similarly, Fidorra, et al., (2015) presented two distinct setups for integrating thermal energy storage into a transcritical CO_2 booster refrigeration system with parallel compression. The findings shows that daily energy consumption reductions of up to 3.5% and 5.6% could be obtained depending on the system layout, with a reduction of 15% of maximum compressor power consumptions. However, there is currently a lack of experimental data to support this research.

Scope 1 emissions savings (% or another quantifiable metric)	No information available
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	Up to 5% with display cabinet 4-14.4 % (depending on the climatic conditions) with the main refrigeration system itself
Quality of scope 2 emissions information	High confidence with display cabinets Medium confidence with refrigeration system
TRL level	TRL8-9 with the display cabinets TRL1-4 with the refrigeration system
Maintainability issues	Replacement of the PCM may be needed
Legislative concerns	n/a
Payback time (years)	More than 5 years

1.18.57. Thermostatic flow control (TFC)

Thermostatic Flow Control (TFC) is a flooded evaporator technology, applicable for capillary-based refrigeration systems, excluding refrigerants with large temperature glide (Zimmermann, 2008). Two capillary tubes and a tube form receiver make up a thermostatic flow controller that is thermally connected to the suction line (Figure 38). It creates a strong, hermetic closed device that needs no maintenance or modification and is therefore suitable for deployment in inaccessible areas, such as when enclosed in isolation foam. The pressure in the receiver—which is controlled by the need for refrigerant in the evaporator—determines how much refrigerant flows to the evaporator. This equilibrium makes sure that the evaporator is flooded and hence fully utilised for all types of charges. It takes the place of the conventional capillary tube for a tiny additional cost (according to the inventor), improves the performance of these devices in both cold and warm environments, and simplifies manufacture because the volume of refrigerant is no longer as important as it is for conventional capillary tubes. The circuit often used for small freezers and refrigerators is generally depicted in Figure 1. The pressure drop between the condenser and evaporator is shared between the two steps, and the receiver pressure is controlled by the difference between gas supplied and gas removed (Evans, 2015). If the heat exchanger removes more gas than supplied by the first throttling step, then the receiver pressure goes down – otherwise the receiver pressure goes up. According to the patent, it is possible to ensure the evaporator is always flooded, though the authors could find no independent evidence for this.

The primary benefits of this system are the improved system efficiency as in any flooded evaporator system (see section on flooded evaporators). The secondary benefit is that this is done without either a pump or a gravity head and float valve allowing it to be economic for smaller systems.

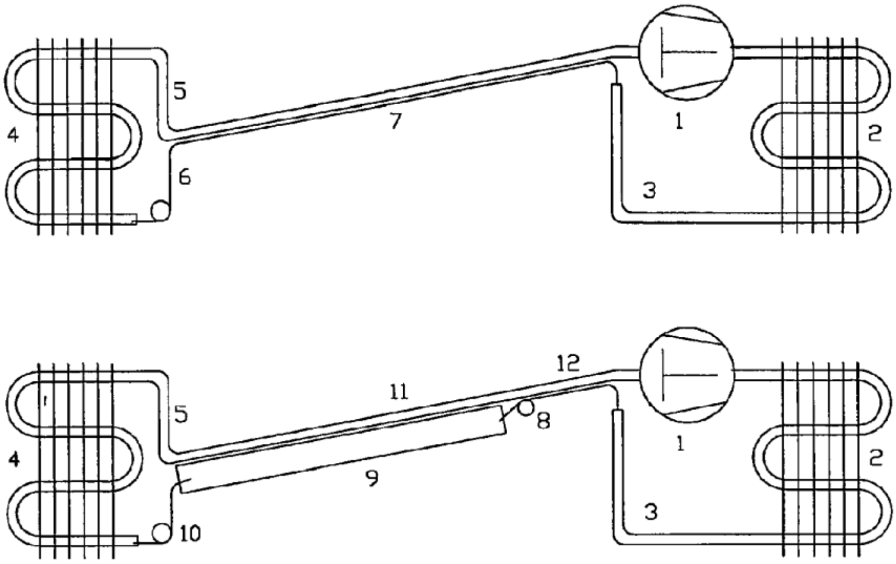

Figure 38. TFC concept (upper diagram conventional capillary system, lower diagram TFC system) Zimmermann, 2008

1: compressor. 2: condenser, 3: liquid line, 4: evaporator, 5: suction line, 6: capillary tube, 7: thermal contact between capillary tube and Suction line, 8: capillary tube, 9: receiver, 10: capillary tube, 11: thermal contact between receiver and suction line, 12: thermal contact between capillary tube and suction line.

Scope 1 emissions savings (% or another quantifiable metric)	Flooded evaporators use more refrigerant so direct emissions would be higher.
Quality of scope 1 emissions information	High confidence
Scope 2 emissions savings (% or another quantifiable metric)	Unknown
Quality of scope 2 emissions information	n/a
TRL level	TRL1-4
Maintainability issues	Unknown

Legislative concerns	Could be an issue in near future due to more refrigerant
Payback time (years)	Unknown

1.18.58. Training and maintenance

Poor cabinet loading, excessively cold set-points, and misuse of features such as night blinds or night set back all lead to increased energy consumption and risk damage to (or reduced quality of) the stored product.

Maintenance staff can cause a significant increase in energy usage through misguided adjustment of set-points or poor commissioning. Every degree warmer the condensing temperature is set, or degree cooler the evaporating temperature is set, will result in a 2 to 4% increase in energy consumption (Action Energy, 2003). Similar losses occur because of dirt/debris build up on condensers as this also increases the condensing temperature. Fennelly (2014) states that dirty condensers are the biggest single reason for non-scheduled service calls.

Electric defrosts on frozen cabinets are only about 15% efficient (85% overhead) (Lawrence and Evans, 2008) and so significant energy wastage can result from an overly cautious defrost schedule. Conversely, excessive frosting of the evaporator reduces the efficiency of the system and can, by reducing air flow within the cabinet, lead to poor product temperature control and increased heat loads through infiltration.

On cabinets with doors, the seals should be inspected, cleaned, and replaced where necessary. A leaking door seal will increase the heat load on a cabinet, increasing the energy consumption and leading to poor stored product temperature control.

Options to reduce energy consumption through training are vast and include better training of staff when using the cabinets, better training of refrigeration engineers, better design of supermarkets and training of cabinet manufacturers to develop more energy efficient cabinets. Therefore, it is difficult to exactly quantify savings. Many options are included in other sections (e.g., defrosting, settings, store operation). Based on the information available, it has been assumed that savings cannot be quantified.

Limited information is available on refrigerant loss reductions through better maintenance. Historical evidence from supermarkets has shown that refrigerant losses can be reduced by around 15% by better maintenance but there is little published evidence to corroborate this. Francis et al., (2017) investigated refrigerant leakage withing two supermarket chains in UK, while analysing 1464 maintenance records. Above 82% of the recorded leakages were mainly due to pipe or joint failures or seal leakage in compressor pack and liquid line. The study highly recommended improvement in design, installations and maintenance of pipework's to reduce the refrigerant leakage.

Scope 1 emissions savings (% or another quantifiable metric)	No published evidence
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	No quantified evidence of savings with poor information in the literature
Quality of scope 2 emissions information	n/a

TRL level	TRL8-9
Maintainability issues	No issues
Legislative concerns	No impact
Payback time (years)	n/a

1.18.59. Trigeneration

Trigeneration (otherwise known as Combined Cooling Heat and Power, CCHP) is the production of cooling, heat and electrical power in one combined process. Typically, this is based on oil or gas fired generators which produce electricity, and in the process generate heat. The heat can be used directly e.g., for hot water or space heating, but it can also be used as required by an absorption chiller (or more rarely an adsorption chiller or a desiccant cooling system) to produce cooling. The proportions of electrical power, heat and cooling can be varied depending on demand. Sources of waste heat and renewables such as biogas can also be usefully exploited in trigeneration systems.

There has been considerable research on trigeneration systems and their performance, summarised in several comprehensive review papers (Cho, Smith and Mago, 2014; Jradi and Riffat, 2014; Liu, Shi and Fang, 2014; Deng, Wang and Han, 2011; Wu and Wang, 2006). The primary generators include internal combustion engines and gas turbines and, with continuing research, fuel cells, Rankine cycles and Stirling engines also show promise. The strategy chosen for operation of trigeneration systems is critical to their efficiency (see, for example, Jradi and Riffat, 2014), with options being to follow thermal load, follow electrical load or to optimise a combined strategy.

Supermarkets have heating, cooling, and electrical consumptions simultaneously. These could be supplied together with energy savings without modification to the refrigeration cycle. Heat recovery systems were reported as one of the most interesting options from an economic and energetic point of view by Fricke (2011). The use of trigeneration specifically for supermarket applications has also been researched. Trigeneration was found as an interesting option in supermarkets which produce energy and carbon emission savings (as detailed in the paragraphs below), especially with CO_2 as a working fluid (Mota-Babiloni et al., 2015). Maidment et al. (1999) theoretically assessed the performance of a CHP system used to supply heat and power to a relatively small UK supermarket. In the standard application, a vapour compression system was used to supply display cabinet cooling, but the addition of absorption cooling driven by waste heat from the CHP system was also assessed. The absorption cooler supplied glycol at -10 °C, and this was used to cool the chilled display cabinets. Primary energy savings of 20% and a payback period of 6 years were estimated. Extending the use of the absorption system to supply the frozen cabinets was found to be impractical. In further work (Maidment and Tozer, 2002), various CCHP configurations and CHP engine sizes were modelled and compared with conventional supermarket energy performance. The optimum configuration was found to be a lithium bromide / water absorption system for chilled water between 7 and 14 °C (the cabinets cooled by cascade vapour compression system in the cabinet), and variation in payback versus engine size for the various configurations was presented for the supermarket considered.

Marimon et al. (2011) compared various configurations of ammonia / water absorption based CCHP systems with two commercial water chillers and an indirect cascaded refrigeration system in low and medium temperature cabinets in a supermarket. It was found that all had payback periods of less than 6 years with lowest payback period of 4.6 years and carbon emission savings of approximately 22.7

tons per year. As in other studies, the authors stressed the impact on such analyses of the price differential between electricity and gas and of energy subsidies.

Micro gas turbine (MGT) based trigeneration systems for supermarkets were modelled by Sugiartha et al. (2009), who found energy and emissions benefits compared with conventional supermarket systems. Operation in a full electrical output mode was found to be preferable to a heat-load following strategy. Payback periods were shown to reduce as the price differential between electricity and gas increased. For an MGT setup with an absorption COP of 0.5 operated on full electrical mode, a payback period of 5.7 years was found. The alternative of using the absorption cooling for space cooling was found by Ge et al., (2013) to also show promise in an MGT-based CHP plant integrated with CO_2 refrigeration. In a MGT system configuration when used for power generation, space cooling, and heating with exhaust heat recovery instead of refrigeration effect generates more than 90% of the required electrical power by consuming much more gas to meet the space heating and cooling demands (Ge et al., 2013). However, there is a residual of 1,354,283 kWh_{th} of heat capacity left due to a lessened cooling demand during the summer. Availability and uptake of trigeneration systems has improved in recent years, but further development and experience in operation are still required before more widespread adoption. Availability and uptake of trigeneration systems has improved in recent years, but further development and experience in operation are still required before more widespread adoption.

Several more recent studies have looked at integrating trigeneration with carbon dioxide (CO_2) refrigeration systems. Suamir, Tassou and Marriott (2012) proposed using the cooling generated by the trigeneration system to condense the CO_2 refrigerant in a cascade arrangement. Cooling produced by trigeneration systems ensure subcritical operation throughout the year condensing CO_2 fluid (Suamir et al., 2012). This ensured that the CO_2 refrigerant was maintained in subcritical conditions at all times. Using an electric to gas price ratio of 3.6, a payback period of just over 3 years was found compared to conventional systems, with energy savings of 30% and greenhouse gas emission savings of 43%. Options for such systems were further explored in Suamir and Tassou (2013). Trigeneration supermarket studies using CO_2 as working fluid of the refrigeration cycle are very common. Suamir and Tassou (2013) modelled supermarket conventional and integrated CO_2 refrigeration and trigeneration energy systems. Trigeneration provides fuel energy and CO_2 emission savings of around 30% and 43% respectively (over the conventional system), with a 3.2 year payback period. An updated study by Lykas et al., (2022) investigated the optimization of a solar driven polygeneration system with CO_2 as a working fluid for the supermarkets aiming at refrigeration, electricity, and heating. The final results show that annual energy and exergy efficiency was 67.8%, and 10.1% respectively with payback period of 7.55 years. Chatzopoulou et al., (2017) reported a feasibility study of an absorption chiller (ammonia-water based system) integrated with a CHP unit in a typical distribution centre from an economic point of view for. A comparative analysis with conventional grid connected systems; a Trigeneration; and a CHP system were conducted. The results show that trigeneration based system is more effective and saved 16% of electricity demand, and 48% energy cost per annum in comparison to the conventional grid connected system. It was found that for the integrated system, energy and cost savings are strongly linked to the energy intensity of the building.

Scope 1 emissions savings (% or another quantifiable metric)	If the remote chiller packs were replaced with a secondary absorption system, it is assumed that there are no direct emissions with this system, as ammonia has a GWP of 0 and this results in 100% savings.

Quality of scope 1 emissions information	Lower confidence and based on theoretical analysis
Scope 2 emissions savings (% or another quantifiable metric)	Based on theoretical results, the possibility of using waste heat from a CHP system to cool chiller packs using an absorption chiller. It was assumed that there is enough waste heat to do this, and this heat would otherwise be wasted, and that grid waste heat is also wasted. With these assumptions, 100% of the remote chiller refrigeration power would be saved.
Quality of scope 2 emissions information	Lower confidence and based on theoretical analysis and depend on the availability of enough waste heat
TRL level	TRL5-7
Maintainability issues	Unknown
Legislative concerns	No impact
Payback time (years)	4.6 years at best with ammonia / water absorption based CCHP systems

1.18.60. Two stage compression

Operating the compressor over a large pressure ratio (high condensing temperature and low evaporating temperature) can require an intermediate pressure step to avoid discharge line temperatures becoming too high. High discharge line temperatures can cause both the refrigerant and oil to decompose, and the system performance degrades. The conventional two-stage cycle-based refrigeration system uses the same components as the conventional single-stage cycle but with two compressors, one for low stage compression and another one for high stage compression. The low stage compressors lift the pressure and temperature from evaporating to an intermediate temperature and pressure values while the high stage compression is to obtain the condenser temperature and pressure. However, the system is expensive in terms of energy consumption if there is no intermediate control strategy for pressure and temperature. Intercooling between the stages reduces the compressor discharge temperature and improves the system COP as well and this has been analysed experimentally and numerically with the optimized intermediate pressure as an important variable for the performance improvement. Three well established approaches for the two stages compression have been reported in the literature and discussed in the following:

- Flash vessel. By separating flash gas from an intermediate receiver and injecting it between the compressor stages, the discharge temperature can be reduced. The liquid from the intermediate receiver that enters the evaporator is at a lower enthalpy and vapour quality than it would have been if expanded in one stage, therefore increasing the capacity of the compressor and the system COP. In addition, compression in the high-stage compressors occurs closer to the two-phase region with lower specific work required. The flash tank approach was investigated by Khan & Zubair (1998), Nikolaidis & Probert (1998) and Torrella et al (2009). Mancuhan, E. (2019) reported a theoretical analysis with flash intercooling using different refrigerants (R717, R134a, R152a and R290, R404A, R507) by finding the optimum operating parameters. The results indicated that R290 has better performance than the R404A and R507A systems in terms of COP with a value of 1.81 at evaporating and condensing temperature of −35 °C and 40 °C respectively. R717 was found to have the highest COP of 2.65 relative to R134a and R152a at evaporating and condensing temperature of -20 °C and 40 °C respectively.

