COLD STORES ROADMAP

The **Zero Emission Cold-Chain (ZECC)** project brings together experts from across several UK Universities to build a series of roadmaps to reach the UK's 2050 net-zero carbon emissions target for the cold chain. This four-year project challenged decarbonisation issues by exploring the techno-economic and behavioural aspects of the cold-chain system and the integration of sectors.

Much of UK's food is dependent on the cold food chain, which is also a significant contributor to the country's energy demand. This project is about thinking thermally and analysing engineering, energy resources, food quality and safety, finance and business aspects to crack the conundrum of sustainable decarbonisation of cooling and the cold chain.

ZECC brings together world-leading researchers, industry, technology innovators and customers such as farmers and retailers to look at the whole system and map the opportunities and challenges to ensure that the chain can support UK-wide Net Zero goals and decarbonise while also meeting demand and being resilient.

Project partners took a whole systems approach toward a sustainable cold-chain by exploring the reduction of cooling within food cold-chain, investigating sustainable technologies and the optimisation of cooling equipment and operations as well as integrating cooling demands into a single efficient system. The approach aligns with the Sustainable Development Goals of the United Nations (12.3).

The ZECC project roadmaps aim to:

- Reduce carbon emissions and reach the UK's 2050 net-zero target
- Reduce food loss while maintaining the nutritional value of produce
- Provide information on energy usage and the future of cooling energy consumption demands, taking a systems approach to demands and their impact on the UK
- Reduce costs as well as identifying economic opportunities

This roadmap in particular focuses on the UK cold storage sector.

Authors and acknowledgements

The ZECC project was led by the University of Birmingham, with London South Bank University, Heriot-Watt University, and Cranfield University as partners in the consortium. The project acknowledges support from the Engineering and Physical Sciences Research Council (EPSRC) under research grant EP/V042548/1.
ZECC also acknowledges the ENOUGH project (EU Horizon 2020 grant agreement No. 101036588) for supporting related research.

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ZECC Cold Stores Roadmap

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Nomenclature

1-MCP	1-methylcyclopropene
ACP	Oxygen stress point
AGV	Automated guided vehicle
AIRAH	Australian Institute of Refrigeration, Air Conditioning and Heating
AMR	Autonomous mobile robot
AS/RS	Automated storage and retrieval system
BAT	Best available technology
BLDC	Brushless DC motors
CA	Controlled atmosphere
CCF	Cold Chain Federation
CES	Corporate environmental sustainability
CHP	Combined heat and power
CI	Carbon intensity
CO_2	Carbon dioxide
COP	Coefficient of performance
DC	Direct current
DCA	Dynamically controlled atmosphere storage
DSR	Demand side response
DX	Direct expansion system
EC	Electronically commutated
EEV	Electronic expansion valve
EI	Energy intensity
ESEER	European seasonal efficiency ratio
ETS	Emissions Trading System
EU	European Union
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FW	Food waste
GHG	Greenhouse gas
GW	Giga Watts
GWP	Global warming potential
HCT	Half cooling time
HFC	Hydro fluorocarbon

HFO	Hydrofluoroolefin
HP	High pressure
HVAC	Heating ventilation and air conditioning
HVAC&R	Heating, ventilation, air conditioning and refrigeration
IOR	Institute of Refrigeration
IPCC	Intergovernmental Panel on Climate Change
kW	Kilo Watt
LCA	Life cycle assessment
LED	Light emitting diode
LP	Low pressure
LPR	Low-pressure receiver
LT	Low temperature
NDC	Nationally determined contribution
NH_3	Ammonia
O_2	Oxygen
ODP	Oxygen depletion potential
PCM	Phase change material
PIR	Polyurethane isocyanurate
PMS	Permanent Magnet Synchronous
PSC	Permanent split capacitor
PV	Photo voltaic
PWM	Pulse width modulation
RCP	Representative concentration pathway
RDC	Regional distribution centre
RES	Renewable energy source
RH	Relative humidity
ROI	Return on investment
RQ	Respiration quotient
SEC	Specific energy consumption
SECT	Seven-eighths cooling time
TEV	Thermostatic expansion valve
TEWI	Total equivalent warming impact
TOA	Total open area
TRL	Technology readiness level
UK	United Kingdom

ULO	Ultra-low oxygen
UNRCCC	United Nations Framework Convention on Climate Change
VFD	Variable frequency drive

Executive summary

In this roadmap we question how the food cold storage sector can decarbonise and rapidly reach net zero. As part of the work, we provide independent reviews of 30 different technologies/strategies that cold stores could apply to reduce carbon emissions and energy consumption. Scope 1 and 2 emissions are covered which encompass emissions from leakage of refrigerants and emissions from direct fuel and electricity use

The reviews were used to identify the individual technologies/strategies that had the most potential to reduce GHG emissions in food cold stores. Only technologies with a high technology readiness level (TRL) were considered as we wanted to assess what was feasible today. Carbon emissions from many lower TRL technologies were often difficult to quantify and many 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 2025 through to 2050 considering changes due to global warming and the electrical grid carbon intensity, as well as the impact of combined technologies/strategies. Two facilities were considered: a frozen and a chilled storage facility. It should be noted that cold stores often have varied operational practices and designs. This means that cold stores should be considered individually and that the cold stores considered in the road map are only examples of the opportunities available to reduce carbon emissions.

For each of the 2 selected facilities we assessed the following scenarios:

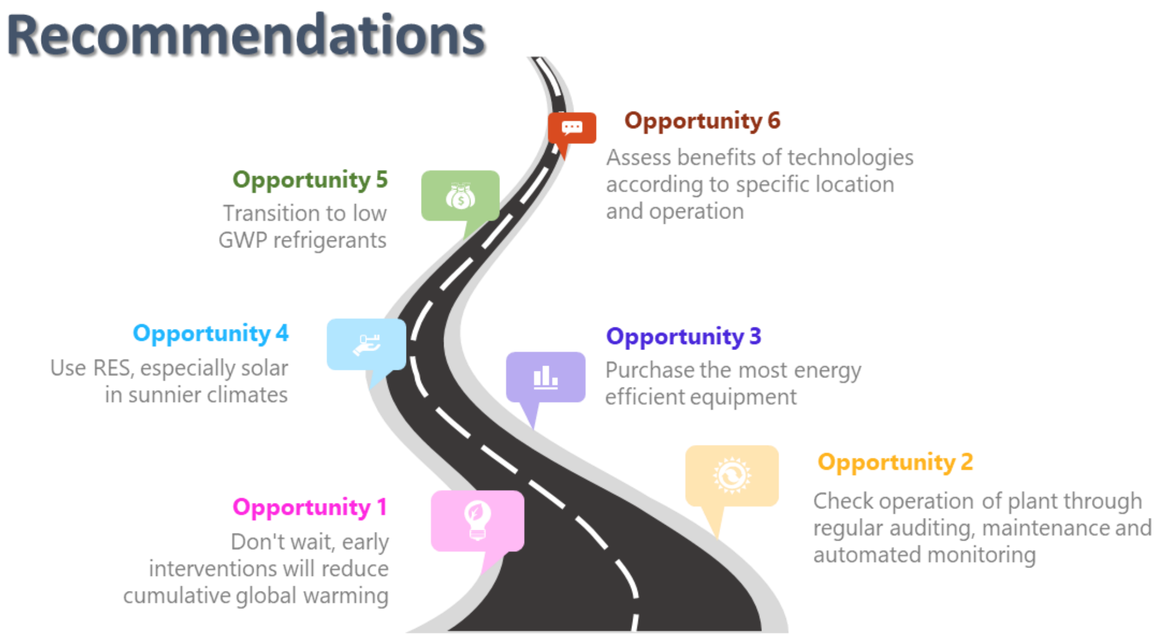
1. Do nothing: the impact of changes due to global warming (two climate change scenarios) and changes to the electrical grid carbon intensity were considered.
2. Minor retrofit: shorter term options that could be applied for cold stores that were not due to be replaced in the near future or undergo major refurbishment.
3. Major retrofit: changes that could be applied either following a major retrofit or to a new cold store.

The scenarios were applied to 2 locations in the UK (London and Aberdeen) and the impacts assessed. These two locations were selected for their different climate.

Results from the reviews and modelling identified routes for the cold storage sector to reduce emissions and enabled the creation of a roadmap through to 2050. Overall, it was estimated that it was possible to reach very close to net zero in 2050 in both locations. The application of zero or very low global warming potential (GWP) refrigerants was critical to the low carbon emissions achieved. The electrical grid carbon intensity was critical in being able to achieve low emissions in 2050.

Although reducing the carbon intensity of the electricity grid is central to lowering future emissions, achieving net zero will also require energy and emission reducing technologies and strategies to limit overall electricity demand and reduce the scale of generation and grid infrastructure needed as more sectors electrify. All the interventions had contribution to reduce carbon with the use of solar photovoltaic (PV) panels and efficient compressors having the greatest impact. It was also clear that monitoring and control, good maintenance and energy audits were opportunities that should be highlighted and had considerable benefits.

Our recommendations to reduce carbon in cold stores are presented graphically below:



1 About this roadmap

Globally, greenhouse gas emissions (GHG) emissions from the food chain are estimated to account for 33% of the total GHG emissions[1]. Emissions from the food chain result from direct (methane from livestock, nitrous oxide from fertilizers, carbon dioxide from land clearing, refrigerant leakage, fuel use) or indirect sources (electricity).

The main emphasises of this road map is to assess the potential for cold storage warehouses to achieve net zero. The sector covers large and small cold stores where food is stored in a chilled or frozen state. Many larger warehouses and regional distribution centres are owned by international conglomerates. On the other hand, many smaller cold stores exist at food processing outlets, in retail stores and catering outlets.

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 cold storage sector is feasible.

2 Introduction

2.1 The market

In the UK, the cold chain sector is a significant part of the food industry and national infrastructure. According to the Cold Chain Federation (CCF), the UK frozen food industry is worth over £8 billion, while the chilled food industry exceeds £11 billion. The sector directly employs more than 16,000 people, including warehouse operatives, drivers, systems analysts and robotics engineers. There are an estimated 1,131 cold stores across Great Britain and Northern Ireland, of which 440 are large facilities and members of the CCF. Among stores reporting storage volume, total cold storage capacity is approximately 34 million m^3, with an average store size of 84,494 m^3[2].