- Direct liquid injection. The direct injection approach was investigated by Torrella et al. (2009) & Cabello et al (2010). This approach uses two stage compression and two stage expansion. A portion of the liquid leaving the condenser is expanded to the intermediate pressure and temperature and is injected into the suction of the high stage compression. As a two-phase refrigerant, the enthalpy and so temperature of the low stage compression discharge is greatly reduced and so has the effect of reducing the enthalpy and again temperature of the high stage compression discharge. A suitable compressor must be selected as there is a higher risk of two-phase refrigerant in the high stage compression suction line.
- Subcooler. Alternatively, liquid from the high pressure condenser is expanded through a heat exchanger which subcools the high-pressure liquid from the condenser, therefore increasing the capacity and COP of the system. The expanded refrigerant from the heat exchanger is injected between the compressor stages, reducing discharge temperature. Use of a subcooler has been investigated by Kauffeld (2016), Torrella et al., (2009, 2010), Roytta et al., (2009), Cecchinato et al., (2009), Cabello et al., (2010) and Turunen-Saaresti et al., (2010).

The schematic diagram for the three two stage compression approaches (the flash vessel, direct injection, and subcooler) discussed above is illustrated in Figure 39. The three approaches were analysed experimentally by Torrella et al (2009) and Cabello et al (2010) by varying condenser pressure with constant evaporating pressure and varying evaporating pressure with constant condensing pressure. The COPs, total resultant pressure ratios, and intermediate pressure were experimentally established. The increase in condensing pressure causes the total pressure ratio to increase which results in lower COP values due the work input increase. The results show that for the subcooler configuration an increase in average COP value of 28% and 10% were obtained in comparison to flash vessel, and direct injection systems.

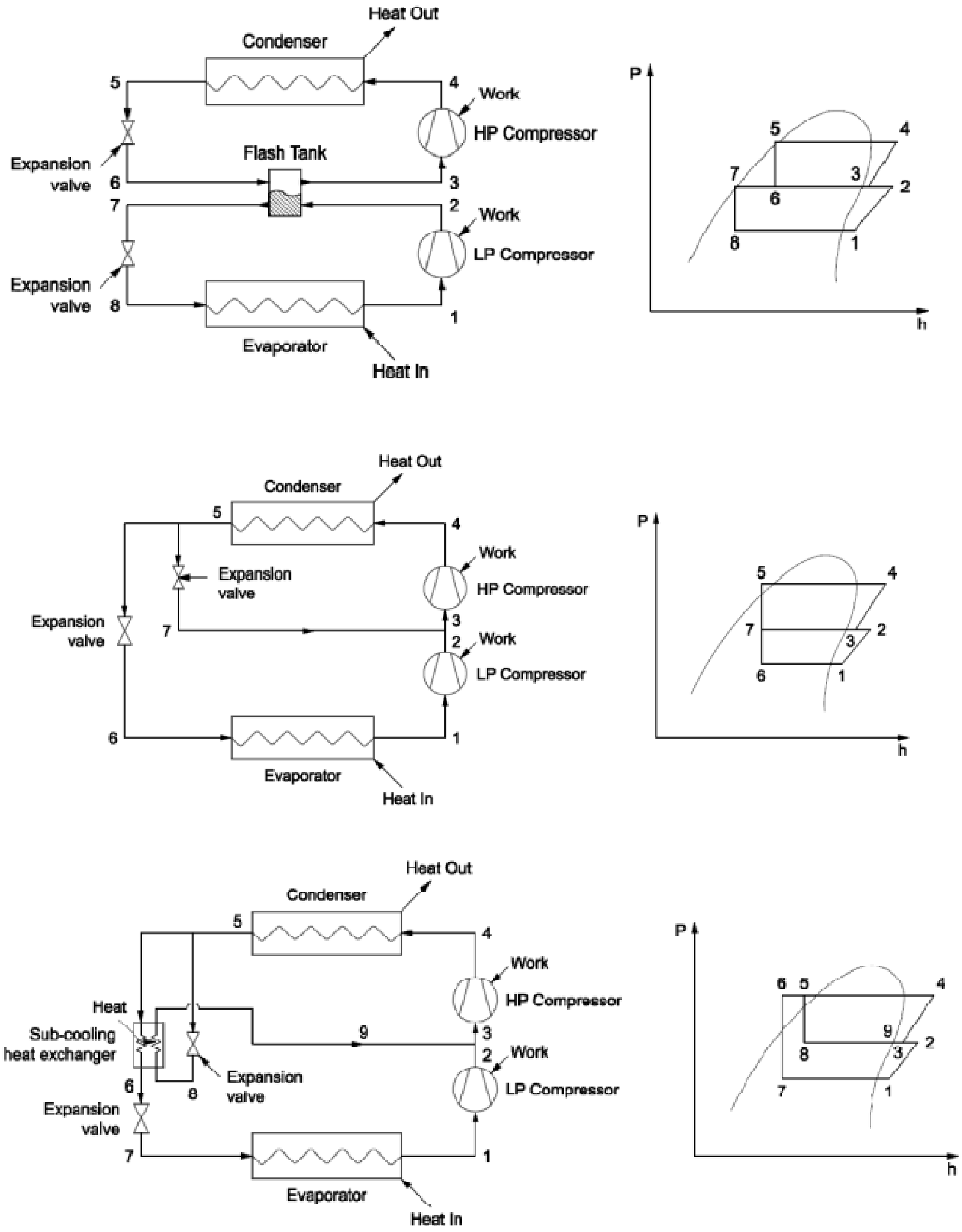

Figure 39. Three two-stage system configurations [Torrella et al (2009)].

Cecchinato et al (2009) investigated two stage cycles using CO_2 as the working fluid. Torella et al. (2010) conducted a second law analysis based on experimental data of a two-stage vapour compression (R404A) facility driven by a compound compressor for medium and low-capacity refrigeration applications (between -36 °C and -20 °C evaporating temperature). They showed that a subcooler gave the best COP. Direct liquid injection gave a lower COP without an optimized intermediate pressure value. Depending on the refrigerant used, energy savings of the order of 10% might be achieved in conventional systems with a subcooler (Kauffeld, 2016). For supermarkets the main benefits of two-stage systems are for R744 (where most of the research has been concentrated). However, when working below evaporating temperatures of about -30 °C, discharge temperatures can also be high for R404A systems; therefore two-stage systems have the same advantages as for R744 systems due to the high discharge temperatures. A dedicated subcooler could be used to increase the cooling capacity and COP value as well. (Qureshi et al., 2013; Mota-Babiloni et al., 2015).

High discharge temperatures can be a problem with transcritical R744 cycles. For freezer racks, compressor exit temperatures of 120–150 °C will be encountered even under isentropic compression conditions (Srinivasan, 2011). Girotto et al., (2004) reported discharge temperatures as high as 200 °C for single-stage compression, and with two-stage compression with inter-stage cooling, discharge temperatures below 140 °C (which is commonly considered an acceptable value for the CO_2 compressor). According to Srinivasan (2011) the benefits with the two-stage compression that are derived as a result are:

a) Operating each stage with a high volumetric efficiency.
b) Reduction of leakage across the piston rings.
c) Increase in isentropic efficiency of each stage.
d) Reduction of discharge gas temperature.
e) Abatement of problems associated with lubricating oils.
f) Reduction in compressor work.

However, these benefits need to be balanced against:

An increase in the number of cylinders and the motors and the need for an additional heat exchanger for sub-cooling and associated increase in costs.

Much of the research is theoretical and is very dependent on refrigeration system design and many supermarket R744 systems are booster systems (see: Refrigerant – Carbon dioxide (CO2, R744)). Sawalha (2008) used a computer simulation model of a centralised CO_2 transcritical system with accumulation tank. Using two-stage compression in the centralised system solution instead of single-stage resulted in a total COP that was about 5–22% higher than that of the reference centralised system. The research showed that the two-stage system can be applied to the high-pressure circuit of the booster system, whilst the low-pressure circuit remains unchanged. Almeida & Barbosa (2011) conducted a theoretical analysis of a two-stage transcritical cooling cycle using R744 as a refrigerant. They predicted that performance of the two-stage cycle was superior to that of the single-stage system by 15%. When the intercooler operated at about the geometric mean of the evaporating and condensing pressures, compared to the single-stage cycle, the coefficient of performance (COP) of the two-stage cycle is improved. Huff et al., (2014) theoretically investigated three two-stage cycle options for the CO_2 cycle. They claimed that a two–stage split cycle outperformed all other options and showed a 38-63% performance improvement over the basic single-stage cycle. Baomin et al. (2022) proposed a multi-stage dedicated mechanical subcooler integrated with R744 booster supermarket refrigeration system in different climate regions of China. Results indicated that the COP improvement of the three-stage dedicated mechanical subcooling system was in the range of 1.12–28.84% compared to the baseline system at an ambient temperature of 0–40 ◦C, and results in lower discharge pressure.

Scope 1 emissions savings (% or another quantifiable metric)	Can result increase in emissions due to more circuits, however this is difficult to quantify, and no clear values are reported
Quality of scope 1 emissions information	Based on assumptions and could not be quantified based on results
Scope 2 emissions savings (% or another quantifiable metric)	The performance improvement strongly depends on the approach used for the two-stage compression process and the refrigerant type used. The literature review reported possible improvements in the range of 5-22% for R744 in supermarkets. An energy saving of 27% for R404A based system and 20% for R134a based system in contrast to basic refrigeration system configurations was reported by introduction of the

	optimal subcooling. The COP value for R290 was higher than R507A, and R404A by 5.2% and 8.3% respectively.
Quality of scope 2 emissions information	Medium
TRL level	TRL8-9
Maintainability issues	Depending the on the two-stage compression approach – extra maintenance of the additional components will be required
Legislative concerns	None
Payback time (years)	Unknown

1.18.61. Vacuum insulated panels (VIP)

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.

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. 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).

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

The thermal conductivity of VIPs is around one fifth of that of the polyurethane foam typically used. So, for a given thickness of wall, the heat gain through the walls could be reduced by as much as 80%. However, 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.

Energy savings can be made but unless space is of a high value, the additional cost of the VIP is unlikely to be justified alongside the option of adding more PU foam. Paybacks demand on howe 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.

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)	80% of heat gain through walls
Quality of scope 2 emissions information	Medium
TRL level	5-7
Maintainability issues	Need to maintain membrane seal
Legislative concerns	None
Payback time (years)	Depends on application, 1.4-12 years

1.18.62. Variable Speed drives (VSDs)

Most motors are designed to rotate at a set fixed speed based on the number of magnetic poles built into them and the supply voltage and frequency applied. Variable speed drives (VSDs) provide effective speed control of AC motors by manipulating voltage and frequency. VSDs save energy by reducing the work output of a motor driven system to match the demand through speed reduction.

In a retail refrigeration system, VSDs can be used to drive the compressors or condenser fans. How much energy can be saved depends on the type of motor. Refrigeration compressors used in retail refrigeration such as reciprocating compressors are positive displacement devices and have a constant torque requirement irrespective of speed. Therefore, the shaft power is determined by the operating conditions (pressure difference) and flow rate, which both effect torque. In general, a reduction in 50% speed would provide a proportional 50% reduction in shaft power. For fans the variable torque characteristic of the fan means that the relationship between flow and speed of the fan is such that the input power reduces in a cube law relationship with the speed reduction.

Overall benefits in terms of energy consumption will only be seen if the increased efficiency of running continually at low speeds compared to running at high speeds and cycling on and off are greater than the efficiency loss of the inverter/drive. VSDs are typically 92-98% efficient (https://www.dalroad.com/wp-content/uploads/2016/03/Variable-Speed-Drives2.pdf).

It is intuitive that reducing the speed of a motor will reduce frictional losses and wear and tear on seals and bearings. However, cooling, and, where applicable, lubrication must be maintained. Cooling is often provided by a fan attached to the motor, and if the speed is reduced, the cooling provided may reduce with speed at a faster rate than the heat generation; this will cause the motor to overheat and fail prematurely. Similarly, where a lubrication mechanism is driven by the motor, lubrication may fail with a reduction in speed.

Retrofitting an inverter drive to an unsuitable motor can lead to (ICE-E, 2012):

- Bearing failures.
- Increased operating temperatures of the core and windings.
- Increased vibrations (supporting structures and mountings should not have resonant frequencies lower than normal operating frequencies).
- Increased operating temperature due to reduced heat dissipation to surroundings.

- Harmonics generated through electric supply.

Many compressor packs for remote systems will already come with VSDs. However, VSDs can often be retrofitted to existing motors. Evaluation of motors and load requirements should be conducted to see where this is feasible.

For most days the refrigeration system does not need to operate at full capacity. A VSD will allow condenser fans to operate at the appropriate speed, which produces a significant reduction in energy consumed. As stated earlier for fans, the energy use is roughly proportional to the cube of the fan speed. Operating at variable speeds will also reduce the frequency of on/off cycling that accompanies full speed operation under partial load, an effect that will reduce the wear and tear on the system.

https://slipstreaminc.org/sites/default/files/documents/publications/vfd-condenser-fan-pilot-project-final-report-public-20191009_0.pdf retrofitted VSDs on condenser fans in 4 supermarkets. Savings varied across stores and condensers. Of the 14 condensers analysed, only one used more energy. Mean annual energy savings were 50%. This equated to an average energy savings per fan horsepower of 1,480 kWh/hp. The average annual dollars saved per horsepower was $150 and the total cost of installation per horsepower was $1,170. Giving a payback time of 7.8 years.

According to https://www.nrel.gov/docs/fy13osti/54243.pdf installing VSDs on condenser fans for the refrigeration system are important measures that should be considered for all retrofit energy efficiency projects. However, adding a VSD on the chiller compressor is a lower priority measures considered less likely to be cost effective or to save a significant amount of energy in most grocery store.

https://singh360.com/resources/article/vfd-drive-refrigeration-systems/ quote a payback of 2 to 3 years for condensers and 1.5 to 5 years for compressors.

Scope 1 emissions savings (% or another quantifiable metric)	None
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	Condensers – 50% Compresses – no reliable data
Quality of scope 2 emissions information	M
TRL level	TRL8-9
Maintainability issues	Potentially increases reliability.
Legislative concerns	None
Payback time (years)	Condensers 2 to 7.8 years. Compressors 1.5 to 5 years.

1.18.63. Water loop systems

Medium and large sized supermarkets generally use a centralised refrigeration system (or refrigeration pack), which circulates refrigerant to the chilled and freezer display cabinets, with the heat absorbed being discharged (from the refrigerant) to the outside air using air cooled condensers sited on the building roof. These systems use a large charge of refrigerant and there are many joints and connectors providing many opportunities for leakage within the system. Leakage rates are therefore high e.g., typically 17% of charge per annum (Accuvio, 2017). In contrast, standalone (integral) refrigerated cabinets (as typically used in smaller supermarkets) require much lower refrigerant charges, and have much lower leakage rates, typically 1.5% per annum (Accuvio, 2017). However, integral cabinets typically use air cooled condensers, with the condenser heat rejected within the supermarket, potentially leading to a large heat gain for the store. One approach to overcoming this problem is to use water cooled condensers e.g., in the form of plate heat exchangers, for each cabinet, with the heat rejected to a water loop. The heat is then transported to externally located water chillers or dry coolers. Some of the rejected heat may be recovered and returned to the store to provide space heating.

Bagarella et al (2014) compared the performance of a series of cabinets with integral refrigeration systems and water loop cooled condensers, with two conventional multiplex i.e. centralised refrigeration systems for supermarkets. They found that providing a variable speed compressor was used to enable capacity control at part load, energy savings of up to 15.8% for the integral refrigerated cabinets compared to a fixed suction pressure multiplex refrigeration system, and up to 8.1% compared to a floating suction pressure multiplex system, were achieved. They also noted that significant reductions in CO_2e emissions could be achieved for the integral refrigerated cabinets, with a reduced 15 year total equivalent warming impact (TEWI) of 56-58%. This was considered to be mainly due to the large reductions in refrigerant charge and low annual refrigerant leakage rate for the water cooled integrated refrigeration system.

Another advantage of using standalone integral refrigerated cabinets is that hydrocarbons (HCs) can be used as the refrigerant in place of the hydrofluorocarbons (HFCs), such as R404A, which has been widely used for centralised supermarket refrigeration systems. However, R404A has a high GWP of 3922, so in response to new F-Gas guidance (F-Gas 2022), many supermarkets have recently replaced it with lower GWP HFC/HydroFluoroOlefin (HFO) refrigerants, for example R448A, R449A, which have GWPs of the order of 1400, or R454C, which has an even lower GWP of 148. Hydrocarbons (HCs) have even lower global warming potentials GWPs, for example, propane (R290) has a GWP of 3, and propene (R1270) has a GWP of 1.8.

Hydrocarbons cannot be used for centralised refrigeration systems in supermarkets due to the large refrigerant charge needed, since regulations (EN378) limit the charge of HCs that can be used (to 1.5 kg in supermarkets), due to their flammability. However, their performance i.e. energy efficiency, as refrigerants exceeds HFCs in many applications.

Pederson (2012) compared the use of hydrocarbons R290 and R1270 with HFC R404A for a refrigeration system with an evaporating temperature of -10°C and a condensing temperature of 35°C, and demonstrated an increase in COP of 8.3% for R290 and 7.9% for R1270 compared to R404A. The increase in COP was 10% for both R290 and R1270 compared to R404A, with a condensing temperature of 45°C.

A trial of integrated refrigerated cabinets, using either R290 or R1290 refrigerant and water loop cooled condensers, in a Waitrose supermarket in the UK, was reported by King et al (2011). Approximately 25% of the heat rejected through the water loop system was reclaimed and used to heat the cold aisles adjacent to the open fronted refrigerated cabinets, thereby partially offsetting the building heating requirement, and effectively combining the refrigerated cabinet cooling with the store heating, ventilation and air conditioning (HVAC) system. It was estimated that when comparing the integrated HC water cooled refrigeration and HVAC system with the traditional centralised HFC refrigeration plant (using HFC R404A), on a whole store basis, an overall CO_2e emissions saving of 32% was achieved. The CO_2e savings included both those from savings in electricity and gas usage, and those due to reduced (high GWP) refrigerant leakage. The refrigerants R290 or R1270 were also compared for use in the integrated water loop cooled refrigeration and it was concluded that R1270 (propene) provided greater capacity and efficiency than R290, so was the preferred refrigerant for this application. A direct comparison of R1270 and R404A in the same application (water cooled integral cabinets) showed consistent energy savings of 16% for both medium temperature (chilled) and low temperature (freezer) applications. It was also estimated that there would be an annual cost reduction for maintenance of at least 44% for the water loop cooled integral cabinets (King et al, 2011).

A performance, costs and emissions comparison of a range of alternative supermarket refrigeration systems was undertaken by Roberts et al (2020). Configurations used included centralised systems using refrigerants with different GWPs (in brackets), namely R404A (3922), R449A (1400) and R454A (148), 5 R744 (CO_2) based refrigeration systems and 2 integral cabinet R290 based/water loop cooling systems. They were evaluated for 3 different countries/ambient conditions, namely Spain, the UK and Finland. Leakage rates for the centralised systems were assumed to be much lower than previously reported (as indicated above), namely 5%, while a leakage rate of 10% assumed for the integral cabinet/water loop systems. It was found that the R404A system produced the highest overall (i.e. combined direct and indirect) emissions, with by far the largest direct emissions, despite the low leakage rate, due to its very high GWP. The other refrigerant systems all produced similar levels of emissions, with some variations between them, except for the R434A based system which produced the lowest emissions of all i.e. 6-15% lower than the next lowest emission system. The R290 based integral cabinet/water loop systems would have been expected to produce lower overall emissions compared to the centralised systems based on the findings from the earlier study of King et al (2011). However, in that study, 25% of the heat rejected through the water loop was recovered and reused for space heating within the store, thereby reducing gas consumption and overall emissions for the store. As the electrical grid decarbonises in the future, the benefits in terms of CO_2 emissions will move further towards low GWP refrigerants (e.g., HCs and R744).

Technology: Water loop systems (plus R1270)

Scope 1 emissions savings (% or another quantifiable metric)	17% of charge for centralised refrigeration system x GWP R404A less 1.5% x combined charge for all integral refrigerated cabinets x GWP R1270 (based on study of King et al (2011).
Quality of scope 1 emissions information	M
Scope 2 emissions savings (% or another quantifiable metric)	11% - based on savings in gas heating and electricity emissions for King et al (2011) system
Quality of scope 2 emissions information	M
TRL level	TRL8-9
Maintainability issues	Much lower refrigerant leakage for integral systems compared to centralised plant and reduced maintenance costs.
Legislative concerns	M - Refrigerant charge for hydrocarbons limited to 1.5 kg for direct system in supermarket (EN378)
Payback time (years)	Unknown

1.19. Ovens

1.19.1. 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. (A. 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 (1m/s-10m/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. (X. D. 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

1.19.2. 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

1.19.3. 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.

1.19.4. 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)

1.19.5. 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 60kW 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 analyze the energy behavior 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.

1.19.6. 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 & 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 & 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 discuss 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 analyzed 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

1.19.7. 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).

1.19.8. 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

1.19.9. 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.

1.19.10. 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

1.19.11. 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 40). 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.

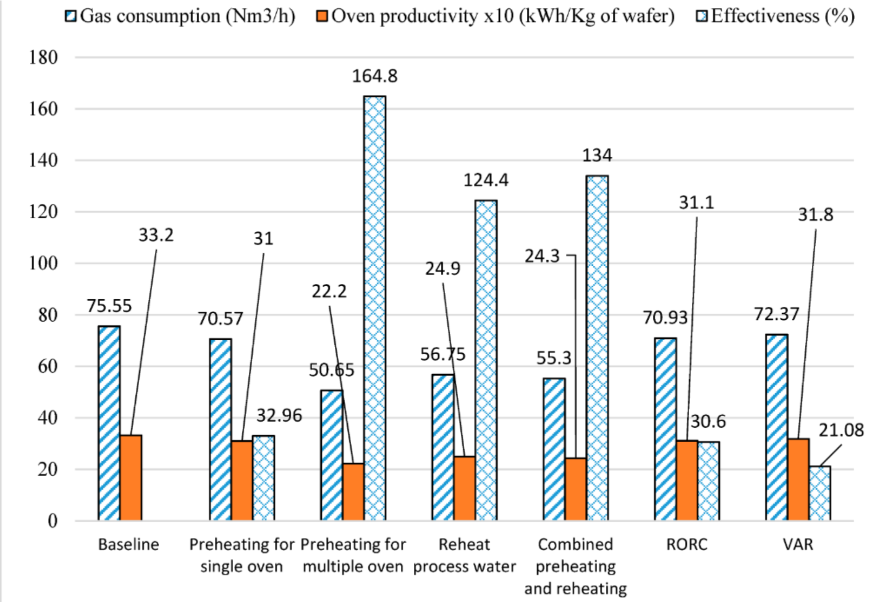

Figure 40. Comparison of heat recovery technologies based on oven's gas consumption, productivity and effectiveness. (taken from Mukherjee et al., 2020).

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.

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)	-
Quality of scope 2 emissions information	-
TRL level	1-4
Maintainability issues	No specific measures needed
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.

1.19.12. 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.

1.19.13. 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

1.19.14. 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

1.20. HVAC

1.20.1. Air conditioning

Air conditioning (AC), which includes cooling and dehumidification, is required in commercial as well as industrial activities (Chua, et al., 2013). In supermarkets air conditioning is common when the display cabinets use integrated refrigeration, but not common with remote refrigeration, except in Mediterranean countries. According to current cooling technology, compressors, cooling towers, chilled and cooling water pumps, and air handling unit fans make up the majority of an AC plant.

Air handling units (AHU) designed for office buildings are often used . The size and type of this system is dependent on the supermarket size; ranging from small units, to large stationary central AC systems. AC systems can be 'packaged systems', when all components are built into a single casing or 'split systems', ducted or non-ducted, where essential components are built into several casings. In some cases, AC systems are reversible; so that it is possible to convert them into a heat pump in the winter. An interesting AC system solution was introduced to the market that consists of the integration of AC into the CO_2 booster refrigeration system. As a result, all thermal services to the supermarket are provided by one single unit, performing refrigeration, AC and heating when required. Karampour and Sawalha (2018) have found that the COP of air conditioning in an integrated CO_2 system is higher than in an isolated HFC-based AC system for ambient temperatures lower than 25 °C. This technology has been widely demonstrated in South European Countries by the H2020 project MultiPACK[43] , showing a 20-25% reduction in the overall specific energy consumption of medium size supermarkets.
High humidity in supermarkets have many drawbacks, e.g. increased thermal load on cabinets, frost formation on evaporators, condensation on glass doors and lids. Despite its advantages, active humidity control is not a widespread technology in the retail sector, and humidity is normally managed by integration with external dry air[44]. According to Arias (2005[45]) 'many research works have tried to quantify the effect of reduced space humidity on refrigeration energy use'. Kosar and

[43] Technical report on verified supermarket packs of the European Project MultiPACK. Leading partner Enex. Publication 30.09.2021

[44] SuperSmart - Expertise hub for a market uptake of energy-efficient supermarkets by awareness raising, knowledge transfer and pre-preparation of an EU Ecolabel. Lead authors: Mazyar Karampour, KTH, Samer Sawalha, KTH, Jaime Arias, KTH. 2016.

[45] Arias, J., 2005. Energy usage in supermarkets-modelling and field measurements (Doctoral Thesis). Royal institute of technology (KTH), Stockholm, Sweden

Dumitrescu (2005[46]) measured 3–21 % reduction in compressor energy use with a 20 % relative humidity (RH) reduction in the space, a 4–6 % reduction in defrost energy, and a 15-25 % reduction in anti-sweat heater energy.

Dehumidification can be achieved with cooling below the dew point in AHU heat exchangers, supplied by cold water or refrigerant; this process requires post-heating and it is normally integrated in the ventilation control. The second method is using desiccant wheels, which can also be integrated in the AHU. Desiccant (e.g. silica gel) need to be regenerated by hot air. Sharma et al, 2014 presented an eco-friendly solution by heat recovery from the refrigeration system; CO_2 can easily accomplish high temperature demand for the regeneration[47].

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 41). The key findings from the paper was 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.

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[46] Kosar, D., Dumitrescu, O., 2005. Hunidity Effects on Supermarket Refrigerated Case Energy. Performance: A Database Review, in: ASHRAE Transactions. p. 1051–1061.

[47] Sharma, V., Fricke, B., Bansal, P., 2014b. Waste Heat Dehumidification in CO2 Booster Supermarket. Presented at the 15th International Refrigeration and Air Conditioning Conference, IIR/IIF, Purdue, Indiana, USA.

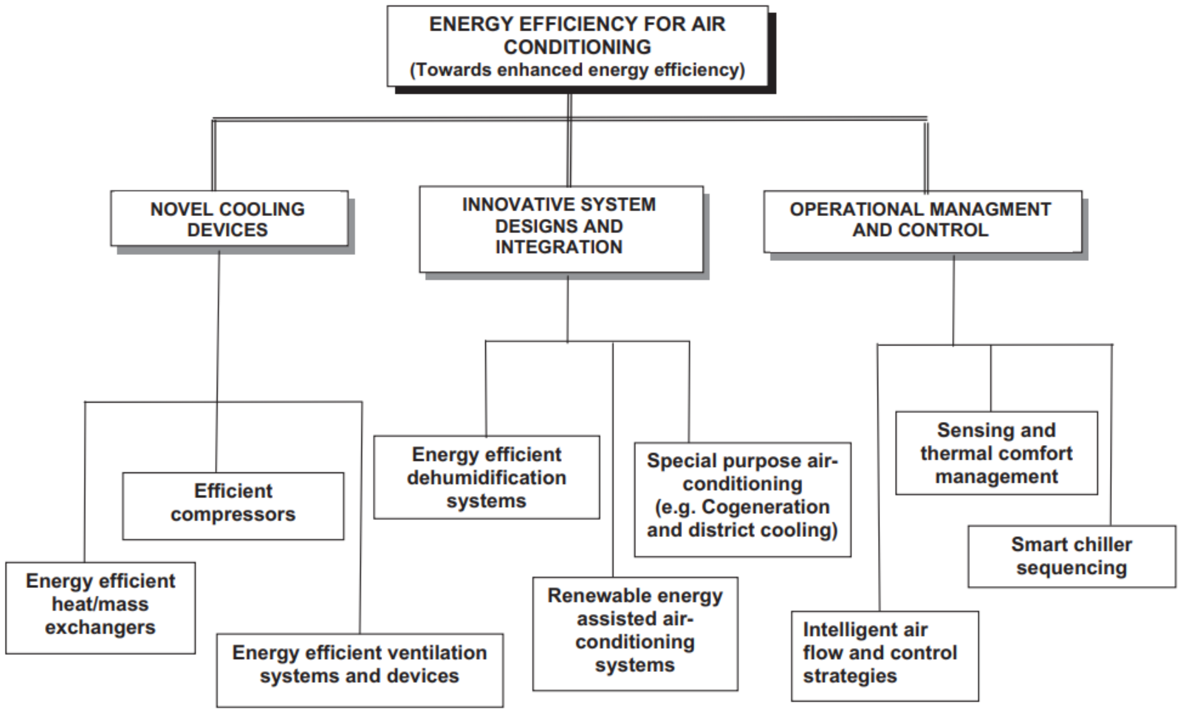

Figure 41. An outline of the technical review for energy efficiency in air conditioning.

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.

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)	33%
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

1.20.2. 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.

1.20.3. 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 store. 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 store is open and another temperature when the store 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 store will be open or not. And if so, at what time will the store be open. If the answer to this is yes, it will be open between 7 am-11 pm. The PLC will check the current temperature in the store in advance and the temperature outside and then calculate how long it takes to heat or cool the store to the desired temperature. The PLC will then start the process of heating or cooling the store, 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.

1.20.4. Boilers with higher efficiency

Heating is a crucial aspect of maintaining a comfortable and welcoming environment for customers and employees in retail and shop spaces. Determining the heat demand and importance of heating for these spaces is essential in providing an optimal temperature that promotes customer satisfaction and increases sales. An optimal indoor temperature ensures customer satisfaction, increased sales, and reduced operational costs and environmental impact.

Various factors such as the building's size, design, location, and activities carried out in the space impact the heating demand. Calculating the heat load of a retail or shop space provides an estimate of the heating requirements needed to meet the indoor temperature demands.

Along with heat demand, considering the efficiency of heating systems is essential. The boiler efficiency is a significant factor to determine the operational costs of the heating system. Efficient boilers provide optimal heat output while minimizing energy consumption, reducing operating costs and carbon emissions.

Therefore, selecting a heating system that matches the calculated heat load while ensuring high boiler efficiency is crucial. Installing an efficient heating system such as a condensing boiler or a heat pump can provide a comfortable indoor temperature while minimizing energy consumption and reducing operating costs.