2.2 UK policy drivers

In June 2019, the United Kingdom became the first major economy to legislate a legally binding net zero greenhouse gas (GHG) emissions target for 2050. It has also committed to reducing emissions by 68% by 2030 (compared to 1990 levels) under its Nationally Determined

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

[2] Cold Chain Federation (CCF), 2026. Cold Chain report 2026. Available online: https://www.coldchainfederation.org.uk/cold-chain-report-2026/

Contribution (NDC) to the Paris Agreement, and by 78% by 2035 in line with the Climate Change Committee's Sixth Carbon Budget[3].

To achieve these targets, the UK Government has introduced a range of cross-sector policies, including:

- **Net Zero Strategy (Build Back Greener)** – outlining actions across energy, transport, buildings and industry to deliver emissions reductions[4].
- **British Energy Security Strategy (2022)** and **Powering Up Britain (2023)** – accelerating renewable and nuclear deployment, including a target of 50 GW of offshore wind by 2030, alongside investment in solar, hydrogen and carbon capture technologies[5,6].
- **Transport Decarbonisation Plan (2021)** – phasing out the sale of new petrol and diesel cars and vans by 2035 and expanding electric vehicle infrastructure[7].
- **Clean Maritime Plan** – reducing greenhouse gas emissions from shipping and promoting low-carbon fuels at UK ports[8].
- **Jet Zero Strategy (2022)** – increasing the use of Sustainable Aviation Fuels (SAFs) and supporting zero-emission flight technologies[9].
- **Environmental Land Management (ELM) scheme** – incentivising landowners to enhance carbon sequestration, biodiversity and sustainable land use[10].

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[3] Climate Change Committee, 2021. *The Sixth Carbon Budget: The UK's Path to Net Zero.* London: CCC. Available at: https://www.theccc.org.uk/publication/sixth-carbon-budget/

[4] Department for Energy Security and Net Zero & Department for Business, Energy & Industrial Strategy, 2021. *Net Zero Strategy: Build Back Greener*. GOV.UK, published 19 October, updated 5 April 2022. Available at: https://www.gov.uk/government/publications/net-zero-strategy

[5] Department for Energy Security and Net Zero; Prime Minister's Office; Department for Business, Energy & Industrial Strategy, 2022. *British energy security strategy*. GOV.UK, published 7 April. Available at: https://www.gov.uk/government/publications/british-energy-security-strategy

[6] Department for Energy Security and Net Zero, 2023. *Powering Up Britain.* London: DESNZ. Available at: https://www.gov.uk/government/publications/powering-up-britain

[7] DfT (Department for Transport), 2021. *Transport Decarbonisation Plan.* London. Available at: https://www.gov.uk/government/publications/transport-decarbonisation-plan

[8] DfT, 2019. *Clean Maritime Plan.* London. Available at: https://assets.publishing.service.gov.uk/media/5d24a96fe5274a2f9d175693/clean-maritime-plan.pdf

[9] DfT, 2022. *Jet Zero Strategy: Delivering Net Zero Aviation by 2050.* London. Available at: https://www.gov.uk/government/publications/jet-zero-strategy-delivering-net-zero-aviation-by-2050

[10] Department for Environment, Food and Rural Affairs (DEFRA), 2023. *Environmental Land Management schemes: overview*. London: DEFRA. Available at: https://consult.defra.gov.uk/elm/elmpolicyconsultation/supporting_documents/ELM%20Policy%20Discussion%20Document%20230620.pdf

- **England Trees Action Plan (2021–2024)** – supporting the planting of at least 30,000 hectares of new trees annually by 2025 to contribute to carbon removal and nature recovery[11].

2.3 Types of food stores

Cold stores can be categorised on their operation temperature or on their function[12].

2.3.1 Cold store temperature categorisation

Chilled cold stores: chilled cold stores generally maintain temperatures between -1°C and 5°C, although some fruit stores for climacteric fruit can operate at higher temperatures. They are commonly used for storing fresh meat, seafood, poultry, and other perishable food items to extend their shelf life.

Frozen cold stores: frozen cold stores generally maintain temperatures below -18°C to preserve goods at frozen conditions. They are used for storing a wide range of frozen products, including frozen meat, fish, vegetables, ice cream, and other frozen food items. The temperature inside frozen cold stores can range from -18°C to as low as -40°C in specialised facilities (e.g., those used for storing sushi grade tuna).

Cold stores can vary in size from small stores used in retail shops (generally <500 m^3) to large warehouses of thousands of cubic metres. Smaller walk-in stores are often assembled from a modular kit, whereas large stores are built on site and are often to a bespoke design. Most smaller stores are privately owned. Larger stores may also be privately owned but some are operated as public cold stores where the owner rents space to end users.

2.3.2 Cold store function categorisation

Controlled atmosphere (CA) stores are used for fruit and vegetables and modify gas concentrations, temperature, and humidity levels to extend the shelf life. By adjusting the atmosphere within the storage environment, the ripening and aging processes of the stored items can be slowed down, preserving their freshness and quality for an extended period.

Regional distribution centres (RDCs): RDCs serve as central hubs for the distribution and storage of perishable goods within a specific region. The facility is strategically located to efficiently receive, store, and distribute products to various retail locations or customers within a designated area. Most of this type of store have sophisticated inventory management systems to track the quantity, location, and movement of products to ensure accurate stock levels and efficient order fulfilment.

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[11] DEFRA, 2021. *England Trees Action Plan 2021 to 2024.* London: DEFRA. Available at: https://www.gov.uk/government/publications/england-trees-action-plan-2021-to-2024

[12] Institute of Refrigeration., 2021. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

Cross-docking: some RDC cold stores incorporate cross-docking operations, where products are transferred directly from incoming shipments to outgoing vehicles without long-term storage. This approach minimises handling and reduces storage time, enabling faster turnaround and delivery.

2.4 Types of refrigeration systems

2.4.1 Direct expansion (DX) plant

Direct Expansion is the simplest and most common design for smaller installations (Figure 1). The compressor discharges to an air- or water-cooled condenser where the hot refrigerant vapour is condensed to liquid and drained to a high-pressure liquid receiver. The liquid refrigerant then travels to the expansion valves on each evaporator, which control the flow of refrigerant into each evaporator.

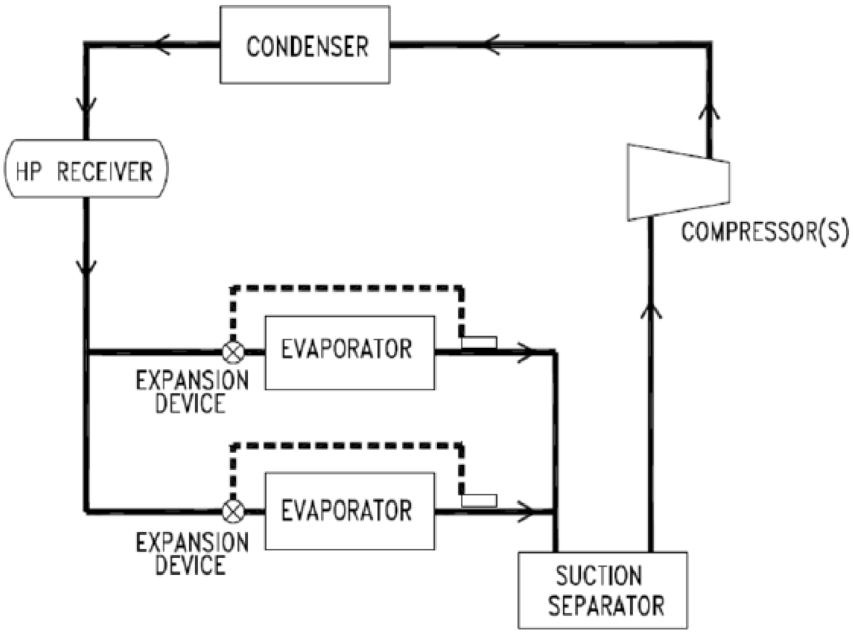

Figure 1. Typical Direct Expansion System

The vapour from the evaporators then returns to the compressor, usually via a suction separator which will remove any liquid droplets including oil. The vapour is recompressed by the compressor and the cycle continues accordingly.

DX systems usually provide the lowest capital cost due to their simplicity but are also usually the least efficient. This is partly because the expansion valve aims to maintain a level of superheat at the evaporator outlet, and the evaporator is usually no more than 50% full of liquid. This significantly reduces the evaporator efficiency as more surface area is needed compared with an evaporator that can be over-fed with liquid (see pumped overfeed and flooded systems below).

2.4.2 Pumped overfeed systems

From an operational energy point of view, a pumped refrigeration system provides the most effective refrigeration at the lowest running cost. These systems make good use of the evaporator surface, but they require a large charge of refrigerant and, if not appropriately designed, may suffer from excessive pressure drop in the return line from the evaporator to the surge vessel.

However, in almost all cases the cost of this type of system may be expected to be higher than for an equivalent capacity DX system.

Figure 2 shows a simplified single stage pumped system. The compressor draws refrigerant vapour from a low pressure, low temperature surge vessel, compresses it and discharges to a condenser, where the high pressure, superheated vapour is cooled and condensed. This high-pressure liquid then passes to an expansion device which regulates the flow of low temperature, low pressure liquid back to the surge vessel. The refrigerant level in the surge vessel is typically maintained at between a third and half full, by means of a float control expansion device. The low temperature, low pressure refrigerant is transferred from the vessel by one or more liquid pumps to the various evaporators.

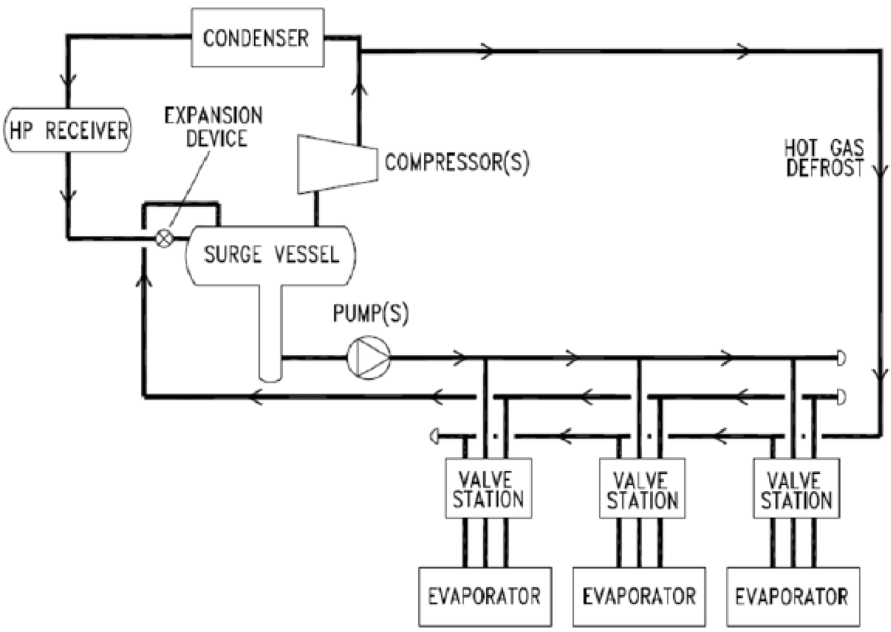

Figure 2. Single Stage Pumped System

A more complex two stage compression pumped system is show in Figure 3. This is more typical in large-scale cold store applications. It can offer a cost effective and efficient system design particularly where the facility operates with multiple chambers and different storage temperatures.