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 pre-process 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 42). 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).

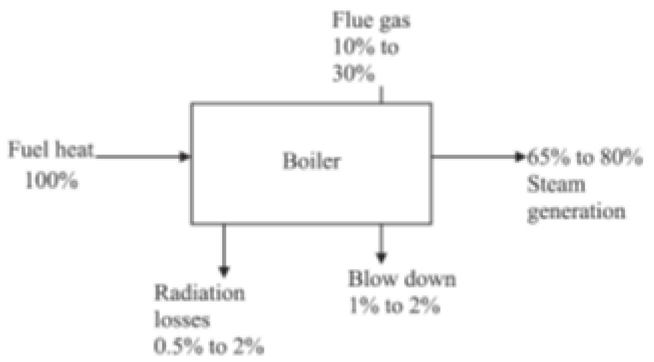

Figure 42. Typical heat balance of a boiler (Barma et al., 2017)

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.

1.20.5. De-stratification fans

The rise of warm air due to buoyancy forces can lead to thermal stratification of the indoor air if no additional measures to mixing the air are applied (compare especially curves A, D and E with B in Figure 43). During the heating season, the increased air temperature beneath the ceiling leads to a higher heat loss due to the larger temperature difference to the outside air. Besides the mixing of the air, the location of the heat supply has a significant influence on the resulting temperature profile, as shown with characteristic temperature profiles in Figure 43. Wang et al. (2019) propose the statistical Beta distribution function defined by two shape parameters to generalize, quantify and categorize thermal stratification phenomena which can potentially be applied in building simulations.

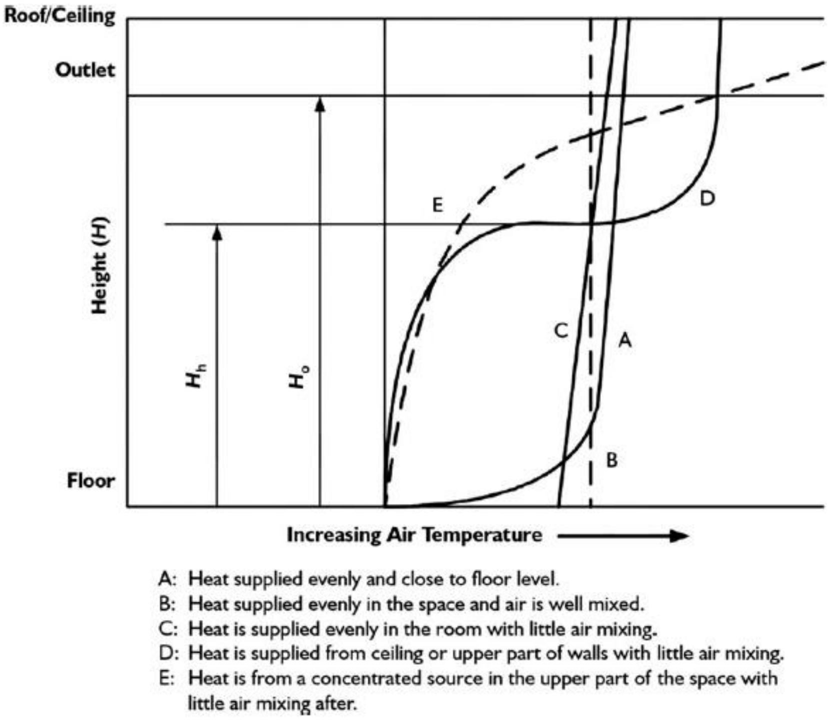

Figure 43. Qualitative characteristic curves of thermal stratification, retrieved from Wang et al. (2019)

The aim of de-stratification fans is to ensure a more uniform indoor air temperature distribution (curve B in Fig.1), thus decreasing the heat losses and by that the heating energy demand of the building. During summer, the provided airflow can increase the thermal comfort at a given temperature, enabling a higher indoor air temperature and thus decreasing the cooling demand. Contrary to that, Saïd et al. (1996), mention that cooling-season stratification can reduce the cooling load because the warm air layer below the ceiling acts like an insulating buffer towards heat gain.

Applicable fans include e.g., ceiling fans (without a housing) or fans including a fan housing (often referred to as "bucket fans"). Limitations are given by the allowable air speeds to prevent draft.

Possible energy savings:

Aynsley (2005) investigated thermal stratification and the heating energy demand of a shipping and receiving warehouse in the state New York (approx. area 5,400 m², ceiling height 9 m). Measurement data show that the difference between the air temperature below heaters (equals the thermostat setting) and the air temperature below the ceiling was 13.4 K without de-stratification fans. Applying the de-stratification fans reduced the fuel demand for heating by 24.5% (comparison based on fuel consumption per heating degree day). While two calculation models from the Literature failed to predict the energy savings within 10% accuracy, the model proposed by the author predicts the energy savings with 6% accuracy by accounting for the temperature profile due to the natural gas fired forced air furnaces mounted approx. 6 m above the floor.

Saïd et al. (1996) studied thermal stratification in large single-cell buildings by example of hangar buildings with ceiling heights of 9.35, 16.2, and 17.1 m. They observed floor-to-ceiling temperature differentials between 4 and 11 K, independent of the ceiling height and type. The heating energy required in case of the 8 K floor-to-ceiling temperature differential was simulated to excess the case of no stratification by 38%.

Wang and Li (2017) studied thermal stratification for two warehouses. In one of them with the size of 12 x 9.3 x 6.62 m (LxBxH), half of the warehouse is divided horizontally to maximize storage space. In this warehouse, a maximum vertical temperature difference of 39 K was observed with an electric forced air heater hanging from beneath the ceiling, pushing the air downwards and no further air mixing measures. Application of a ceiling fan lead to the best de-stratification results with a maximum temperature difference of approx. 10 K, leading to energy savings of around 40%.

Armstrong et al. (2009) investigated a 8,600 m² combined manufacturing and warehouse facility in the Toronto area. The use of de-stratification fans lead to gas savings of 19.3%, although the operation of the fans was not always optimal (during the measurement campaign, both up- and downward airflow were tested). Through the fans, the ceiling temperature was reduced by 4 K and the floor temperature increased by 1.5 K, leading to a maximum temperature difference of less than 0.5 K.

Aynsley (2007) gives typical figures for energy savings through de-stratification in the cold season with 10% per 3 m of ceiling height. The estimated air conditioning energy savings through allowing a 3 K higher room temperature due to a 1 m/s air movement provided by the de-stratification fans are given with approximately 20%.

Scope 1 emissions savings (% or another quantifiable metric)	Not applicable
Quality of scope 1 emissions information	Not applicable
Scope 2 emissions savings (% or another quantifiable metric)	<u>19-40% cold season heating energy savings:</u> 24.5% measured (Aynsley, 2005) 38% simulated (Saïd et al., 1996) 40% warehouse with horizontal partly division, measured (Wang and Li, 2017) 19.3 % measured, non-optimal operation (Armstrong et al., 2009) 10% per 3 m ceiling height, estimation (Aynsley, 2007) <u>air conditioning energy savings:</u> approx. 20% due to 1 m/s air speed (Aynsley, 2007)
Quality of scope 2 emissions information	high, but very specific to the actual building, climate condition and existing heating system
TRL level	8-9
Maintainability issues	No data for maintenance intervals found
Legislative concerns	According to Saïd et al. (1996) stratification may be beneficial to keep the working zone clean of pollutants in manufacturing plants, which should not be of concern in retail warehouses.
Payback time (years)	2.6 (Aynsley, 2005)

1.20.6. 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 at the store. 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)

1.20.7. 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

1.20.8. Heat pumps, heat recovery 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 in supermarkets. This is also reflected by the Directive 2012/27/EU 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 recovery, heat pumps and radiant heat usually occur together, they are considered in a joint technology review.

According to Galvez-Martos et al. (2013) an average store in Europe has a final energy consumption of about 700 kWh/(m²·a). For heating approx. 100 kWh/(m²·a), for refrigeration approx. 350 kWh/(m²·a), for lighting approx. 145 kWh/(m²·a) are used. The remaining amount is used for other purposes (e.g. cashier, slicers, …).

Figure 44 shows an energy flow diagram of a supermarket including heat recovery from the refrigeration system.

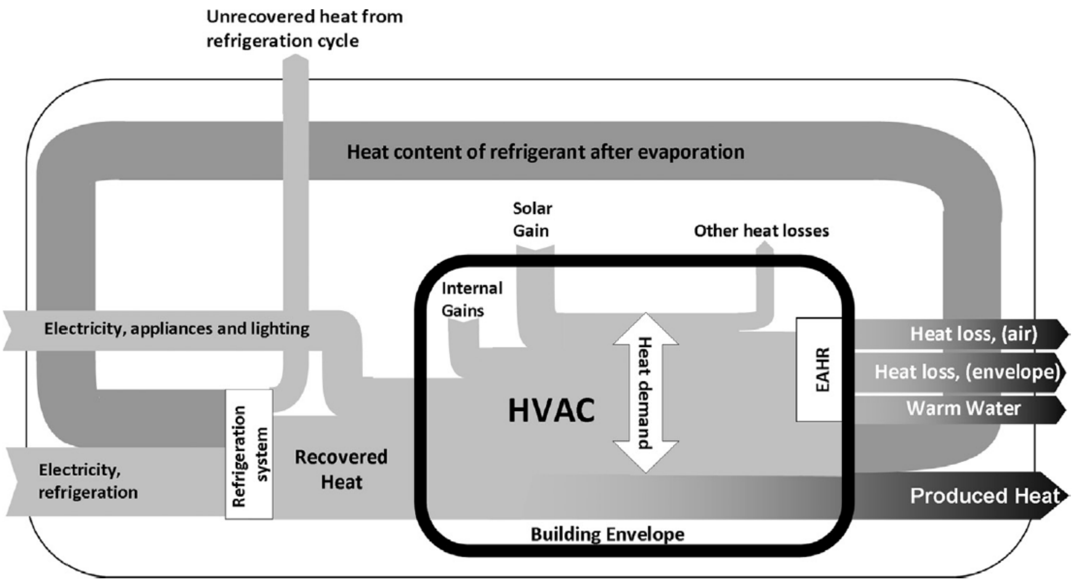

Figure 44: Energy flow diagram of a supermarket including heat recovery (Galvez-Martos et al., 2013)

Normally waste heat from the refrigeration systems is expelled via air-cooled condensers or cooling towers. Modern chillers, in particular those using ammonia (NH_3, R717) or carbon dioxide (CO_2, R744) as refrigerant offer a significant potential to recover waste heat at useful temperature levels (also greater than 50 °C). The recovered heat can in general be used to reduce the consumption of appliances, such as heating or domestic hot water (DHW). If a direct waste heat recovery from the refrigeration systems is technically not feasible, e.g., due to a low available temperature, a heat pump can be used to further increase the temperature of the waste heat suitable for e.g. heating or DHW. Furthermore, to reduce the energy losses caused by the necessary air exchange to ensure comfortable conditions in the supermarket, heat recovery from the exhaust air can be implemented. According to Galvez-Martos et al. (2013) the heat demand can be significantly reduced or even omitted especially in a well-insulated building by using waste heat recovery via the refrigeration and ventilation system. Furthermore, a part of the heat (produced heat) could also be commercialized, although a distribution infrastructure is required.

Galvez-Martos et al. (2013) quantified the possible energy reduction potential of an average European store with 29 %, i.e. from 700 kWh/(m²·a) to 495 kWh/(m²·a) by using natural refrigerants and glass lids on the display cabinets as well as heat recovery from the refrigeration systems.

If heat recovery from the refrigeration systems is used for heating purposes, the efficiency is significantly influenced by the temperature of the available heat and the required temperature. Therefore, the heat distribution system must be adapted accordingly to the requirements to achieve the highest possible benefit. For heating purposes in general a low-temperature heating system based on radiation with largely sized heat transfer areas, i.e., floor or ceiling heating system, is suitable.

Zając (2019) summarized that, it is important to properly design installations responsible for heating and cooling of facilities like supermarkets. In order to reduce the energy needed to a minimum it is important to reduce the required temperatures for heating and cooling.

In the following, an overview of different implementation variations as well as already implemented systems gathered from a literature review will be given for the three technologies heat reclaim, heat pumps and radiant heat. Since there already have been a lot of publications, this technology review is only an excerpt without claiming for a complete overview.

1.20.9. Direct heat reclaim

Ventilation system

According to Wallin and Claesson (2014) in new buildings the thermal losses through the building envelope and through air infiltration are greatly reduced compared to the buildings which were built more than 20 years ago, making ventilation the single biggest source of thermal heat loss. For older buildings the thermal loss through ventilation is normally the most dominant factor due to a high air exchange rate. The thermal loss from ventilation can account for more than 50 % of the total thermal loss of the building. To reduce the influence on the energy performance due to heating of ventilation air, a heat recovery system is nowadays usually implemented.

To meet the ventilation requirements in conditioned spaces, AHUs can be used. AHUs are composed of heating and cooling coils. In very simple systems heating and cooling coils are used to provide the desired temperature and relative humidity in the conditioned space. More sophisticated systems which are nowadays state of the art also include heat recovery systems in the AHU. A simplified schema of an air handling unit (AHU) with an integrated heat recovery system (primary and secondary air to air heat exchangers) and a ventilated space (e.g., building) is shown in Figure 45.

The return air leaving the conditioned space (point G in Figure 45) is divided into two streams. Part of the air enters the mixing box as recirculated air, the remaining part enters the primary heat exchanger as exhaust air. The relation between the recirculated and the exhaust air is given by the necessary air exchange rate depending on e.g., amount of people. Depending on the temperatures of the fresh and return air, the fresh air is either precooled ($t_N < t_A$) or preheated ($t_N > t_A$) in the primary heat exchanger. In cooling mode this will reduce the load of the following cooling coil.

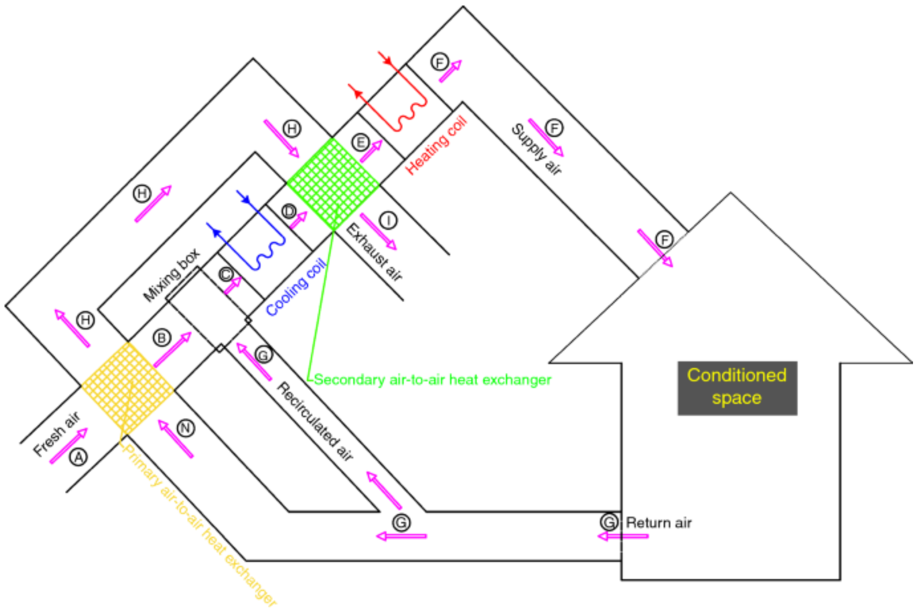

Figure 45: Simplified schema of an air handling unit (AHU) and a conditioned space (e.g. building) (Kalbasi et al., 2020)

To ensure a sufficient dehumidification, the temperature of the supply air after the cooling coil (point D in Figure 45) might be very low and therefore the secondary air to air heat exchanger can be used to increase the temperature of the supply air (point E in Figure 45) and reduce the load of the following heating coil. Several different types are available for the heat recovery from the exhaust air, whereby one of the most common types is the energy wheel. This is a so-called regenerator which can not only transfer heat but also moisture.

Roulet et al. (2001) analysed the performance of the heat recovery in ventilation systems by means of numerous measurement data from the field. It was shown that the achieved heat recovery effectiveness which was defined as the amount of heat recovered to the heat recovery potential (e.g., exhaust air (point H) cooled to the outdoor conditions (point A)) by assuming balanced intake and exhaust airflow rates, varied significantly from system to system. The best systems have shown a heat recovery effectiveness of 80 – 90 %. Taking also exfiltration and infiltration losses into account, Roulet et al. (2001) have defined a global heat recovery efficiency which was significantly lower than heat recovery effectiveness of the heat recovery system. The best systems have shown a global heat recovery efficiency of ≈ 60 - 70 %.

Refrigeration system

According to Cecchinato et al. (2010) heat recovery from refrigeration systems in supermarkets has been typically done by elevating the condensing pressure to a level where the coolant fluid at the outlet of the condenser has a temperature suitable for e.g. heating system. Figure 46 shows a simple schema of the integration of a heat recovery system in a refrigeration system via an intermediate circuit. Within this heat recovery solution, the 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. Otherwise, the whole or only parts of the waste heat can be rejected by means of an air cooler.

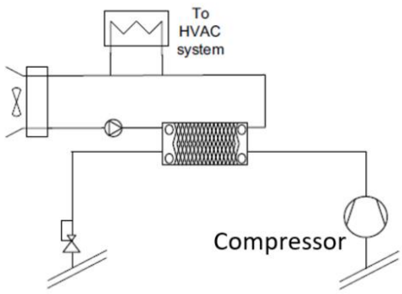

Figure 46: Simple scheme of a direct heat recovery solution via an intermediate circuit and a floating condensation pressure (Sawalha, 2013)

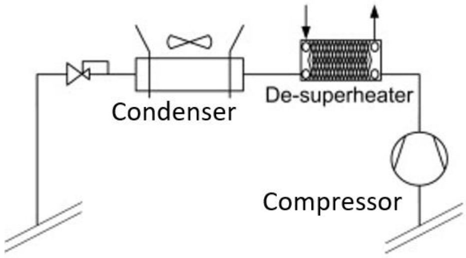

Figure 47: Simple scheme of a direct heat recovery solution via a desuperheater (Sawalha, 2013)

If a higher temperature at a low heating demand has to be covered, a heat recovery via a desuperheater, before the air-cooled condenser can be implemented. Figure 47 shows a simple schema 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.

Zühlsdorf et al. (2018) has numerically investigated the direct heat recovery of a refrigeration system with CO_2 in a supermarket. For the heat sink a district heating network (DHN) with an inlet temperature of 45 °C and an outlet temperature of 70 °C was chosen. Increasing the condensation pressure of the reference refrigeration system with a cooling capacity of 100 kW has shown that ≈80 kW can be recovered at an additional electrical power input of ≈20 kW at the compressor.

Indirect heat reclaim via heat pumps

Ventilation system

To increase the heat recovery from the exhaust air of the ventilation system a heat pump can be integrated in the AHU. Figure 48 shows a simplified schema of an AHU with an energy wheel ("ROTATING HEX") and the integration of a heat pump for heat recovery. The proposed system of Wallin and Claesson (2014) extracts heat from the exhaust air stream and "lifts" the temperature to a level suitable to reheat the return water of the ventilation heating coil ("AUX HEATER"). The motivation for this system is that it is technically viable in many existing ventilation systems and the heat pumps can also be retrofitted in the existing system.

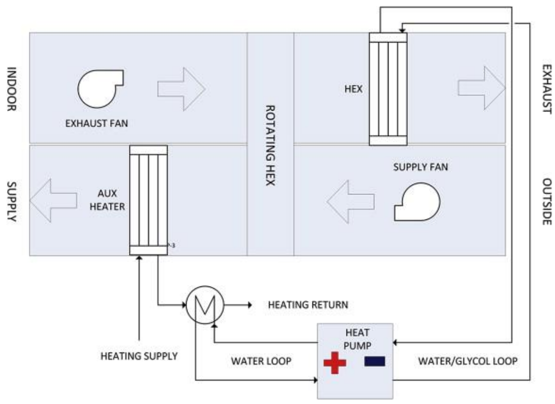

Figure 48: Simplified schema of an AHU with an energy wheel and an additional heat recovery with a heat pump (Wallin and Claesson, 2014)

According to Wallin and Claesson (2014) heat recovery systems with only a rotating heat exchanger have shown a global recovery rate of about 60 to 70% of the energy in the exhaust air on an annual basis. Including a heat pump in the exhaust gas stream the heat recovery rate of the AHU can be significantly increased, whereby the sizing of the heat pump and the efficiency have a major impact. The heat pump used for the studies had a seasonal performance factor (SCOP) of 3, leading to an overall coverage of the heat demand of the AHU of 97 %.

Refrigeration system

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. Figure 49 shows a simple schema of a heat pump cascade system. In this solution, the heat pump extracts the heat from an intermediate circuit, which is used to cool the condenser. If the rejected heat of the refrigeration system is used by the heat pump the refrigeration system can operate at a relatively low 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 (pressure) of the refrigeration system depending on the operating conditions. This will lead to a reduced efficiency of the refrigeration but increased efficiency of the heat pump. 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 50 shows a simplified schema of the integration of a heat pump after an air cooled condenser.

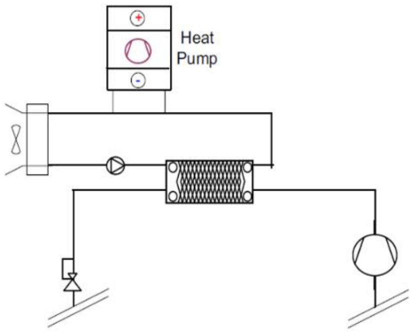

Figure 49: Simplified scheme of a heat recovery with a cascade system (Sawalha, 2013)

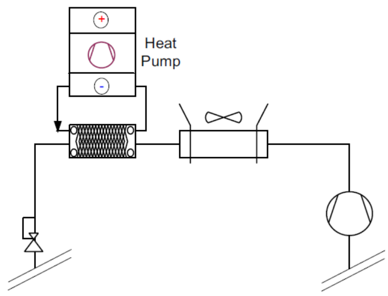

Figure 50: Simplified scheme of a heat recovery by means of a heat pump integrated after the aircooler (Sawalha, 2013)

Zühlsdorf et al. (2018) numerically investigated a system that uses a heat exchanger to utilize the de-superheating of the refrigerant for a district heating network as well as a heat pump for the recovery of the heat of condensation. A district heating network (DHN) with an inlet temperature of 45 °C and an outlet temperature of 70 °C was chosen. For the reference refrigeration system with a cooling capacity of 100 kW the combination of both heat recovery options have shown a heat recovery potential of ≈150 kW at an additional electrical power input (refrigeration system and heat pump) of ≈40 kW.

The results of Zühlsdorf et al. (2018) have shown that the direct heat recovery at a floating condensation pressure appears to be thermodynamically promising during the summer months, when the system already operates at a higher condensation pressure and the additional electrical energy required for the compressor to enable heat recovery is low. At colder periods (autumn/spring and winter), the indirect heat recovery via a cascade heat pump showed higher thermodynamic performances. Furthermore, by means of a cascade heat recovery system with a heat pump, a higher amount of heat at an improved performance can be recovered. The economic evaluation of Zühlsdorf et al. (2018) has shown that the additional investment costs for a heat recovery system via a heat pump could be compensated by considering the entire lifetime of the systems.

Minea (2010) has also analysed heat recovery of refrigeration systems by means of a heat pump. He found that the compressor discharge pressure can be significantly reduced due to de-superheating. By using secondary fluid (brine) loops on the refrigerating, freezing and condensing sides of supermarket refrigeration systems, , the charge of primary refrigerants can be reduced by more than 60 %. However, this would be at the expense of efficiency, due to the extra heat exchangers. If CO_2 was the refrigerant, this would not be necessary.

Additional applications of heat pumps in supermarkets

Besides heat recovery from a ventilation or refrigeration system, a heat pump can also use different heat sources to heat a supermarket. Garcia et al. (2011) have numerically investigated the application of a ground source heat pump for heating and cooling in a supermarket. It was shown that the primary energy consumption of a supermarket can be reduced by ≈30 %. It was also noted that the reduction of the energy consumption of a supermarket can be further reduced by considering the available waste heat of the refrigeration systems in a supermarket.

Radiant heating and cooling

Radiant heating heats a building mostly through radiant heat, rather than conventional methods by i.e., convection. According to ASHRAE (2008), a technology is designated as radiant heating or cooling, if the amount of energy exchanged with the environment 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 store temperature can be slightly reduced. Caritte et al. (2015) analysed the influence of the temperature setpoint on the total heat demand and found out that, a reduction of the store temperature setpoint of 1 K 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 by not significantly effecting the thermal comfort.

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)	Waste heat recovery from the ventilation system Recovery effectiveness of exhaust air heat exchanger:

	60 – 70 % (Wallin and Claesson, 2014) 80 % (Kassai, 2019) 80 – 90 % (Roulet et al., 2001) Global heat recovery effectiveness (including exfiltration and infiltration) 60 – 70 % (Roulet et al., 2001) <u>Waste heat recovery from the ventilation system incl. a heat pump</u> Coverage of the energy demand of an air handling unit (AHU) of 97 % (Wallin and Claesson, 2014) <u>Waste heat recovery from the refrigeration systems</u> Reduction of an external heat demand for heating by 100 kWh/(m²·a) (complete substitution) (Galvez-Martos et al., 2013) By means of a floating condensation pressure (increased condensation pressure during heat recovery) ≈80 % of the refrigeration capacity can be recovered for the use in a DHN (45 °C → 70 °C) at a slightly increased electrical energy input at the compressor (Zühlsdorf et al., 2018) Using a direct heat recovery (desuperheating) and a heat pump ≈150 % of the refrigeration capacity can be recovered for the use in a DHN (45 °C → 70 °C) at a slightly increased electrical energy input at the compressor of the refrigeration system and an additional electrical energy input for the compressor of the heat pump (Zühlsdorf et al., 2018) <u>Heat pumps</u> Reduction of the primary energy consumption by 30 % by means of a ground source heat pump (Garcia et al., 2011) <u>Heating</u> 25 % reduction of the total heat demand by reducing the temperature set point by 1 K (Caritte et al., 2015)
Quality of scope 2 emissions information	Data is mostly gathered from peer-reviewed literature. It has to be noted that the estimations made, are very specific on the actual building, climate condition and installed systems
TRL level	TRL8-9 (for all technologies)
Maintainability issues	No data for maintenance intervals found
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)	<u>Waste heat recovery from the refrigeration systems with a heat pump</u> ≈4 years (Zühlsdorf et al., 2018) ≈4 – 7 years (Baxter, 2003)

1.20.10. Natural/passive ventilation

Passive ventilation utilizes the forces of nature and physics, supplying fresh air to the building and extracting moist stale air, using the passive effects of wind speed or differences in internal and external air pressure (Monodraught, 2020; Permagard Products Ltd., 2022). Natural ventilation techniques are traditional methods having their undeniable benefits: they are sustainable, low carbon ventilation system that does not use fans or pumps (Monodraught 2020).

The energy consumption of naturally ventilated buildings is typically less than half the energy used in air-conditioned buildings. The application of natural ventilation leads to further opportunities of savings. Maintenance costs decrease, initial capital costs are lower typically by 15% and operating costs can be 40% less in terms of energy consumption (Passivent, 2019).

Natural ventilation strategies for commercial buildings (Passivent 2019):

Cross ventilation achieves good air change rates driven by pressure differences across the building. This method uses controllable high-capacity inlets/outlets on two opposing building façades and can achieve penetration depths of up to 5 times the floor-to-ceiling height.

Single-sided ventilation, usually through large façade opening devices, is mainly driven by wind turbulence. Relatively low ventilation rates are achieved except with penetration depths of less than 2, 5 times the floor-to-ceiling height. Penetration depths are based on typical office low occupant densities and are not applicable to higher occupant densities such as teaching spaces and seminar rooms.

Mixed-mode ventilation: Natural ventilation alone may not be suitable for some rooms due to their depth, internal heat loads or other factors. In these cases, some mechanical assistance can be incorporated e.g., low powered boost fans in outlets or local comfort cooling devices.

Passive stack ventilation (PSV) is the most effective natural ventilation strategy as it uses a combination of cross ventilation, buoyancy and the suction effect as the wind passes the terminal. It can ventilate to twice the depth of cross ventilation, up to 10 times the floor-to ceiling height, as the outlet can be in the centre of a building. It can be an effective night cooling strategy as internal and external temperature differences at night are typically high, so increasing convection. PSV stacks can range from large central atria to local stacks feeding to roof-mounted terminals.

Displacement ventilation uses wind driven roof-mounted terminals with separated chambers to channel air down into the building regardless of wind direction. The cooler, denser air displaces warmer, lighter air upwards, which is drawn out through the leeward chambers of the terminals. This method can be used as part of a night cooling strategy.

Night cooling uses the lower external temperatures at night to reduce the temperature of the building fabric, by means of automatic ventilation devices. The cooled thermal mass of the building is used the next day to reduce internal temperatures. It is best suited to heavy weight structures. A night cooling strategy in a suitable building design can reduce peak internal temperatures by 2-3 °C the following day. Natural night cooling by lowering the ambient temperatures can delay the use of energy consuming cooling equipment.

Tools of passive/natural ventilation

Air curtains create a barrier preventing the mixing of outdoor and indoor air having different temperature and humidity (mitigating the need for cooling or heating), and preventing dust, dirt and insects to enter (Evans, 2018).

Wind towers, windcatchers or wind scoops are traditional features of the Islamic architecture, being present for centuries. "Wind flowing around a building causes separation of flow which creates a positive pressure on the windward side and a negative pressure on the leeward side of the building. Due to its height the wind tower enhances the positive pressure on the windward side; it is then directed through the tower into the building. Airflow follows the pressure gradients within the structure and exits through purposely designed openings and as well as through the leeward side of the tower. The size and location of openings (e.g., windows, doors, etc.) and distribution of internal party walls have a great impact on encouraging cross flow and mixing of the indoor air. The principal factor is the buoyancy which depends on the temperature difference and the height.” (Yang and Clements-Croome 2012)

Other passive vents are also available. Condensation control vents work by allowing damp air out of the building and clean dry air back in, lowering the moisture in the air and reducing condensation (Permagard Products Ltd., 2022).

Phase change materials (PCM) can contribute to achieve optimal air temperature by absorbing heat gains in the daytime through their melting process, and releasing the heat at night while solidifying, therefore reduce cooling energy consumption and overheating (Lizana et al. 2019).

Design and requirements of the ventilation systems

In the design process of a building’s ventilation system, several factors need to be considered, including store location and orientation, making it potentially more prone to higher wind penetration; entrances (by means of door sizes, positions and opening frequency) providing opportunity to uncontrolled ventilation (Passivent 2019).

Air infiltration through door openings can be limited with a wind lobby at the entrance and with applying air curtain at the top of the internal entrance/ exit door (Sawaf et al. 2011).

In food retail stores different, usually not isolated thermal zones are present simultaneously, both refrigerated cases and cooking equipment can be found, having great influence on the air quality and humidity inside the building (Karampour, Sawalha, and Arias 2016).