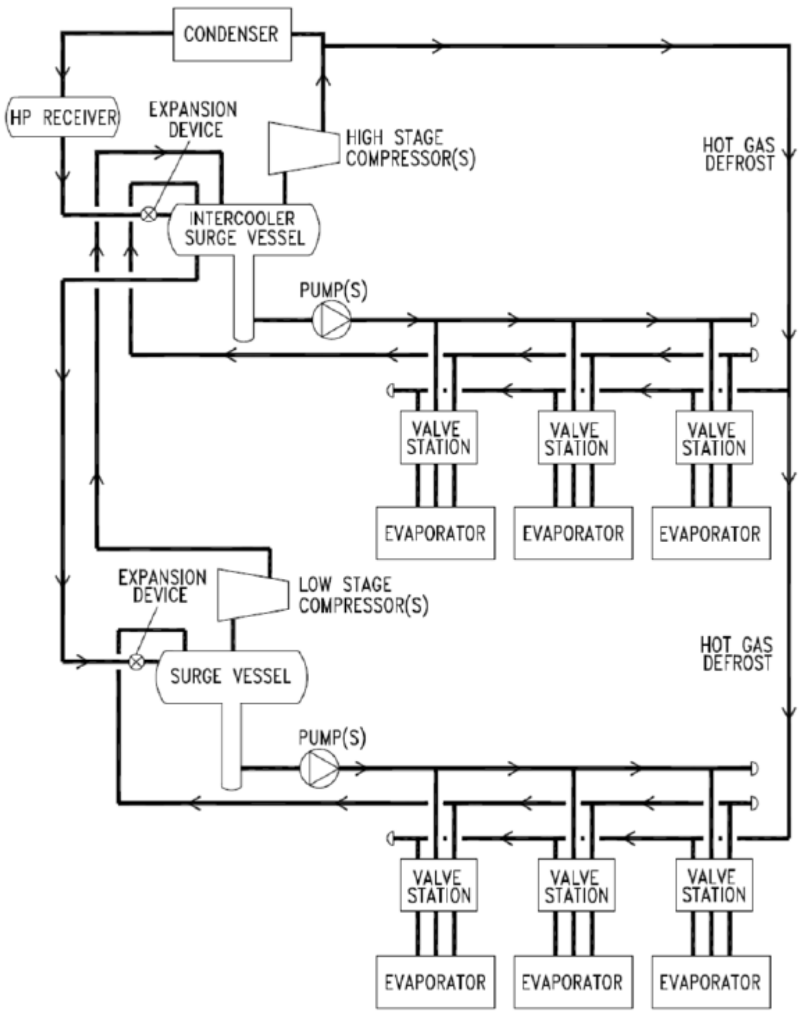

Figure 3. Two Stage Pumped System

The use of a float control expansion device to meter liquid refrigerant from the receiver to the surge vessel and pumping to the evaporators allows the system to take full advantage of reducing condensing pressure when the ambient temperature falls. This, along with other design features that are common with these systems, can deliver energy usage that is less than half that of an equivalent capacity direct expansion system.[13] With multiple evaporators, the system also offers the opportunity to carry out cooler defrosting using a portion of the waste heat from the high stage compressor. To improve efficiency, the low temperature surge vessel must be fed chilled liquid from the intercooler surge vessel and not the HP receiver.

[13] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

2.4.3 Pumpless overfeed systems (low pressure receiver (LPR) systems)

An alternative to the pumped overfeed system is the well-established pumpless overfeed system (Figure 4). In this system, the compressor draws refrigerant vapour from a low pressure, low temperature vessel, known as a low-pressure receiver (LPR). It compresses the vapour and discharges it to a condenser, where the high pressure, superheated vapour is cooled and condensed. The condensed high-pressure liquid passes through a sub-cooler in the LPR to an expansion device, which regulates the flow of low temperature, low-pressure liquid refrigerant to the evaporator(s). For this system no liquid receiver is required.

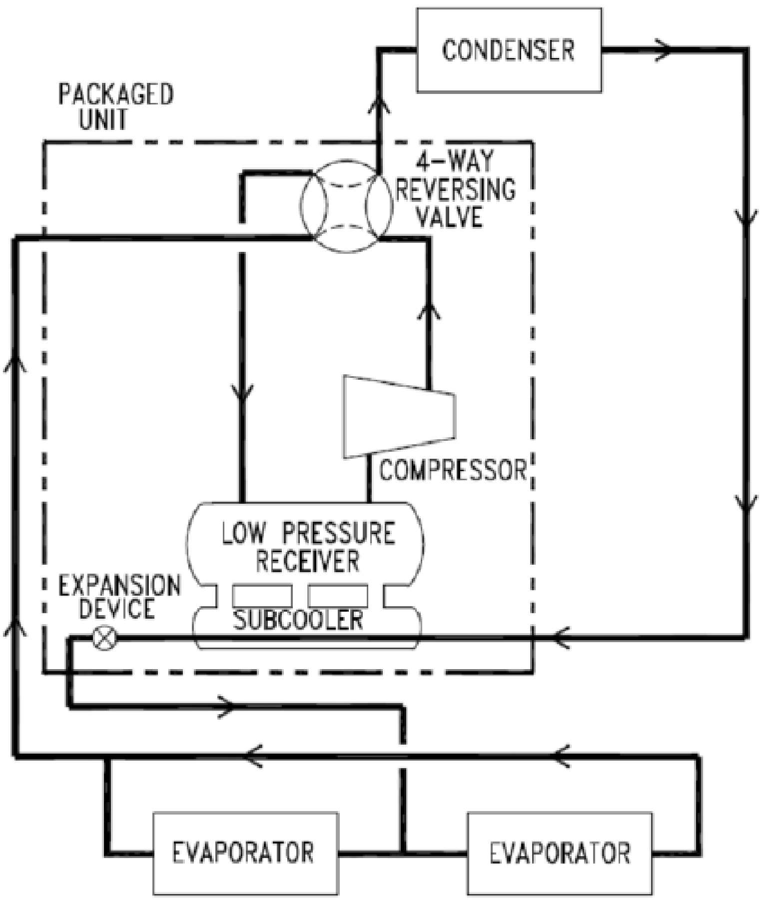

Figure 4. Pumpless overfeed system.

The system has the benefits of offering reduced complexity and hence lower capital cost compared to a pumped system, while matching its efficiency, and delivering substantially better efficiency compared to a DX system. The system is ideal for installations where there are a limited number of temperature-controlled chambers and where the compressor and LPR packaged unit can be placed close to each evaporator(s) thus eliminating long pipe runs. Its major limitation is in the number of evaporators that can be operated with any one circuit, ideally one or two, and certainly no more than four. This is due to the need for balanced pressure drops in each of the liquid lines to individual evaporators to ensure equal liquid distribution. In addition, only one operating temperature can be accommodated per circuit. In recent years R717 has been the refrigerant of choice for such systems, which allow a very low specific refrigerant charge compared to pumped systems.

2.4.4 Gravity fed flooded systems

For a small store with only two or three small rooms, a simple gravity fed flooded design could be an efficient and economical solution (Figure 5). High-pressure vapour flows from the compressor to the water- or air-cooled condenser. The condensed refrigerant is collected in a high-pressure receiver and passes through an expansion device to a surge vessel at the evaporator(s) it serves. The liquid flows to the evaporator(s) by gravity in a thermosiphon with large diameter pipes which allow the refrigeration vapour to rise to the top of the low-pressure receiver from where they return to the compressor.

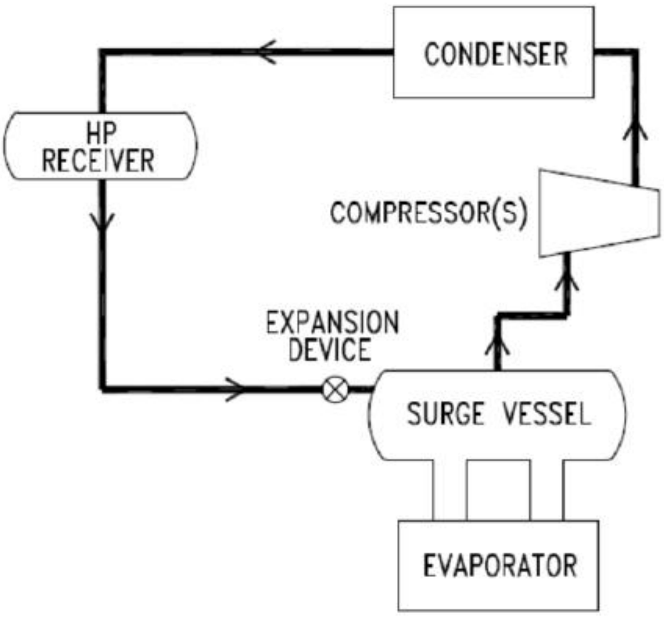

Figure 5. Typical Gravity-Fed Flooded System

The efficiency of such a system is excellent and R717 is usually the refrigerant. Economies in capital cost arise because there are no pumps, and the plant is compact and located close to the cold chamber.

2.4.5 Cascade systems

A cascade system, comprising two refrigerant circuits with different refrigerants, can be used to combine the best features of different refrigerants. The most common arrangement in cold stores is to use a low-temperature R744 (Ammonia) circuit to supply the evaporators in cold and chill rooms, but with a high-temperature R717 circuit to reject heat in a conventional condenser. This arrangement reduces the R717 (carbon dioxide) charge and keeps it out of occupied areas but avoids the very high pressures that would be required to reject heat directly from the R744 circuit (as it remains in sub critical operation). It is common to arrange the interstage temperatures of the two circuits (the R744 condenser and the R717 evaporator) so that the higher-pressure R744 can serve the chill store evaporators from a pumped liquid supply without using a compressor or expansion valve. This type of system is typically more expensive than a direct R717 system but cheaper and more efficient than a system using a secondary fluid such as glycol.