Ventilation is essential for maintaining the quality of the products and to provide the required air change rate to limit the concentration of pollutants, smell, mould, fog and bacteria (Karampour, Sawalha, and Arias 2016). It must be noted that the use of filters against outdoor physical and chemical contaminants does reduce the flow rate of air exchange by a factor of 2 to 20 (depending on the mean pore size of the filter and the number of filtration stages; higher if HEPA grades and activated carbon smell adsorbers are installed). Such filter cabinets may also be equipped with diaphragm valves or swing check valves to control the direction of air flow and prevent backflow in case of sudden air pressure changed, which is important in maintaining the efficiency and effectiveness of the natural ventilation system.

A minimum air intake flow rate ranges between 0.3-1 cfm/ft^2 [1.5-5 lit./s·m^2] (Clark 2015).

The supermarkets’ energy consumption and emissions show wide variations affected by the type and size of the store, business and merchandising practices and refrigeration and environmental control systems used (Tassou et al. 2011).

If food or food raw materials are processed, prepared or stored in the building, additional aspects have to be taken into account. According to food hygiene regulations (“REGULATION (EC) No 852/2004 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 29 April 2004 on the Hygiene of Foodstuffs” 2004), additional requirements include the ensuring of sufficient mechanical or natural ventilation, avoidance mechanical airflow from a contaminated area to a clean area, and the construction of ventilation systems has to enable readily accessibility of filters and other parts requiring cleaning or replacement, and ensuring adequate natural or mechanical ventilation for sanitary conveniences.

Chapter III of regulation (EC) No 852/2004 has an important role in the European Union's legal regulations related to food safety, which contains regulations on "Guidelines on good practice". Based on the provisions of the regulation, member states must encourage the development of national and community guidelines on good practice for hygiene and the application of HACCP principles. Chapter III Article 7 deals with the development, dissemination and use of guidelines, Article 8 deals with national guidelines, and Article 9 with Community guidelines. Under Article 7, the dissemination and use of both national and Community guidelines shall be encouraged, and food business operators may use these guidelines on a voluntary basis (Berczeli, István, and Judit 2009).

As an example, the Hungarian guideline (GHP) for food retailers formulates the following requirements regarding natural ventilation (National Trade Association of Hungary 2018):

Doors and windows opening to the outside must be equipped with insect nets so that they can be easily removed for cleaning. As an alternative solution, e.g., also an air curtain may be used.

Windows used for ventilation must be easily accessible from floor level.

The entrance used for moving goods and the customer entrance must be kept closed when not in use.

If open windows can lead to food contamination, they must be kept closed during work.

In units using natural ventilation, special attention must be paid to the prevention of contamination of unpackaged food.

To ensure that the design of the food retail building meets the various and fairly complex requirements regarding ventilation (air quality, temperature, humidity, control of dust and other pollutants), the application of complex HVAC systems is common, although the implementation of natural ventilation techniques to reduce carbon footprint and enhance efficiency is an environmentally friendly way of cost reduction.

Scope 1 emissions savings (% or another quantifiable metric)	n/a (100%)
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	n/a (100%)
Quality of scope 2 emissions information	L
TRL level	8-9
Maintainability issues	None. (There are no maintainability issues in the case of passive ventilation techniques, although cleanability is an important requirement.)
Legislative concerns	None. (There are no legislative concerns in the case of passive ventilation techniques, however usually the application of passive ventilation alone is not enough to meet the requirements of ventilation food retail.)
Payback time (years)	Unknown (N/A)

1.20.11. 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

1.21. Other/ancillaries

1.21.1. 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^{2}K.

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^{2}K (RSI value of 3.85).

Hill (2015) 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/(m2 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/m2·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 (B.P. 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., 2019) carried out numerical simulations of thermally anisotropic building envelope (TABE). These add thin conductive layers between the insulation (shown in Figure 51). 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.

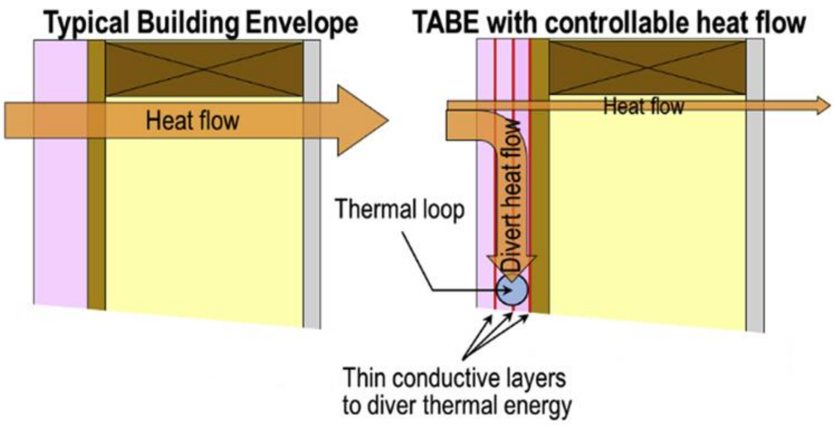

Figure 51. Thermally anisotropic building envelope.

Combined FEA and EnergyPlus 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

1.21.2. Building glazing optimisation

Glazing allows for entry of daylight and as such reduces the need (and energy use) for artificial lightning. However, glazing is also a 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 supermarkets.

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^{2}K 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^{2}K. 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 the 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 optimising 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, 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

1.21.3. 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 centers 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.

1.21.4. 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/m²/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/m²/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 m² while the second has a total surface of 4830 m². 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/m² 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.

1.21.5. 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.

1.21.6. 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 (Yuwei Qin and Arpad 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[R] 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[R] (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

1.21.7. 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)

11. BIBLIOGRAPHY FOR REVIEWS

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12. ENERGYPLUS MODELLING

Supermarkets are complex due to the interactions between the external ambient conditions, the display cabinets, the store HVAC system, and internal heat loads (equipment, customers, lighting). Computer models can generate a better understanding of how all these factors interact and have been used to aid designers and engineers decide on the best options to reduce carbon emissions.

Work to model supermarkets has been carried out by several researchers. Arias (2005) used CyberMart to simulate building heating and cooling loads, HVAC systems and seven different refrigeration systems in supermarkets. Differences between some measured and simulated values were found and it was concluded that fully validating the model across a whole year was not possible due to lack of data and some limitations in the capabilities of CyberMart. Hill (2015) assessed the capability of three modelling tools: Simplified Building Energy Model (SBEM), an Excel Model, and EnergyPlus (US Department of Energy) and concluded that the freeware EnergyPlus model was the most appropriate tool to analyse the complex interactions in supermarkets. In addition, OpenStudio is a user-friendly interface platform designed to facilitate the process of whole building energy modeling through EnergyPlus. Initially, Openstudio did not include the refrigeration module, which led Hill (2015) to use EnergyPlus directly through the intermediate data format (IDF) Editor interface. Unfortunately, no user-friendly interface incorporating a refrigeration system like OpenStudio existed at that time.

However, with the release of a newer version of OpenStudio that supports refrigeration, along with other systems, the ENOUGH project's use of EnergyPlus through OpenStudio was introduced to examine the retail sector, assess the impact of various opportunities to reduce carbon emissions and to determine how close to carbon neutrality stores could become by 2050.

1.22. Supermarket subsystems

The various boundaries of a supermarket are presented in Figure 52. It shows different subsystems in a supermarket such as the occupants, HVAC system, refrigeration system, cabinet system, lighting, equipment, and heating sources.

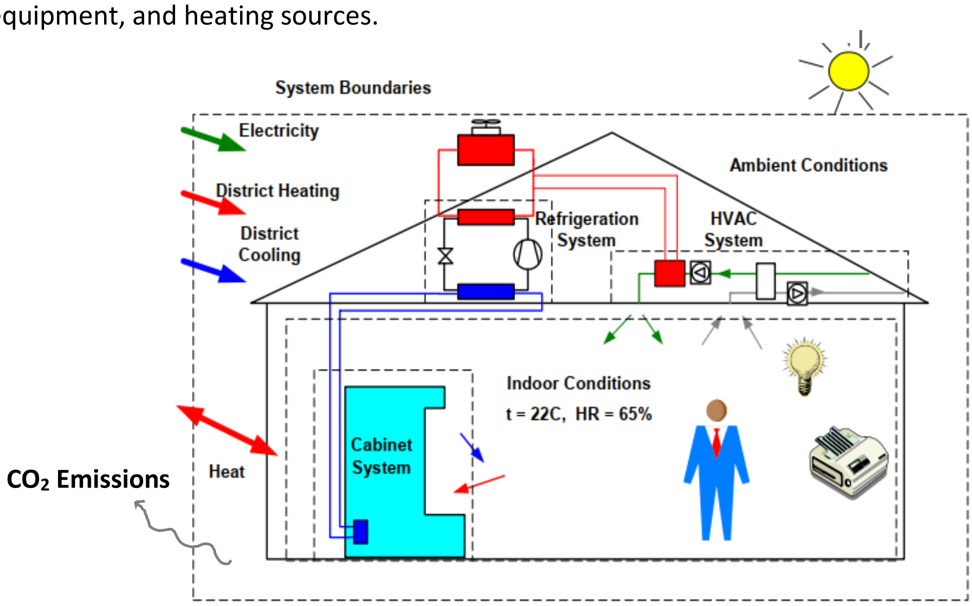

Figure 52. A conceptual scheme of the different subsystems in a supermarket and their interconnections, Taken from Arias (2005)

The impact of outdoor climate on energy usage in supermarkets is significant, affecting both the refrigeration system and indoor climate in multiple ways. Factors such as outdoor temperature, relative humidity, solar irradiation, and wind speed influence the indoor climate via the building envelope, ventilation system, and infiltration.

The thermal properties and structure of components, including walls, floors, roofs, and windows, determine the heat or cooling gains and heat transfer through the building envelope.

Ventilation systems provide comfort and acceptable indoor air quality by supplying air from outside, which is heated or cooled in the HVAC system based on the desired indoor conditions. Infiltration, caused by temperature differences and wind velocity, occurs through exterior doors and windows.

Lighting and equipment contribute significantly to a supermarket's energy performance, with the heat emitted affecting heating or cooling loads.

People, including customers and employees, also emit heat, moisture, and carbon dioxide, impacting heating and cooling needs. The number of occupants varies based on supermarket profiles and daily and weekly patterns.

Cabinets exchange heat and moisture with the surrounding air, requiring suitable indoor conditions to minimize cooling loads and prevent elevated product temperatures and frosting. Cold air entrainment from cabinets into the surroundings also affects heating and cooling requirements.

The supermarket control system manages operating schedules for lighting, equipment, HVAC systems, and temperature set points during different seasons and open or closed times.

Therefore, supermarkets are complex systems that require careful study to reduce energy consumption and greenhouse gas emissions.

1.23. Modelling methodology

The main objective of the model is to use an industry standard freely available software that allows to simulate the complex interactions between the different parts involved in a supermarket (HVAC, refrigerated cabinets, fans, outdoor climate, lights, people, electrical equipment, etc.).

By varying specific parameters and technologies like location, doors on refrigerated cabinets, type of heating, refrigerants, use of heat pump, etc., small and medium-sized supermarkets (measuring 600 m^2 and 2100 m^2, respectively) were simulated. The outcomes of these distinct simulations provide crucial data to assess the energy efficiency of a supermarket.

1.24. Softwares and interfaces

The softwares used in this study consisted of EnergyPlus V22.2.0 simulation engine, SketchUp Pro (Trimble Inc.) 2022, and OpenStudio (NREL, ANL, LBNL, ORNL, and PNNL) V1.5.0. The required cooling and heating capacity and total energy consumption for the modelled scenarios were computed using these tools. The model geometry was created using SketchUp, while OpenStudio was used to modify properties such as weather files, construction, materials, occupancy, internal loads, schedules, water, HVAC, and refrigeration systems. EnergyPlus was used to simulate energy consumption, and the results were displayed using the OpenStudio graphical user interface. The workflow of the modelling in this study is illustrated in Figure 53.

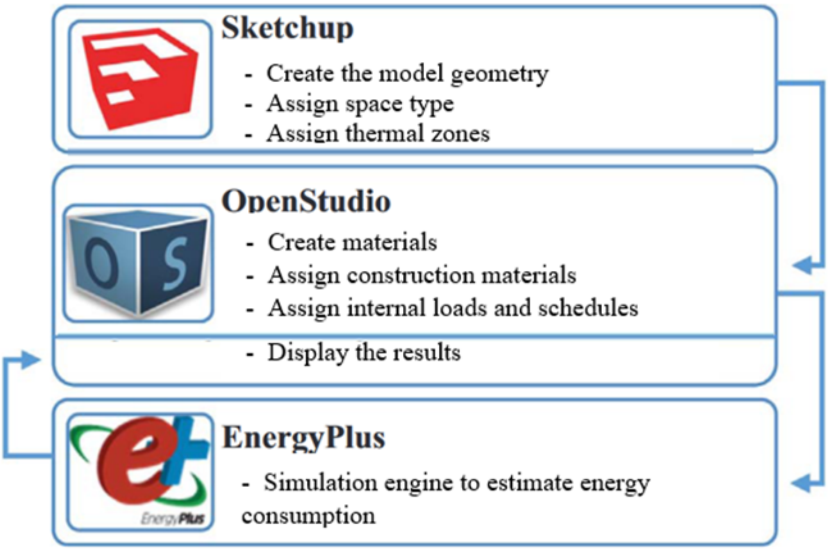

Figure 53. Workflow for modelling and simulating a building

1.25. Case study modelling

Using the data collected during the survey performed at a medium sized French supermarket, a first case study was simulated. In a second step, different parameters and technologies were varied one by one to assess their impact on energy consumption and GHG emissions.

Figure 54 shows a detailed modelling methodology adopted in all the work:

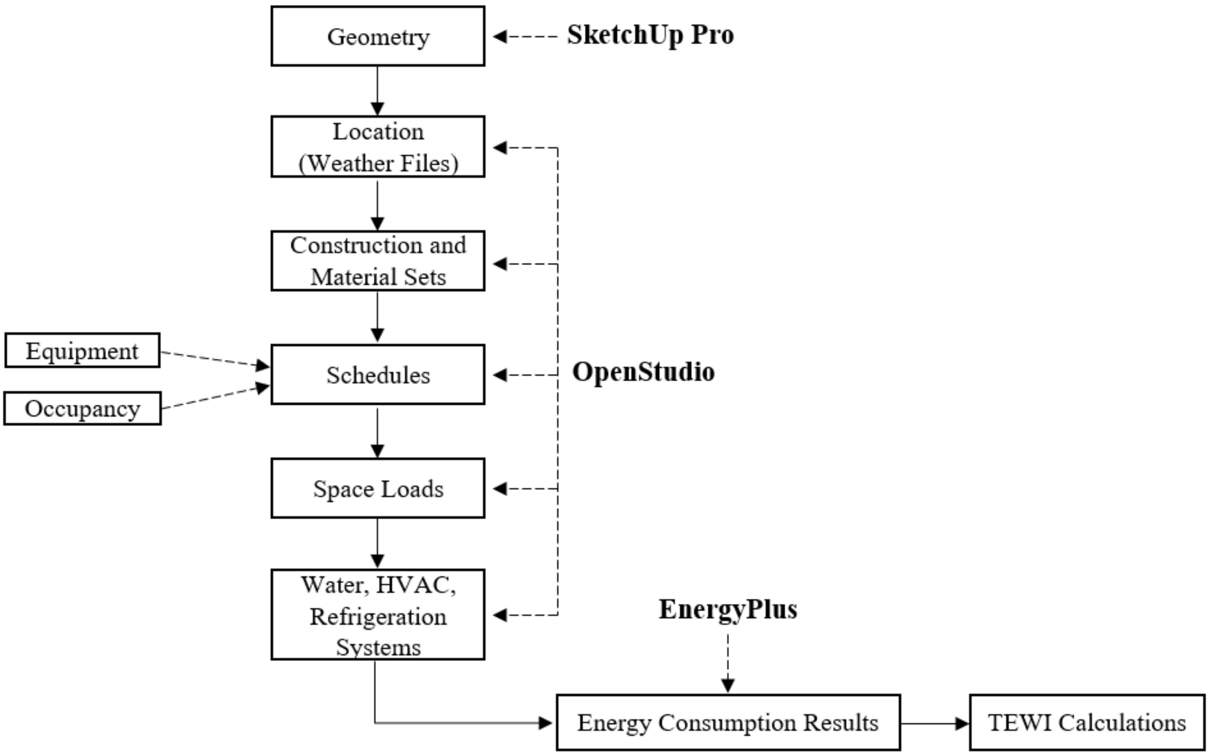

Figure 54. Methodology of work for modelling and simulating the case studies

1.25.1. Building envelope

A medium size supermarket with a floor area of approximately 2100 m² was first modelled. The geometry was created on SketchUp ensuring that the building type was assigned to a supermarket and that the surfaces had proper boundary conditions. The created supermarket had 5 spaces. The name of the space types and their corresponding floor area is shown in Table 15 below.