A typical arrangement is shown in Figure 6, which includes hot gas defrost, although it should be noted that the gas for defrosting has to be generated independently of the compressor discharge which is not at high enough pressure.

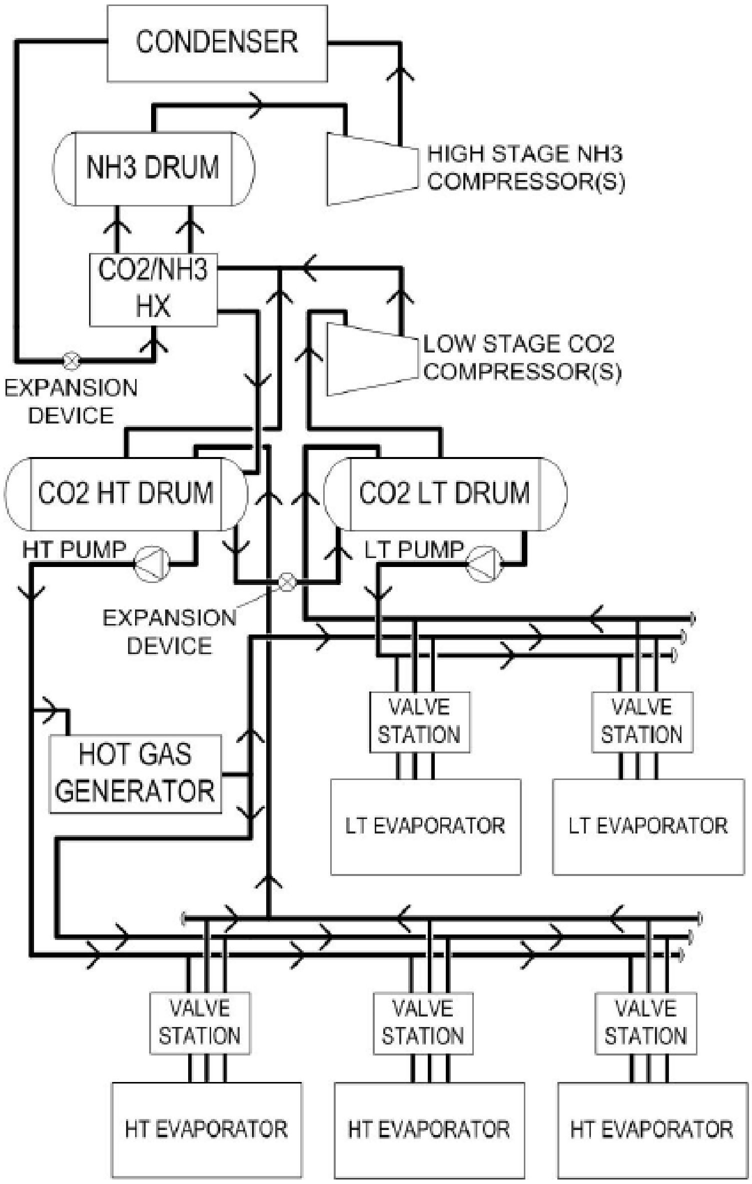

Figure 6. Typical R717/R744 cascade system

2.4.6 Absorption refrigeration

An absorption cycle is a heat-activated thermal cycle. It exchanges only thermal energy with its surroundings, and no appreciable mechanical energy is used.

Such plants have advantages, including:

(a) No large rotating machinery is used
(b) Reclaimed heat can be used, from sources including low pressure steam or hot water derived from the exhaust and cooling system of an engine.

Very few absorption refrigeration plants have been installed for cold store projects, probably due to the scale of cooling required and lack of available heat reclaim.

2.4.7 Secondary refrigerants

Secondary refrigerant is a term used to describe the intermediate fluid used in an indirect cooling system. The secondary refrigerant can be a single-phase liquid, suitable for use at the operational temperature range, such as a glycol, brine or alcohol solution. It can also be a two-phase fluid, with liquid being pumped to the evaporators and vapour returning to a heat exchanger for condensing back to liquid. Recently, R744 has seen increased use as a two-phase secondary refrigerant. It offers significant operational benefits both in capital cost, through smaller pipe diameters and air coolers than traditional single-phase secondary refrigerants, and in reduced energy costs, with pumping powers between 10% and 20% of those for traditional single-phase secondary refrigerants.

The application of indirect systems utilising secondary refrigerants is most commonly an option for applications where R717 is to be the primary refrigerant. There are however arguments against the use of secondary refrigerants in these circumstances, which can be summarised as:

(a) They add another step of temperature difference for heat exchange between the refrigerant and the air, which requires a correspondingly lower evaporating temperature in the secondary refrigerant cooler, of typically around 5 to 8 K. This leads to an increase in size and cost components and an increase in power consumption for the primary refrigeration system of between 10% and 20%

(b) In addition to increasing the primary refrigerant plant power consumption, the secondary refrigerant circuit must also be pumped, adding further to the energy consumption.

Further information on cold store design and construction can be found at:

*The **IOR Cold Store Code of Practice** is a key reference document for cold store designers. It provides an independent and authoritative overview of the process involved in the construction of cold store projects, buildings and insulation and refrigeration design. The Code is intended to assist those responsible for specifying the requirements for a refrigerated store by outlining all the design elements of a modern cold store.*

***Part 1 "Scope and Specification"** is primarily aimed at the non-specialist end user and provides an overview together with key elements relating to the design and specification process. Templates to assist these processes are given in the appendices. (2016)*

***Part 2 "Design & Construction"** in-depth information regarding cold store construction, detailed descriptions of specific cold store features (e.g., structural design, insulated panel selection and installation, vapour sealing, fire protection, racking etc.) (2015).*

***Part 3 "Refrigeration Systems"** provides in-depth information regarding refrigeration plant considerations and design (revised 2020).*

*Free download templates are also available to Code users: **Appendix A - Key Design Template, Appendix B - General Information Records.***

***Appendix C - Supply Storage and Accommodations, Appendix D – References**.*

3 Current Trends

3.1 Electrical energy use

Cold storage rooms are energy-intensive facilities due to the continuous operation of refrigeration systems required to maintain low temperatures. Asano and Mugabi stated that within cold storage facilities, 60–70% of the electrical energy may be used for refrigeration[14]. This means that there are considerable incentives for cold store operators to reduce energy usage.

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[14] Asano, H. and Mugabi, N., 2013. Actual energy conservations by using NH_3/CO_2 refrigeration system. *Proceedings of the 3rd International Conference of Saving Energy in Refrigeration and Air-Conditioning*, Chonnam National University, Yeosu, Jeollanam-Do, Korea

Studies on the energy used in cold stores have demonstrated that energy consumption can vary considerably and that this was due to a variety of factors[15,16,17]. Surveys have demonstrated that energy savings of around 30-40% are achievable by optimising usage of the stores, repairing current equipment and by retrofitting of energy efficient equipment.

Until recently, limited data was available on the energy performance of cold stores. A large survey published by Evans et al in 2015[18] contains a large data set detailing performance of UK cold stores. The statistical analysis indicated that frozen and mixed stores were not statistically different in their specific energy consumption (SEC) and so are considered together. Although there is a clear relationship between size of the store and energy used there are also stores that are much more efficient or less efficient than the majority (Figure 7 and Figure 8).

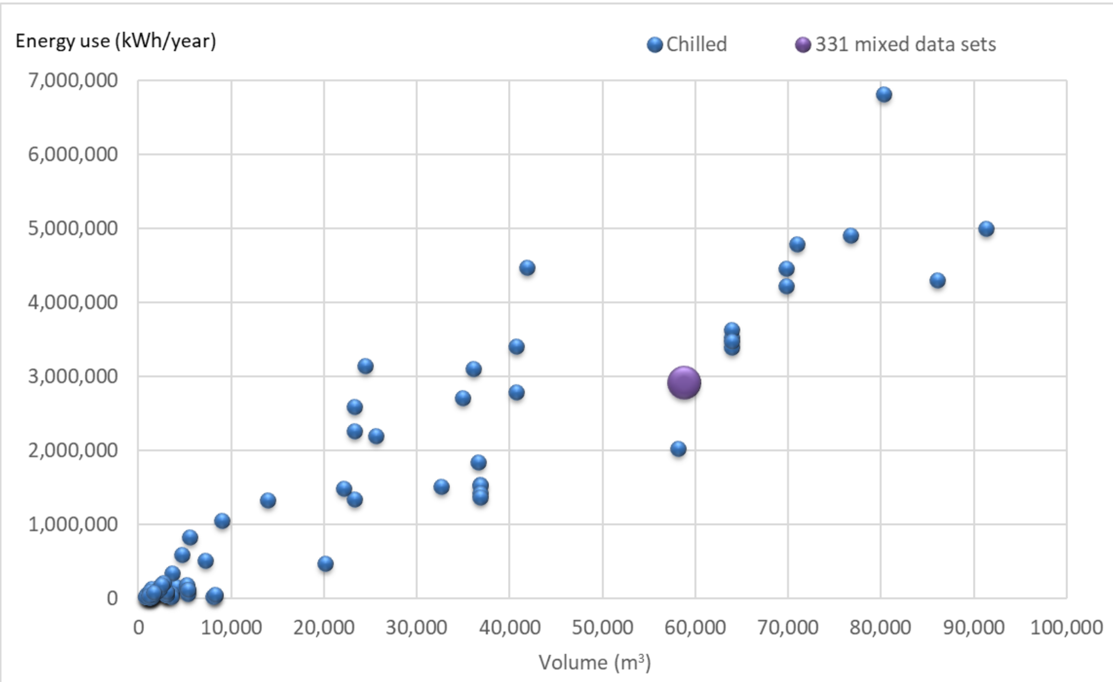

Figure 7. Energy used by chilled stores.

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[15] Evans, J.A. and Gigiel, A.J., 2007. Reducing the energy consumption in cold stores. *Proceedings of the 22nd IIR International Congress of Refrigeration*, Beijing

[16] Evans, J.A. and Gigiel, A.J., 2010. Reducing energy consumption in cold storage rooms. *Proceedings of the IIR ICCC*, Cambridge

[17] Evans, J.A., Hammond, E.C., Gigiel, A.J., Foster, A.M., Reinholdt, L., Fikiin, K. et al., 2014. Assessment of methods to reduce the energy consumption of food cold stores. *Applied Thermal Engineering*, 62, pp.697–705. https://doi.org/10.1016/j.applthermaleng.2013.10.023

[18] Evans, J.A., Foster, A.M., Huet, J.-M., Reinholdt, L., Fikiin, K., Zilio, C., Houska, M., Landfeld, A., Bond, C., Scheurs, M. and Van Sambeeck, T.W.M., 2015. Specific energy consumption values for various refrigerated food cold stores. *Proceedings of the 24th IIR International Congress of Refrigeration*, Yokohama, Japan

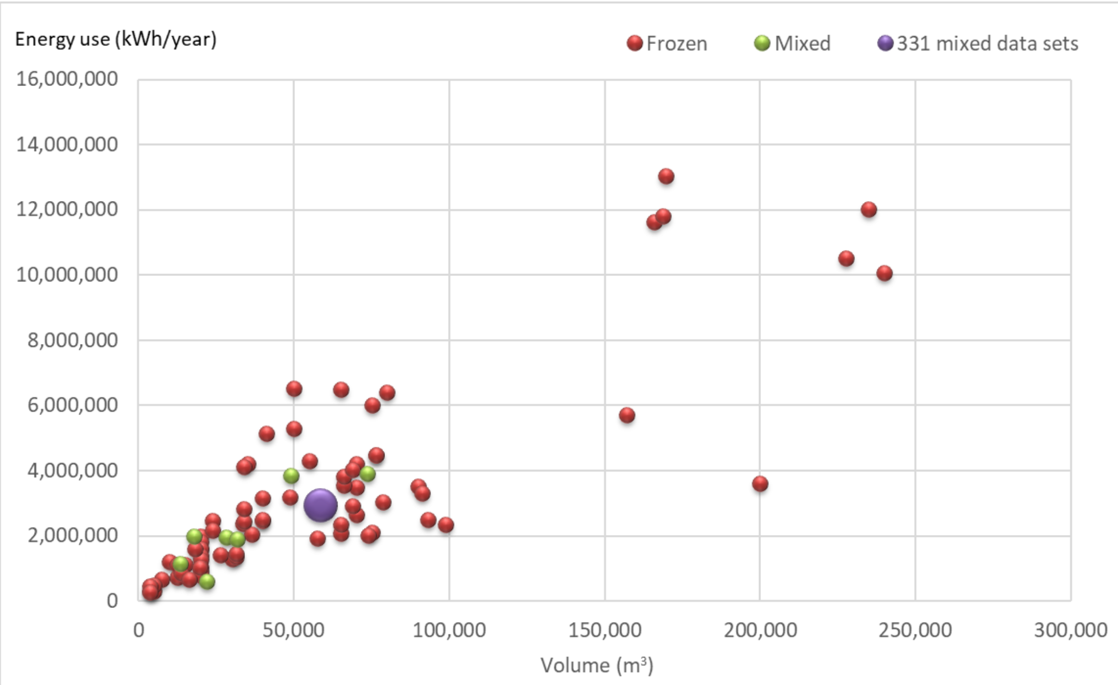


Figure 8. Energy used by frozen and mixed-use stores.

3.2 Best available technology (BAT)

Being able to compare performance of a facility with others is extremely useful. Although facilities may not be directly comparable, having a benchmark provides the end user with a method to determine their relative efficiency and to monitor their performance over time.

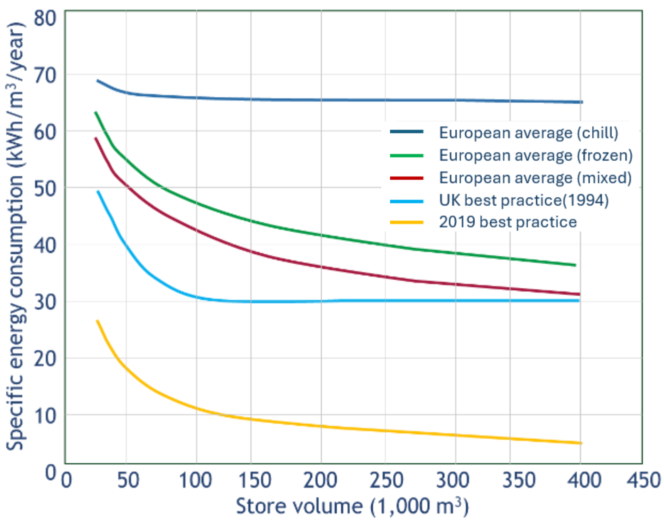


Figure 9. Best practice SECs.

Benchmarks are usually over a period of a year but can also be used to compare performance over comparable periods of usage and ambient conditions to see if there is fall off in performance that might be related to operation and maintenance.

Error! Reference source not found. presents a range of published benchmarks for UK and Europe [19]. There is a wide variation which shows that the 2019 figures are far more ambitious than previous benchmarks.

Comparing the benchmarks to the data collected by Evans et al.[18] indicates that the current stock uses considerably more energy than the 2019 benchmark and many stores use more than the 1994 best practice (Figure 10 and Figure 11). 2026 data published by the Cold Chain Federation (CCF) indicates that the specific energy consumption (SEC) varies between 20 (large, chilled stores) and 150 kWh/m^3/yr (small, chilled stores) and between 25 (large, frozen stores) and 105 kWh/m^3/yr (small, frozen stores) [2].

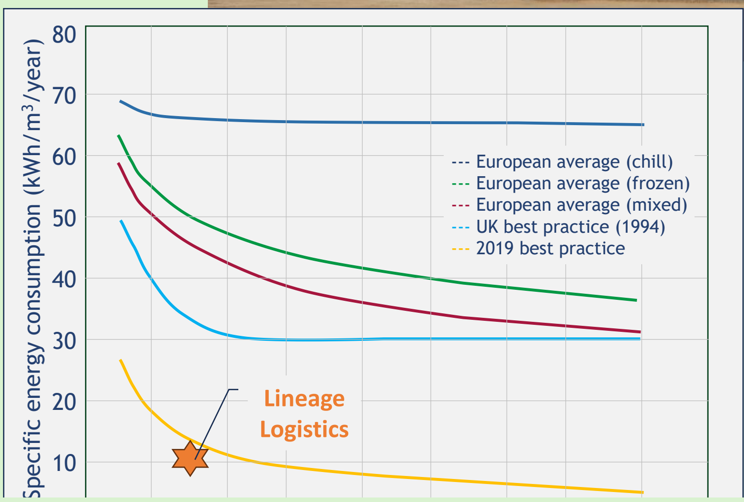
These results show that there are large differences in SEC, which may be due to specific conditions at the stores. It is estimated that applying improved design and technologies will reduce the stores' energy use. Information presented by Pearson[19] indicates that a store built in 1990 was capable of achieving the 2019 benchmark assuming that the difference in SECs is related to efficiency and not just usage. Work based on mathematical modelling by Evans et al (2015[18]) indicated that benchmark SECs can be achieved, but stores need to

Case study: Star Refrigeration and Lineage Logistics

Lineage is the largest, temperature-controlled logistics provider in the world with over 1.4 billion cubic feet of storage capacity. They have ~200 facilities in seven countries across North America, Europe and Asia.

The Linage freezer store in Peterborough (UK) is a 75,000 m^3 cold store operates at -24°C with a refrigeration capacity of 600 kW. The store has a capacity of 15,000 pallet spaces and is automated.

The store is operated from 2 Star Azanefreezer 2.0 Ammonia refrigeration plants. Analysis over a year shows that the store consumed 12 kWh/m^3/year which exceeds the 2019 best practice benchmark.



[19] Pearson, A., 2022. Beyond refrigeration: next steps for the future of low carbon RACHP. *IOR Annual Conference – Beyond Refrigeration*, December 2022, Institute of Refrigeration

reduce heat loads to a minimum, have high efficiency refrigeration systems and be extremely well operated to get close to the best benchmarks.

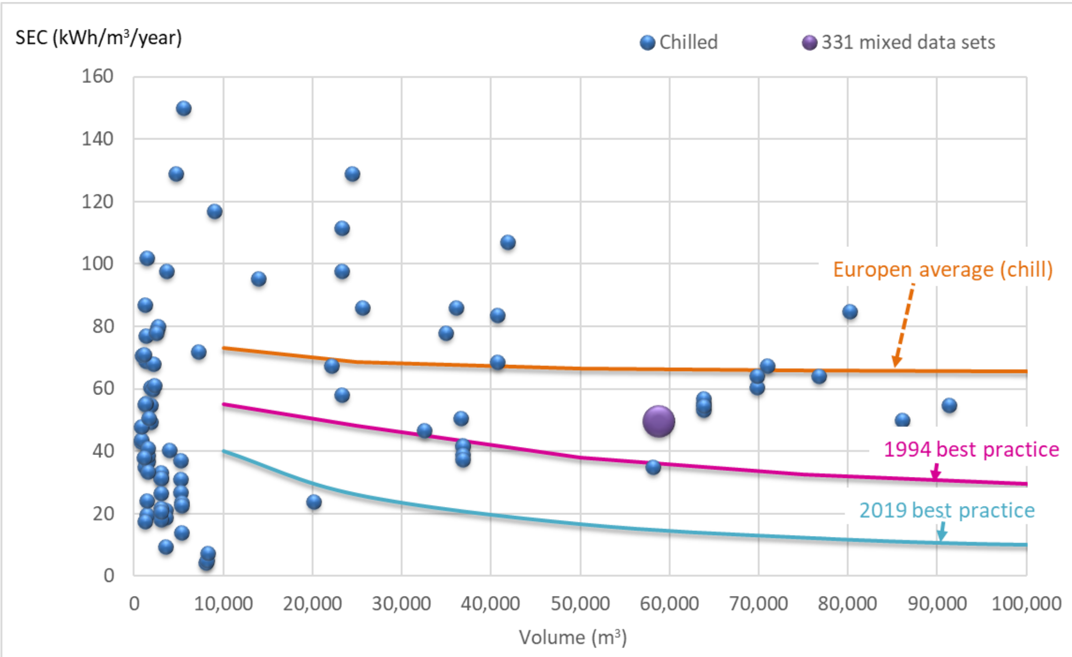


Figure 10. SEC of data from chilled stores compared to benchmarks (highest SEC values removed from graph to aid clarity).