Table 15. Table showing the space type names with their corresponding floor area.

Space type	Floor area (m^2)
Sales area	1,085
Cold storage area	526
Dry storage area	267
Office area	111
Machines area	111

Figure 55 shows the geometry of the supermarket adopted in the simulation. The office area has one window located on an external wall. Additionally, by using the OpenStudio Plug-In (which was downloaded from the OpenStudio website) in SketchUp, the geometry was exported to an OpenStudio Model file (OSM) for further work to be carried out.

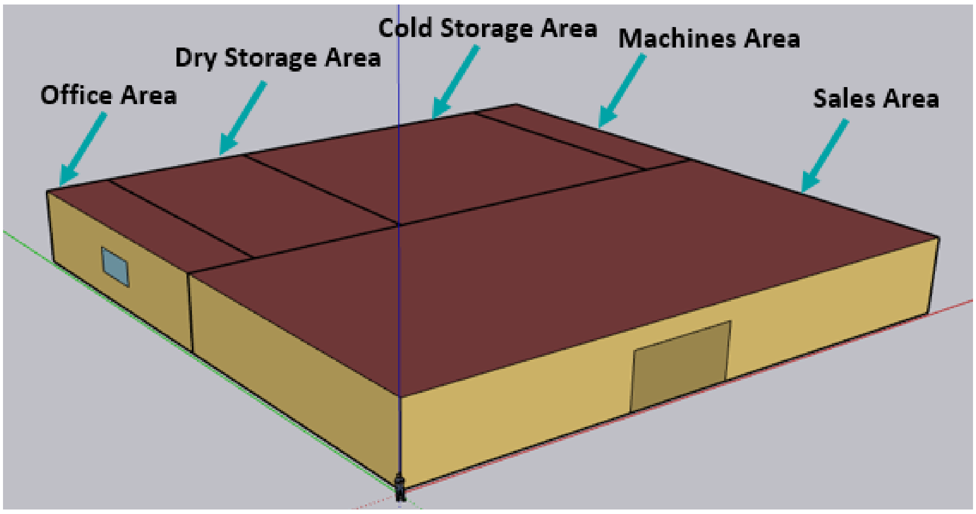

Figure 55. Geometry of the MS supermarket with its space types

1.25.2. Schedules

The individual loads in spaces are a strong function of occupancy and schedules, which usually varies with the time of day and day of the week. To model energy use and thermal loads accurately, we need to capture occupant, lighting, and equipment schedules.

The opening hours of the supermarket, number of people, lighting, equipment, and the hours of operation of different components like ovens for bakery were added in the schedule tab to define each space.

1.25.3. 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.

Since there was no information about the materials used in the construction of the building of the case study supermarket, a default construction set in the library related to a supermarket envelope defined by the American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) was loaded. Using this default construction set, materials from OpenStudio's built-in libraries were automatically loaded within the set.

1.25.4. Load definitions

Space Load definitions fall into several categories including people, lighting, electric, gas, and other equipment uses. Depending on available data, the power consumed by most loads is typically entered in OpenStudio in one of three ways: Rated power consumed by an individual unit within a space, or power consumed per unit of floor area, or power consumed per occupant in a space.

The simulation incorporated various lighting fixtures such as individual lamps, desk lamps, fluorescent tube arrays, emergency exit lights, and more. Additionally, appliances such as cash registers, printers, vending machines, microwaves, ovens, basic refrigerators, etc., were also considered.

1.25.5. Hot water systems

Water use equipment was modelled in a similar way to electric equipment. First, a definition is created to represent a piece of equipment such as a toilet or sink. Then, the peak flow rate, the number of toilets and the maximum target temperature for the heating were specified. Figure 56 shows a hot water system that includes a pump, a service water loop with a water heater on the supply side and a water use connection on the demand side.

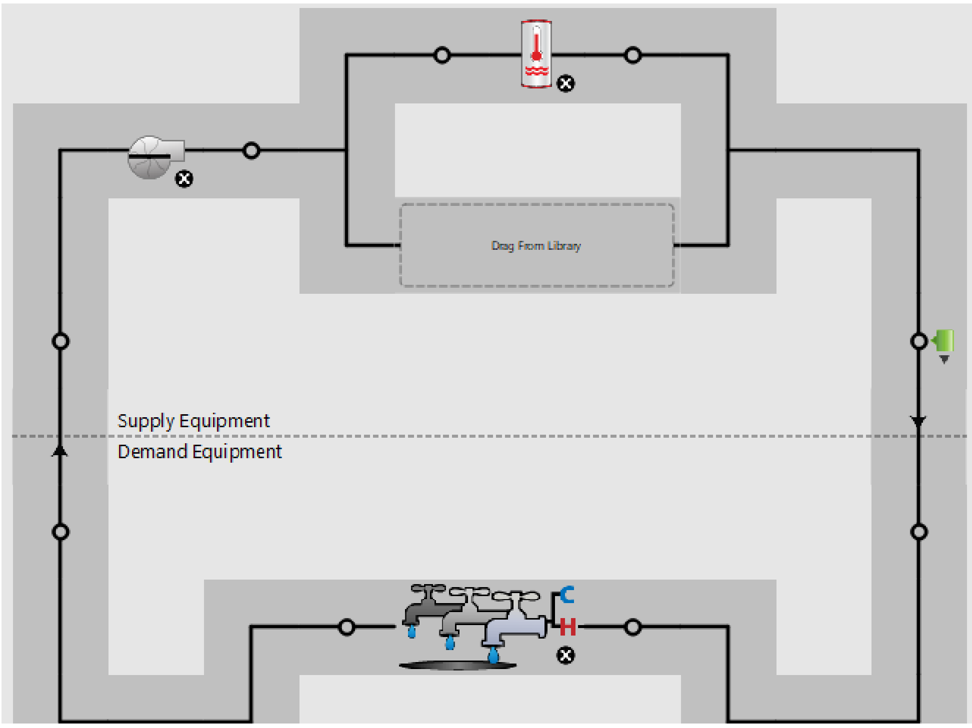

Figure 56. Adding a hot water loop for the MS supermarket

1.25.6. 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 in OpenStudio are "auto sized". This means that equipment flow rates, heating and cooling capacities, and other related properties are automatically determined by the EnergyPlus engine using a sizing algorithm driven by the load generated by thermal zones. The HVAC's control logic attempts to follow the thermal zone's thermostat set point. OpenStudio can model complex air conditioning units like air handlers using the "Air Loop HVAC" model. It is a modelling container where we can drag and drop sub-components such as fans, heating coils, cooling coils, and various equipment. As the name suggests, Air Loop HVAC is based on a closed loop concept with different supply and demand sides (see Figure 57).

Based on the case study, the HVAC system for the supply side in the sales area had a cooling coil, an electric heating coil, a fan supply, and an outside air system. The demand side is used to connect thermal zones which are the cold storage area and the sales area using a variety of zone terminal units. The office area is controlled by a packaged terminal air conditioner (PTAC) which is independent of the other areas. OpenStudio modellers often have a choice between using the Air Loop model or using other pre-built HVAC objects for a specific purpose.

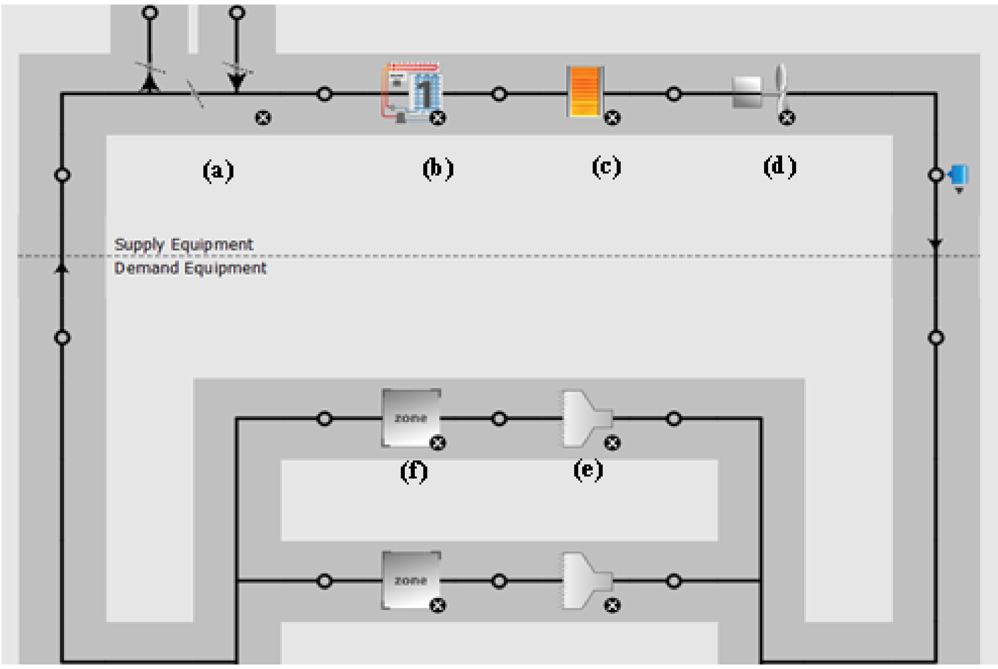

Figure 57. Adding a typical HVAC system for the MS supermarket: (a) Outside air system, (b) Cooling coil, (c) Electric heating coil, (d) Fan, (e) Zone terminal units, (f) Zone

1.25.7. Refrigeration systems

OpenStudio recently included refrigeration systems and components. EnergyPlus can model a wide variety of systems and components found in commercial and industrial applications. It has a wide variety of components included in the library like refrigerated display cases, walk-in coolers, compressors, condensers, heat exchangers, etc… Additionally, any refrigerant can be modelled by providing tabular thermodynamic data for the refrigerant. Components such as display cases, compressors and condensers can be created by dragging and dropping them from the library tab to the appropriate location in the refrigeration system.

An example of a refrigeration system based on the case study supermarket is shown in Figure 58. Due to the absence of the R744 booster system in OpenStudio, a measure was developed to establish a connection between EnergyPlus and OpenStudio, allowing for the simulation of the R744 booster system. The simulated R744 booster refrigeration system was composed of a gas cooler, a flash tank, 4 medium temperature (MT) compressors that work in both subcritical and transcritical operations linked to chilled cabinets and cold stores and 4 low temperature (LT) compressors that only work in subcritical mode linked to frozen cabinets and cold stores. Evaporators were present inside the refrigerated cabinets.

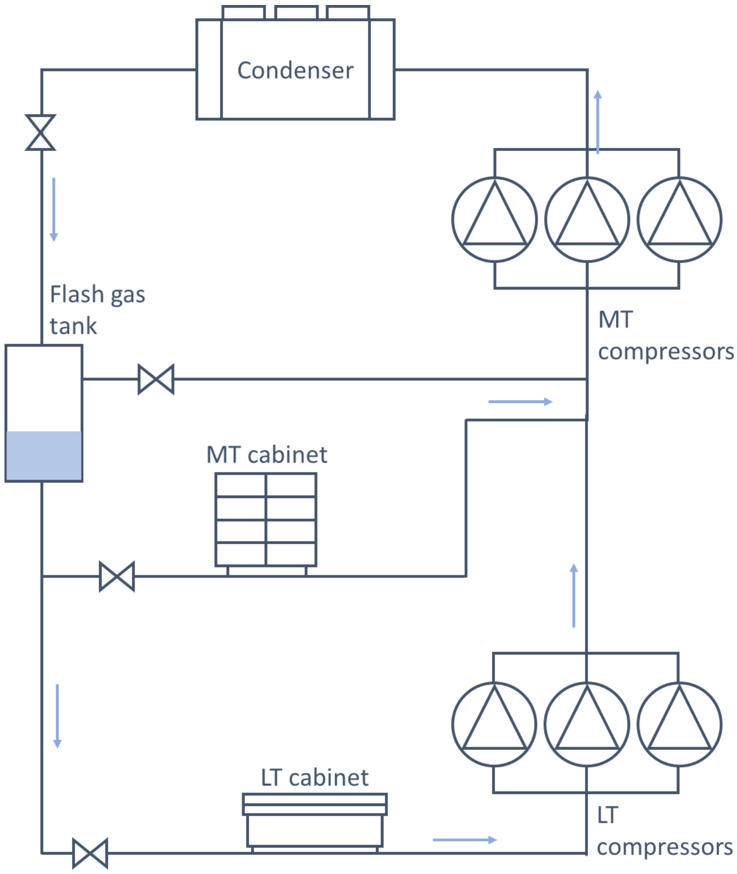

Figure 58. Adding a refrigeration system for the MS supermarket

1.25.8. Case study supermarket

The model was calibrated against data from Foster et al. (2018a) for energy use in an average UK supermarket (based on data from one retailer), because data concerning the breakdown of energy and many other parameters in the French store were missing. Data used in the Foster et al. (2018a) study contained information on the division of energy used within UK stores from store sub-metering. A mean value was used to represent an average store. This mean store size of 5,845 m^2 store was larger than the store modelled in Paris of 2,100 m^2. It has been reported by Foster et al. (2018a) that the total energy consumption of supermarkets above ~2,000 m^2 is relatively linear with the size of the store. It was therefore assumed that the energy consumed by the larger UK store could be linearly adjusted to the size of the French store. Using a baseline store, the calculation of the refrigerant charge for the supermarkets was based on Foster et al.'s (2018b) reported 3.7 kg per meter of cabinets.

The average UK store was used to calibrate the model. It operated on R404A and used gas heating (with a boiler efficiency of 0.8). However, as R404A is only used in old stores and the French store was using a R744 booster system, it was assumed that the calibration store operated on R744.

Many parameters were studied, and many trial-and-error simulations were conducted varying many variables to reach acceptable correlation with the real data of the average UK store. Table 16 presents the data from the UK store adjusted for size with the French store and the resulting energy consumption predicted by the model after calibration. There is another portion of energy in the average store named others. This portion could be added anywhere since it is unmetered and gave us flexibility in calibrating our model.