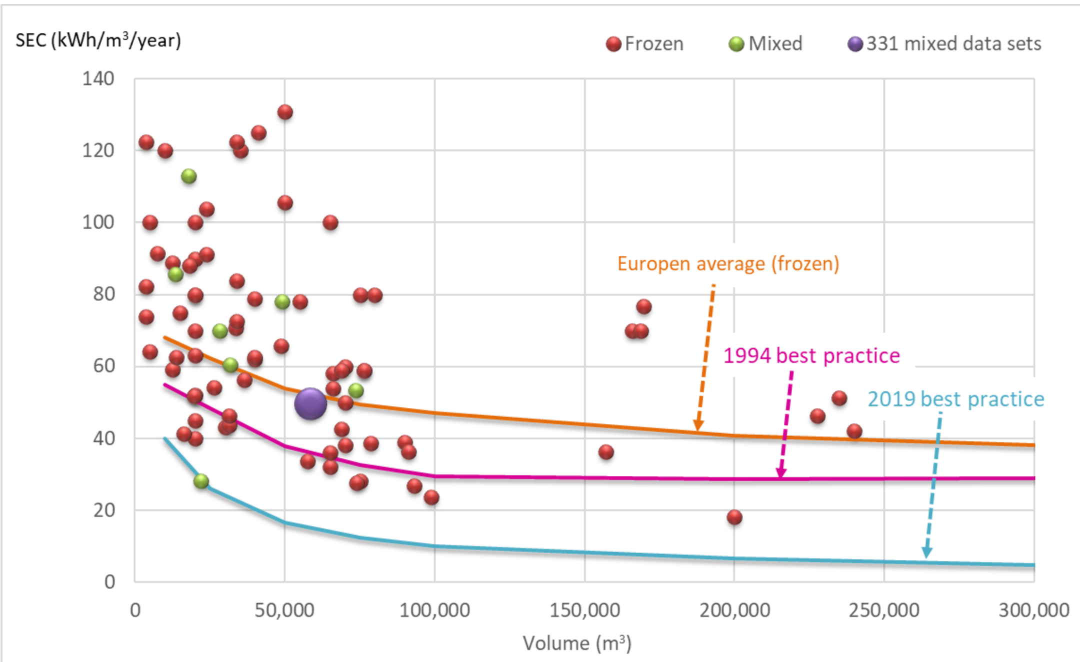


Figure 11. SEC of data from frozen and mixed-use stores compared to benchmarks (highest SEC values removed from graph to aid clarity).

3.3 Energy costs

The International Institute of Refrigeration has estimated that electrical energy consumption of cold stores accounts for 10-15% of operating costs [20]. In cold storage facilities, about 60-70% of the energy costs concern refrigeration. There are many possible improvements, which are low in cost (e.g. improved door protection, defrost operation, control settings and repairs). Most of these improvements result in a short payback time of less than 1 year. There is a large potential for energy reduction by optimisation of the cold stores [21].

There has been a significant increase in electricity prices since 2021 and consequently reducing energy use has become increasingly important, and this is likely to continue for the foreseeable future. According to the 2026 CCF report, wholesale energy costs have increased by 141% between 2018 and 2025[2].

In the light of these developments, measures to decrease energy demand are gaining importance. The increased prices potentially decrease the payback time of investments related to energy savings, however the future development of energy prices on the long term are questionable.

3.4 Economic pressures

The financial crisis has impacted both operators and customers. The COVID-19 pandemic had a huge impact with cold stores being a vital part of the covid response. The cold storage sector was an essential part of ensuring food was available to consumers. The pandemic (as well as Brexit in the UK) tended to increase the demand for cold storage space, and this was positive for the industry but caused issues for customers who were less able to access storage space at short notice. This has tended to lead to customers setting up longer term arrangements with cold stores to ensure sufficient storage capacity for products. A major current issue that has been reported is the lack of available cold storage space, which may reflect limited investment due to increased costs and pressure on margins[22].

Inflation and the economic crisis have had impacts on maintenance and equipment costs as well as restricting investment due to higher interest costs. At the same time labour and the costs for transportation have increased due to increased wages, fuel prices, changes in transportation regulations, and disruptions in supply chains.

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[20] Duiven, J.E. and Binard, P., 2002. Refrigerated Storage: New Developments. *Bulletin of the International Institute of Refrigeration (IIR)*, No. 2002-2.

[21] Evans, J.A. and Hammond, E.C., 2014. Assessment of methods to reduce the energy consumption of food cold stores. *Applied Thermal Engineering*, 62, pp.697–705. https://doi.org/10.1016/j.applthermaleng.2013.10.023

[22] Cold Chain News., 2023a. Lack of warehouse space causes problems for logistics providers. *Cold Chain News*, 27 June. Available at: https://www.coldchainnews.com/lack-of-warehouse-space-causes-problems-for-logistics-providers/

3.5 Energy management

Energy management systems can aid reduction in energy consumption and costs. Increasingly there is a drive for certified energy management systems, often from regulatory bodies. A number of systems are available and include:

- Environmental performance such as resource use, waste management and pollution are covered in ISO 14001 which is an international standard that sets out the requirements for an environmental management system.
- Energy performance indicators and an energy baseline for a business is covered by ISO 50001 which is an energy management system standard that is used by organisations to manage and reduce energy use and costs.

Potentially there is overlap between these 2 standards. Both provide ways to protect the environment through policies, objectives and processes. However, ISO 50001 focuses on energy usage whereas ISO 14001 concentrates on environmental protection in general.

- Energy Savings Opportunity Scheme (ESOS) – certification to ISO 50001:2018 is a route to compliance. This is a mandatory energy assessment scheme to ensure that UK enterprises are energy efficient. An assessment every 4 years is required and applied to organisations that have over 250 members of staff or have a turnover of more than £44m and an annual balance sheet of over £38m (or the company is part of a larger organisation, which falls within the above clauses).
- Streamlined Energy Carbon Reporting (SECR) – larger UK organisations must report annually on energy use, energy efficiency actions taken, and energy efficiency opportunities. The reporting methodology used must be stated and must be robust, transparent and widely accepted. Companies are encouraged to provide information on scope 3 emissions.
- Climate Change Agreement - is a voluntary scheme applied in the UK since the early 2000s. It provides a discount on the climate change levy (a tax on energy bills) in return for meeting energy efficiency targets. It is claimed that a 19.3% improvement against a 11.7% target has been achieved (using a 2008 baseline).

3.6 The labour market

The cold storage industry is reported to have significant challenges in recruitment, retention and upskilling of employees. Improved pay and conditions as well as career and development opportunities are being used to encourage new entrants into the labour market.

As cold stores become more automated, they will require less staff and operators will need new skills to program systems and operate robots. There is also an ongoing interest within the industry to examine methods to achieve net zero, increase sustainability and improve operation and design of stores which in turn will attract new talent.

3.7 The environment

The rise in global temperature is an important indicator of climate change which is largely caused by anthropogenic activities emitting greenhouse gas emissions. Between 2013 and 2022, the global mean near-surface temperature was 1.13 to 1.17°C warmer than in the pre-industrial era. UK heats up even faster than the global average with increases of the land temperature between 2.04 to 2.10°C. The UK recorded its warmest year on record in 2025, with a mean annual temperature of 10.09 °C in a series dating back to 1884 [23].

Due to higher temperatures, the number and intensity of heat waves is also increasing. A heatwave is defined by the Met Office as a period of at least three consecutive days where the daily maximum temperature meets or exceeds a specific threshold, which varies by region from 25 to 28°C. Warm spells in the UK have also become significantly longer, with their average duration increasing from around 5.3 days during 1961–1990 to over 13 days in the decade 2008–2017 [24].

Increasing temperatures also bear a challenge to cold stores. Large industrial cold stores are generally designed to a higher specification, incorporating high-performance insulation and controlled building envelopes that limit heat transfer and maintain stable internal temperatures even when ambient conditions fluctuate [25]. Furthermore, the large quantity of stored products provides significant thermal mass, which absorbs heat gains and reduces temperature fluctuations by storing cooling energy within the stored goods themselves [26]. Consequently, smaller storage rooms, which typically contain less thermal mass and may be built to less rigorous specifications, are more susceptible to changes in ambient temperature. It is clear that extreme temperature events are becoming more common, and this is having an impact on refrigeration systems. A recent report from Imperial College has indicated that a 2°C increase in average UK summer temperature increased refrigeration energy demand by 6%[27]. The same report also found greater levels of break down in hotter weather increasing

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[23] Met Office, 2026. *2025 is double-record breaker: UK's warmest and sunniest year on record.* Exeter: Met Office. Available at: https://www.metoffice.gov.uk/about-us/news-and-media/media-centre/weather-and-climate-news/2026/2025-is-double-record-breaker-uks-warmest-and-sunniest-year-on-record

[24] Met Office, 2023. *UK and global extreme events – Heatwaves*. Exeter: Met Office. Available at: https://www.metoffice.gov.uk/research/climate/understanding-climate/uk-and-global-extreme-events-heatwaves

[25] Nautical Direct, 2025. *Temperature control in warehouses: how much do you need?* Available at: https://nautical-direct.com/temperature-control-in-warehouses-how-much-do-you-need

[26] Altwies, J., Reindl, D.T. and Braun, J.E., 2002. *Passive thermal energy storage in refrigerated warehouses*. International Journal of Refrigeration, 25(1), pp.149–157. https://doi.org/10.1016/S0140-7007(00)00080-3

[27] Levey, S. and West, S., 2020. Warmer summers risk chilling energy bill rises at supermarkets. *Imperial College London News*, 3 July. Available at: https://www.imperial.ac.uk/news/198934/warmer-summers-risk-chilling-energy-bill/

maintenance bills. All of this is bad news for cold stores when food may be wasted if refrigeration systems can no longer cope with the warmer conditions.

In order to tackle climate change, member countries of the United Nations Framework Convention on Climate Change (UNFCCC) have committed to the Paris Agreement which aims to limit the global temperature increase to below 2°C (above pre-industrial levels) and ideally to less than 1.5°C by 2050[5]. Transitioning to renewable energies and implementing energy efficiency measures are important contributions to the reduction of GHG emissions.

In order to protect the environment from refrigerant leakage, the trend is increasingly towards natural refrigerants. These substances are known for their low global warming potential (GWP) and ozone depletion potential (ODP) and offer a more sustainable an environmentally friendly alternative. The topic of natural refrigerants will be discussed in detail in the following chapter.

3.8 The move to low GWP refrigerants

Many larger cold stores use R717 as a refrigerant (industry estimates that ~45% of UK cold stores use R717) [2]. A growing trend is for newer R717 systems to have lower charges which are factory assembled and built. Some larger and medium sized cold stores (~9%) use R744 Numbers of systems are still relatively low but growing [2]. The majority of other larger stores and almost all smaller stores will apply an HFC refrigerant or possibly an hydrofluoro-olefins (HFO) blend refrigerant.

This is primarily driven by legislative pressure from F-Gas Regulations, which aim to reduce the GWP of refrigerants used in all refrigeration sectors. Although Great Britain (GB) is no longer part of the EU, it retained and incorporated Regulation 517/2014 into domestic law following Brexit. The UK currently operates its own F-Gas regime, based on the 2014 Regulation but amended through UK legislation, and it does not automatically adopt subsequent EU revisions.

In March 2024, the EU replaced this regulation with Regulation (EU) 2024/573 [28], introducing stricter phase-down schedules and controls. There was initially uncertainty regarding whether GB would align with this updated F-Gas Regulation, the UK Government has since launched a consultation on proposed reforms to the domestic F-Gas regime. As part of any new legislation the UK Government must ensure that the UK is able to achieve the Montreal Protocol (Kigali Amendment) phase down of HFC consumption by 85% by 2036 and also achieve the net zero carbon budget by 2050. The Department for Environment Food and Rural Affairs (DEFRA) are responsible for the proposed changes to the regulation in GB. They are proposing that the current HFC phase down is amended from 1 January 2027 with a move

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[28] European Commission., 2025. *EU legislation to control fluorinated greenhouse gases (F-gases)*. Climate Action – European Commission. Available at: https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-legislation-control-f-gases_en

from a target of 79% cut to a target of 98.6% cut by 2048. No changes to the placing on the market prohibitions already applied in Annex III of the GB regulation are proposed.

Additionally, the EU regulation references Per- and Polyfluorinated Substances (PFAS). The regulation states that 'PFAS are chemicals which resist degradation and potentially have negative effects on health and the environment'. It states that 'undertakings should consider using alternatives, where available, which are less harmful for health, the environment and the climate'. Most HFOs and some HFCs are PFAS and PFAS regulation is currently being considered by the European Chemicals Agency.

4 Future Issues and Trends

4.1 Increased use of renewables

Solar energy generation for cold stores is feasible if sufficient roof area or land adjacent to the cold store are available. Recent increases in energy costs have made the benefits of solar panels greater. Information from the UK indicates that 29% of cold stores who are part of the UK climate change agreement now have solar panels[2]. If the energy generated from renewables can also be stored (electrically) there is the potential to benefit from demand side response (DSR) periods or use the stored energy at periods when energy costs are higher. The energy demanded by the cold store generally aligns well with solar power generation with peak cold store loads at around midday when solar radiation is at its maximum. The share of energy generated by photovoltaic (PV) panels that can be used on-site can be increased by incorporating energy storage. In cold storage facilities this can be achieved either through electrical storage or by using the thermal mass of the stored product as a form of passive thermal energy storage, allowing refrigeration loads to be shifted in time by pre-cooling the product when renewable electricity is available [29].

4.2 Integration (of heating and cooling)

Currently there is limited consideration of thermal integration within cold stores. However, this is an area that installers and operators are beginning to investigate. It is feasible to reclaim heat and use this heat for generating hot water, for dehumidification for door curtains or to heat office areas within an establishment. Similar systems have been applied in other sectors of the food chain and generally have reclaimed heat from CO_2 refrigeration systems where the opportunities for heat reclaim are greater. Integration is not simple in existing outlets as they have not been designed for thermal integration. However, thermal integration could be designed into new facilities and with increasing energy costs such systems will have greater

[29] Arteconi, A., Hewitt, N.J. and Polonara, F., 2013. *Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage*. Applied Thermal Engineering, 51(1–2), pp.155–165. https://doi.org/10.1016/j.applthermaleng.2012.09.045

commercial feasibility. An example is Dearnsdale Fruit [30], they installed a heat recovery system that is saving the business £20k per year. Waste heat is recovered from the cold store refrigeration system which is used for heating hot water. The system can generate up to 1,800 litres of hot water per hour which is mainly used in the pack house and for hot water for staff (showers).

4.3 Automation and robotics

Automation works best when there are repetitive tasks and where products are consistent. Automation and robotics technologies offer several advantages in terms of efficiency, accuracy, and safety in cold storage operations. Automated systems can efficiently track and manage inventory in food cold stores. Sensors can scan and rapidly identify products, record their locations, and update the inventory database. This reduces manual errors and ensures accurate stock control and streamlined supply chain management.

Cold stores can also apply automated guided vehicles (AGVs) or autonomous mobile robots (AMRs) which can retrieve products from a cold store and place them in designated areas. This improves operational speed, reduces labour costs, and minimizes the risk of product damage. Robots can also carry out repetitive activities such as palletising or depalletizing products. Due to the repetitive nature of these tasks, robots can work accurately at speed in often quite restrictive areas. Robots are also capable of efficient and accurate order picking and fulfilment operations.

Robotics and automation are expensive to install. Currently they are only applied in large warehouses where the initial costs can be balanced against the reduced labour costs.

4.4 Advanced controls

An increasing focus has been on measurement and analysis to assess efficiency and identify where maintenance issues may be beginning to develop. This requires sub metering of energy and often creating ‘digital twins’ of the cold store to identify when performance moves away from the optimum. The benefits are claimed to be significant as even small adjustments can have impact on energy bills. In addition, such systems can identify where maintenance problems are beginning to occur, and this means that service engineers are able to spot faults early and to be able to carry out remedial actions quickly and in a planned manner.

4.5 Training and skills

Cold stores are becoming increasingly automated and there is greater reliance on AI driven temperature monitoring, robotic handling of products and advanced smart inventory management. This generates a new need for training and skills to program, operate and manage such systems and requires upskilling of employees who will have completely different

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[30] Cold Chain News., 2023b. Heat recovery system saves fruit business £20,000. *Cold Chain News*, 26 June. Available at: https://www.coldchainnews.com/heat-recovery-system-saves-fruit-business-20000/

skills to those of current employees. Employees will need to have greater digital literacy and better understanding of how to manage digital platforms, data analytics, and other software used in cold storage operations.

All businesses are placing a greater emphasis on sustainable operational practices. This is an area where workers will need new and enhanced skills to adopt eco-friendly practices. As part of sustainability and also due to the impact of energy price increases there is likely to be greater emphasis on energy management. Better training on design, operation of equipment and operational practices which minimise energy use are likely to be valued more in the future.

4.6 Integration into electricity grid

Potential exists for all electricity users to better integrate into the grid. Demand side response (DSR) is when electricity users reduce electrical demand to help balance the grid. Most DSR periods are requested by grid operations at peak energy usage times (typically early evening). Although DSR does not save energy, it enables the more carbon intensive power generation facilities to be turned off/down during DSR periods and so carbon is saved. Operators are often paid to remove load from the grid making DSR an economic proposition. This has been common in large food cold stores (mainly frozen stores) for many years. Most DSR periods are approximately 30 minutes but may last for up to an hour. Other sectors of the food chain have recently embraced how they can benefit from integrating into national electrical grids.

4.7 Circular economy and food waste

Food waste is a major environmental and economic problem, as it contributes to greenhouse gas emissions and resource depletion. By applying circular economy principles and practices to cold stores, multiple benefits, such as reducing environmental impacts, saving costs, enhancing quality and safety, and creating new value-added products from food waste can be achieved. One example is the redistribution of surplus food through food banks and secondary markets, where refrigerated storage is used to extend shelf life and allow safe transport of surplus products to consumers rather than disposal [184].

The future of the food cold storage sector lies at the intersection of circular economy principles and improved food waste prevention. Although cold stores themselves generate relatively limited physical waste, they play a critical role in reducing food losses across the supply chain by maintaining product quality and extending shelf life. As global concerns surrounding climate change and sustainability intensify, cold stores face an array of emerging issues that require a shift towards more resource-efficient and resilient systems. Sustainable cold store designs will therefore prioritize energy optimization, reduce environmental impact from refrigeration systems, and greater integration of renewable energy sources. Building upon the comprehensive roadmap, several critical themes emerge that will shape the trajectory of the sector in the coming years.

5 The food cold storage roadmap

The focus of this report is to assess the technologies and strategies available to the food cold storage sector to reduce their carbon emissions. This covers the emissions that they generate today, and how future emissions to 2050 could become zero carbon. 30 different technologies and strategies were reviewed in detail to assess their opportunities to reduce carbon. This covered technologies that could be applied to the refrigeration in clod stores.

6 Technologies/strategies

GHG emissions saving technologies/strategies were initially identified and listed. In total 30 technologies and strategies were reviewed (see Detailed technology/strategy reviews). Technologies/strategies were only included if they had the potential to reduce GHG emissions. A comprehensive review of each technology was carried out and any references listed. The reviews compared and contrasted available information (peer reviewed papers, conference papers, grey literature, manufacturers data, personal experience) to provide a critical assessment of the validity of the information. The proportion of GHG 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 (**Error! Reference source not found.**).

Most of the 30 technologies and strategies had potential to be applied relatively rapidly. Some were direct retrofit options, but others would be more appropriately incorporated into a new facility. Whether savings were scope 1 or 2 were assessed. The TRL level of the technology is noted in **Error! Reference source not found.**. Only options with a TRL of 8-9 are considered for full assessment as it is not possible to guess the impact that lower TRL technologies might have in the future.

Scope 1 emissions

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

Scope 2 emissions

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

Table 1: Review summary information included at the end of each review.

Information	Comments
Scope 1 emissions savings (% or another quantifiable metric)	Overall savings that the review indicated.
Quality of scope 1 emissions information	How robust is the available information?
Scope 2 emissions savings (% or another quantifiable metric)	Overall savings that the review indicated.
Quality of scope 2 emissions information	How robust is the available information?
TRL level	Marked as: TRL1-4 TRL5-7 TRL8-9 TRL 1 - basic principles observed TRL 2 – technology concept formulated TRL 3 – experimental proof of concept TRL 4 – technology validated in lab TRL 5 – technology validated in relevant environment TRL 6 – technology demonstrated in relevant environment TRL 7 – system prototype demonstration in operational environment TRL 8 – system complete and qualified TRL 9 – actual system proven in operational environment
Maintainability issues	Any relevant issues are listed.
Legislative concerns	Any relevant issues are listed.