Table 16. Breakdown of annual energy consumption in the MS UK store

	HVAC	Interior equipment	Heating	Refrigeration	Lighting	Water systems + pumps	Others	Total
Calibration store (kWh/year)	56,430	158,107	199,575	236,741	101,714	16,776	122,450	891,793
Simulated UK store (kWh/year)	56,497	160,603	195,128	238,075	103,525	16,883	----------	770,711
% difference	0.1%	1.6%	-2.2%	2.8%	1.8%	0.6%	----------	-13%

The input variables for the case study supermarket considered are shown in Table 17. Some of the information came from a visit to the store. Where there was no adequate information, estimates were used from similar studies and expert knowledge. It's important to mention that while we initially used default sets, certain values were altered when we calibrated the model using data of the average store.

Table 17. Attributes of the MS case study supermarket

	2,100 m^2 store (total area)
Location	Paris (France)
Opening hours	8:30 am – 9 pm (Monday-Saturday) 9 am – 1 pm (Sunday)
Typical number of customers/day	1800
Sales area (m^2)	1085
Store height (m)	6
Store fuel source	100% electrical energy
Display cabinets and cold stores	

	2,100 m² store (total area)
Remote display cabinet details: (Sales area)	

	Case length (m)	Case height (m)	Operating T (°C)	Rated Cooling capacity (W/m)	Fan (W/m)	Light (W/m)	Defrost (W/m)
Chilled	83.75	1.5	3	500/1000[48]	30	20	Off cycle
Frozen	18.75	1.5	-18	400	30	20	1400
Defrosting			0.5 hour each twice per day, only on frozen cabinets				
Anti-sweat heater			None for chilled, 100 W/m for frozen cabinets				

Type of expansion valves applied	Electronic expansion valves	
Type of cabinet fan motors	Electronically commutated	
Refrigeration system	CO_2 booster system (R744)	
	Compressors	R744 Bitzer: 2GSL-3K-4SU (subcritical low stage) – 4FTC-20K (transcritical high stage)
	Gas cooler	Capacity Q (W) = 12500 ($T_{gas\ cooler}$ –$T_{ambient}$)[49] Variable speed fan, 3.75 kW maximum power[49]
	Evaporating temperature	Chilled/Frozen: -5°C/-30°C[50]
	Cabinet infiltration schedule[51]	For open cabinets (do nothing scenario): 1 (no barrier to infiltration) during the day – 0.2 at night (night blinds) For closed cabinets (minor/major retrofit scenario): 0.3 during the day – 0.1 at night (with doors on cabinets)

[48] When simulating cabinets with doors, a rated cooling capacity of 500 W/m was used, while cabinets without doors were assigned a rated cooling capacity of 1000 W/m.

[49] The condenser was dimensioned based on the climate of Rome which is the warmest country, and then was employed in the other countries. Foster et al. (2018b) stated selecting the maximum rated fan power as 3% of heat rejection Q(W).

[50] CO2 Product Guide 2021 for Refrigeration. Emerson. Applications co2-product-guide-2021-for-refrigeration-applications-en-gb-4217772.pdf (emerson.com)

[51] Metal/plastic coverings may be installed on refrigerated display cases during unoccupied hours which would significantly reduce sensible case credits (e.g., air infiltration) compared to occupied hours when the coverings are removed. Adding doors on cabinets also considerably reduces the sensible case credits.

	2,100 m^2 store (total area)	
	Rated latent heat ratio[52]	0.2 without doors on cabinets – 0.3 with doors on cabinets
	Minimum condensing temperature (°C)	10°C (subcritical)[53]
	Transition temperature (°C)	27°C outdoor temperature to switch from subcritical to transcritical operation[53]
	Design temperature difference of gas cooler	3 K greater than ambient T[53] (transcritical) 10 K greater than ambient T (subcritical)
	Receiver pressure (R744)	40 bar
Refrigerant Charge (kg)	380	
Refrigerant leakage (/year)	10%	
Number of cold stores	8	

Cold store details: (Cold storage area)

Walk in cooler no.	Total surface area (m^2)	Height of doors (m)	Operating T (°C)	Cooling coil capacity (W)	Fan (W)	Light (W)	Defrost (W)
1-2	43	2	-18	4690	735	120	2500
3-8	43	2	3	4690	735	120	2500

Insulated floor U value: 0.207 W/m^2. K

Insulated surface U value facing zone: 0.235 W/m^2. K

Stocking door U value facing zone: 0.3785 W/m^2. K

Bakery	
Number of ovens	5

[52] For estimating the latent air infiltration load, the model requires that the user provide the latent heat ratio (LHR) for the refrigerated cases at rated conditions. It typically ranges from 0.1 to 0.3 depending on case configuration (e.g., multi-deck open case versus glass door reach-in) and case operating temperature.

[53] Sharma, V., Fricke, B., & Bansal, P. (2014). Comparative analysis of various CO_2 configurations in supermarket refrigeration systems. International journal of Refrigeration, 46, 86-99.

	2,100 m² store (total area)
Bakery Schedule	3h per day, Monday to Saturday 1h on Sunday
Fuel	Electrical
Heat output	18 W/m²
Floor area	20 m²
HVAC	
Type of HVAC System	Air handler unit without heat recovery
Heating	Electrical
Cooling DX Rated COP Heating efficiency Fan pressure rise Fan total efficiency Motor efficiency Controlled thermal zones Outside air (OA) schedule Heating design supply T Cooling design supply T	3 1 (electric resistive) 620 Pa 0.7 0.9 Sales area, office area, cold storage area 1 during the day (OA supplied) and 0 during the night (OA intake closed) 40°C 14°C
Heating thermostat	21°C/19°C during the day/night (sales area) 18°C/16°C during the day/night (office and cold storage area)
Cooling thermostat	24°C
Building	
Construction set	ANSI/ASHRAE/IES Standard 90.1 ASHRAE 169 – Climate zone 5C Supermarket 2013
Material set	Concrete, gypsum, typical insulation, etc.
Store lighting type	LED (part of the sales area) Fluorescent tubes T5-T8 (everything else)

	2,100 m² store (total area)			
Loads		People (people/m²)	Lights (W/m²)	Electric (W/m²)
	Sales area	0.086111	12	19
	Office area	0.053820	10	3.875009
	Machines area	0.035951	2.62	2.906256
	Cold Storage area	0.035951	2.62	-
	Dry Storage area	0.053820	2.62	3.336812
	Different schedules during opening and closing hours			

1.25.9. EnergyPlus calculations

The most important formulas used by EnergyPlus when running the simulations in OpenStudio are detailed in this section. They are taken from the Engineering Reference Documentation for EnergyPlus which contains detailed explanations and calculations (U.S. Department of Energy 2022).

The total load on the refrigerated case evaporator is made up of various components:

$$Q_{case} = Q_{walls} + Q_{rad} + Q_{inf,sens} + Q_{inf,lat} + Q_{lights} + Q_{as} + Q_{def} + Q_{fan} + Q_{restock} \qquad \text{(Eq. 1)}$$

where: Q_{case} is the total load on the refrigerated case evaporator (W); Q_{walls} is the heat transfer through case walls due to the difference between the refrigerated case operating dry-bulb temperature and the zone air dry-bulb temperature (W); Q_{rad} is the radiant heat transfer to the refrigerated case (W); $Q_{inf,sens}$ is the sensible heat transfer by air infiltration to the refrigerated case through the air curtain or via door openings (W); $Q_{inf,lat}$ is the latent heat transfer by air infiltration to the refrigerated case through the air curtain or via door openings (W); Q_{lights} is the lighting heat load (W); Q_{as} is the anti-sweat heater load (W); Q_{def} is the defrost heat load (W); Q_{fan} is the fan heat load (W); $Q_{restock}$ is the sensible load on the refrigerated case due to restocking of products that are at a higher temperature than the case (W).

$$Q_{fan} = P'_{fan,oper}\,(L_{case})(1 - SCH_{defrost}) \qquad \text{(Eq. 2)}$$

where: $P'_{fan,oper}$ is the operating case fan power per unit length (W/m); L_{case} is the case length (m); $SCH_{defrost}$ is the fraction of time case is being defrosted (0 to 1).

$$Q_{lights} = P'_{lights,installed}(L_{case})(SCH_{lights})(F_L) \qquad \text{(Eq. 3)}$$

where: $P'_{lights,installed}$ is the installed case lighting power per unit length (W/m); SCH_{lights} is the case lighting schedule value (0 to 1). A maximum schedule value of 1.0 means the lights are fully on at the installed case lighting power level. Schedule values of 0 indicate the lights are off and 0.5 at half-power; F_L is the fraction of lighting energy to case.

$$Q_{as} = P'_{as}\,(L_{case})(F_{as}) \qquad \text{(Eq. 4)}$$

where: P'_{as} is the case anti-sweat heater power per unit length (W/m); F_{as} is the fraction of anti-sweat heater energy to case.

$$Q_{restock} = SCH_{restock}(L_{case}) \quad \text{(Eq. 5)}$$

where: $SCH_{restock}$ is the refrigerated case restocking schedule value (W/m).

$$Q_{def} = P'_{def}\,(L_{case})SCH_{defrost} \qquad \text{(Eq. 6)}$$

where: $P_{'def}$ is the case defrost power per unit length (W/m); $SCH_{defrost}$ is the case defrost schedule value (0 to 1).

$$Q_{inf,lat} = Q_{case,rated}(LHR_{rated})(RTF_{rated})(SCH_{cc})(LatentRatio)L_{case} \quad \text{(Eq. 7)}$$

where: $Q_{case,rated}$ is the case rated total cooling capacity per unit length (W/m); LHR_{rated} is the latent heat ratio of the refrigerated case at rated conditions; RTF_{rated} is the runtime fraction of the refrigerated case at rated conditions; SCH_{CC} is the case credit fraction (schedule value, 0 to 1); LatentRatio is the ratio of actual latent load to rated latent load on the case, based on latent case credit curve.

For Q_{walls}, $Q_{inf,sen}$, Q_{rad}:

The case loads due to wall heat conduction, radiation, and sensible air infiltration are estimated by the model as a single lumped value (sensible case credits). The sensible case credits are calculated by subtracting the known loads at rated (std) conditions (fan, lighting, anti-sweat heater, defrost and latent case credits) from the rated total cooling capacity of the case which is provided by the case manufacturer ($Q_{case,rated}$).

$$Q_{cc\ sens,rated} = [Q_{case,rated}(RTF_{rated})(1 - LHR_{rated}) - P'_{lights,std}(F_L) - P'_{as}(F_{as}) - P'_{fan,std}]\ L_{case} \quad \text{(Eq. 8)}$$

The same logic applies for the Walk-In cases (cold storage rooms), so:

$$Q_{refrigeration} = Q_{cases} + Q_{walkIns} \quad \text{(Eq. 9)}$$

where: Q_{case} is the total load on the refrigerated case (W); Q_{walkIn} is the total load on cold storage rooms (W).

$Q_{compressor}$ of a R404A DX system or a transcritical CO_2 is calculated by correlation coefficients, C_x, either directly from compressor manufacturers or from cubic curve fits predefined in EnergyPlus. For convenience, correlation coefficients for R404A/CO_2 compressors from several manufacturers have been included in the EnergyPlus refrigeration compressor coefficient database and were used for the calculations.

1.25.10. *Small store*

A smaller store (convenience store was modelled). This had a total floor area of 600 m^2 and had the same 5 spaces as the big store: sales, offices, dry storage, cold storage, and a machine room, with areas of 390 m^2, 28 m^2, 56 m^2, 98 m^2 and 28 m^2, respectively. As mentioned before, it is important to state that certain values like the loads in the spaces were altered when we calibrated the model using data of a real average store. All the parameters were kept the same except for the following which were:

- Typical number of customers = 1200 per day
- Refrigerant = R448A (GWP = 1387)
- Refrigerant charge = 232 kg
- R404A/R448A Compressors = Copeland-DISCUS-3DF3-120E-TFD
- Minimum condensing temperature = 21°C
- Capacity of the air-cooled condensers: R404A/R448A simulations
  Q(W) = 5400 ΔT, rated fan power P = 1.6 kW (MT cabinets and cold stores)
  Q(W) = 800 ΔT, rated fan power P = 0.24 kW (LT cabinets and cold stores)
- Capacity of the gas cooler: R744 simulations
  Q(W) = 2500 ΔT, rated fan power P = 0.75 kW
- Evaporating temperatures = Chilled/Frozen: -8/-33°C for HFC/HFO blend[50]
- HVAC fan pressure rise = 260 Pa

- Bakery floor area = 15 m^2
- Length of chilled cabinets = 51.4 m
- Length of frozen cabinets = 11.45 m
- Number of cold chambers = 2
- Number of ovens = 2
- Electric load in the sales area = 28.5 W/m^2
- Lights load in the sales area = 23.5 W/m^2
- No hot water system was considered for this supermarket

For direct expansion (DX) R448A simulations, the refrigeration system was split into two racks (one for low temperature and one for medium temperature cabinets and cold stores) with an air-cooled condenser and 2 compressors each. For R744 simulations, the same system methodology was used as the MS supermarket.

The information in Table 18 shows the adjusted data for a small UK store compared to an average store from Foster et al. (2018a) data. The energy consumption predicted by the model after calibration is also presented. It's worth noting that the average store used as a comparison did not have a hot water system, which is consistent with all the other stores used to represent the average.

Table 18. Breakdown of annual energy consumption in the SS UK store

	HVAC	Interior equipment	Heating	Refrigeration	Lighting	Total
Calibration store (kWh/year)	8,600	83,976	86,431	128,388	67,770	375,165
Simulated UK store (kWh/year)	8,653	83,464	105,617	124,422	66,900	389,056
% difference	0.6%	-0.6%	22%	-3%	-1.3%	3.7%

1.25.11. 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. Referring to Brackney et al. (2018), since the weather varies from a year to another and from a country to another, a method was developed to combine several years of weather data into a "typical" meteorological year (TMY). TMY represent the average annual weather and a range of extreme weather conditions for a given location. Additional weather information can be found in Design Day (DDY) files, which describe the extreme climatic conditions for a location in a day. They are often used in HVAC systems since they must maintain the building comfortable during extreme conditions. TMY and DDY data are essential and important inputs to any OpenStudio model as they represent the environmental conditions that the building will face. They are freely available for many locations and can be downloaded in EPW and DDY formats from https://energyplus.net/weather.

To simulate the first supermarket based on real data, we downloaded the weather files associated with Paris (France) where the supermarket was located.

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

1.26. Total equivalent warming impact (TEWI)

Based on the British Refrigeration Association (1996), the TEWI characterises CO_{2e} emissions and is a useful tool to study the impact of supermarket systems on global warming. The TEWI combines the direct and indirect emissions of CO_{2e}. For any system, TEWI is based on the following relation:

$$TEWI = (GWP \times m \times L) + (E \times \beta) \quad \text{Eq. (10)}$$

Where TEWI is the kg of CO_{2e} produced during a year; $(\mathrm{GWP} \times \mathrm{m} \times \mathrm{L})$ are direct emissions of CO_{2e} due to refrigerant leakage; $(\mathrm{E} \times \beta)$ 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 (kg); L is the leakage rate per year; E is the electrical energy consumption per year (kWh/year); β is the CO_{2e} equivalent emissions per kWh of electrical energy produced (kg CO_{2e}/kWh). A UK Government figure of 0.184 kg of CO_{2e} per kWh was used for the combustion of natural gas (NG) (UK Government, 2016). GWPs (100-year horizon) for HFC/HFO blend were taken from the IPCC AR4 report (2007). The same refrigerant charge was considered for all refrigerants in the small supermarket. The leakage rate in European countries was assumed to be 10% per year. According to Aurora (2021), the electrical carbon emission factor was 0.057 kg CO_{2e}/kWh for France in 2020.

Figure 20 includes additional data from Aurora (2021) modelling for the remaining countries that were analyzed.

1.27. Bibliography for modelling

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