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

Technology	TRL level	Where applied:		Carbon savings		
		Retrofit	New	Scope 1	Scope 2	Scope 3
Automation	8-9		x		x	
CO_2 scrubbers	8-9	x		x		x
Compressors and their controls	8-9		x		x	
Condenser control	8-9	x			x	
Defrosts and defrost controls	8-9		x		x	
Demand side response (DSR)	8-9	x		x		
Doors and door protection	8-9	x			x	
Dynamic control atmosphere storage systems	8-9	x		x		x
Electronic Expansion Valves	8-9	x			x	
Energy storage (thermal and electrical)	5-7		x		x	
Evaporative and adiabatic condensers	8-9	x	x		x	
Evaporator fans and fan speed controls	8-9	x			x	
Free cooling	8-9		x		x	
Heat reclaim/recovery	8-9	x			x	
High temperature CA storage	1-4 / 5-7	x			x	
Humidification	8-9		x			x
Insulation	8-9		x		x	
Internal loading and unloading bays	8-9		x		x	
Lighting and light controls	8-9	x			x	

Technology	TRL level	Where applied:		Carbon savings		
		Retrofit	New	Scope 1	Scope 2	Scope 3
Maintenance	8-9	x		x	x	
Monitoring	5-7	x		x	x	
Orientation and aspect ratio of store, and outside cladding	8-9		x		x	
Postharvest treatments	8-9	x			x	
Refrigerants	8-9	x	x	x	x	
Renewable energy (solar electricity)	8-9	x	x		x	
Renewable energy (solar thermal)	8-9	x			x	
Stacking patterns	5-9	x	x		x	
Temperature control set points	8-9	x			x	
Underfloor heating	8-9		x		x (heat reclaim)	
Waste technologies and impact of changes (landfill, AD, incineration etc)	8-9		x		x	x

6.1 What can we learn from the reviews?

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

Potential to save carbon:

Low (L): <5% potential saving

Medium (M): >5%, <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 (**Error! Reference source not found.**). 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.

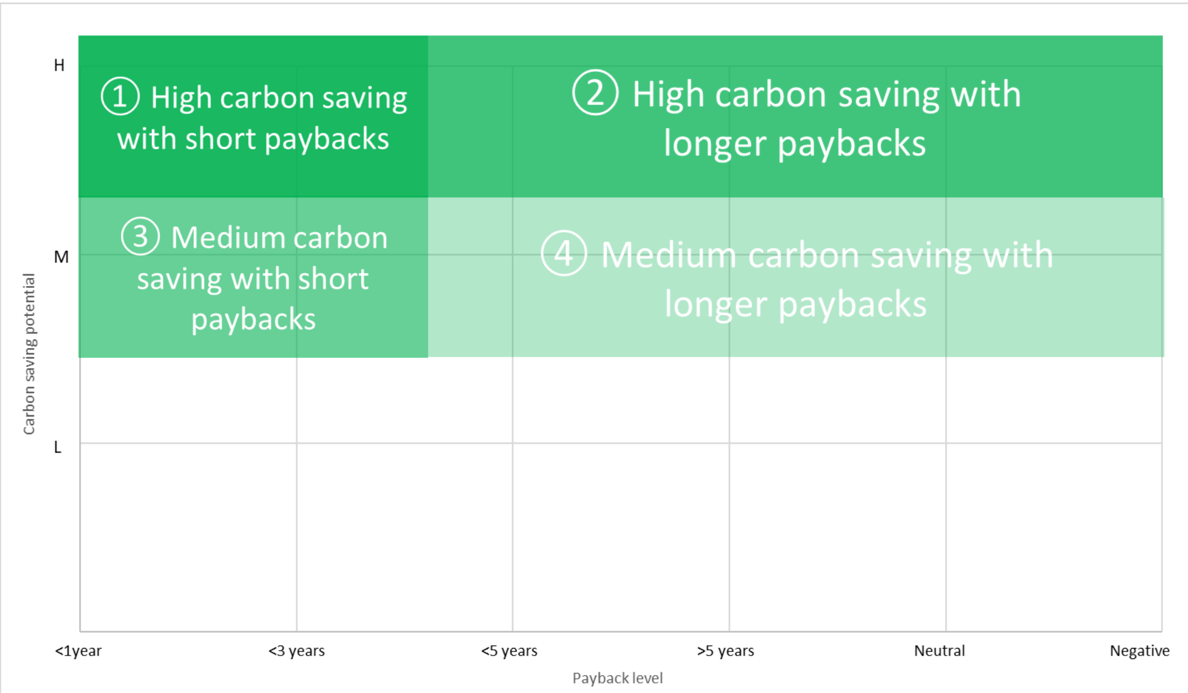

Figure 12. Potential carbon savings and payback sectors.

Technologies with a TRL of 8-9 were assessed using the above methodology. Results are presented in Figures 13 and **Error! Reference source not found.**. It should be noted that several technologies could be applied as a minor or major retrofit and that several technologies could only be applied to certain store formats. Only technologies/strategies that had universal applicability were selected for 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. Only technologies with a TRL of 8-9 were included in the modelling.

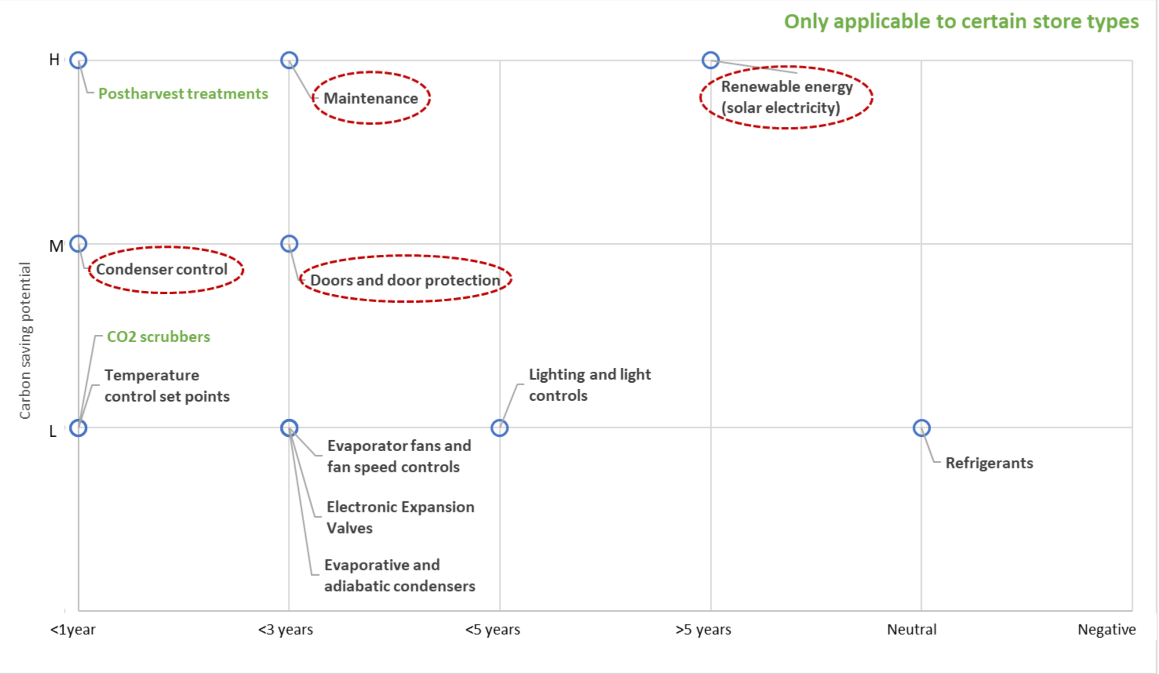

Figure 13. Minor retrofit options.

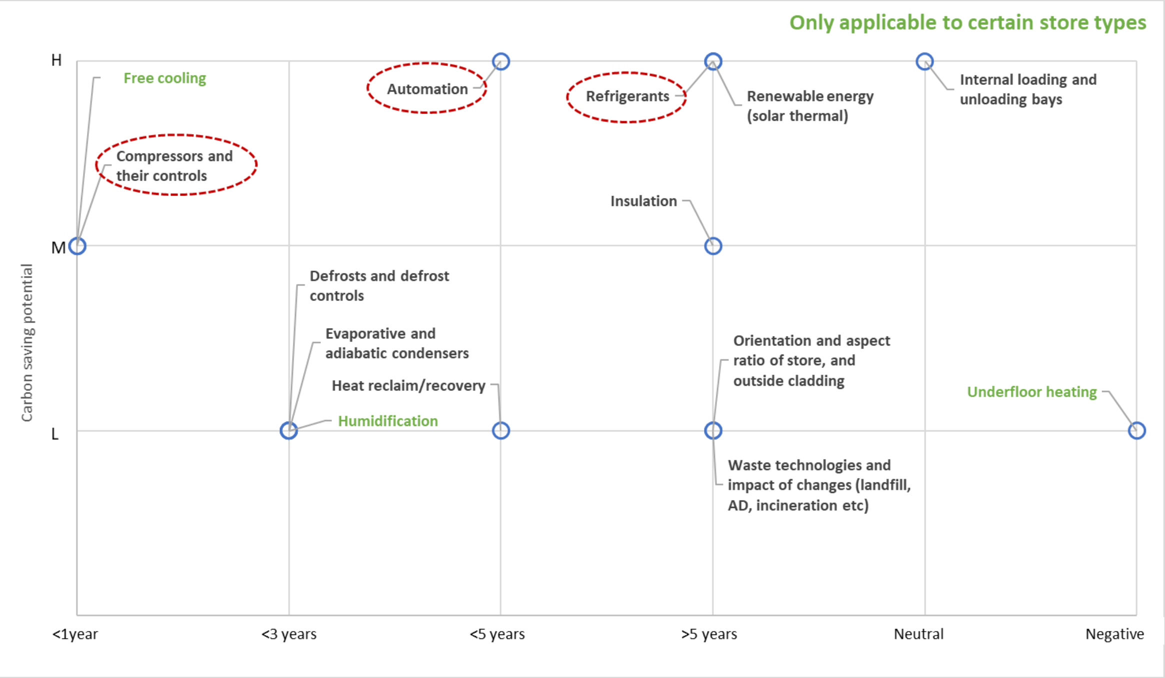

Figure 14. Major retrofit options.

7 What strategies should we apply to get to zero carbon in cold stores?

The technology options with the most potential were then applied using a mathematical model (ice-e model [31]) in two locations, London and Aberdeen to assess their potential to reduce carbon emissions.

7.1 Scenarios

Scenarios such as 'do nothing' and ones that applied minor and major retrofits were considered.

7.1.1 Do nothing

This considered the GHG emissions if the cold stores considered 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 intensity were applied for 2050. Climate change scenarios included Representative Concentration Pathways (RCP) of 4.5 and 8.5. RCPs are climate scenarios showing possible futures based on greenhouse gas levels with RCP 4.5 representing moderate emissions and about 2 – 3°C warming, and RCP 8.5 representing high emissions and around 4°C or more of warming by 2100 [32].

COLD STORES MODELLED

Two typical cold stores were modelled.

STORE 1

*A **43,758 m³ chilled mixed produce store** (operating at 3°C) used to store food for delivery to end users. The store had relatively heavy usage and operated using a direct expansion HFC refrigeration system.*

STORE 2

*A **60,760 m³ frozen store** (operating at -18°C) used to store pallets of frozen vegetables. The store was automated, having a conveyer entrance. R717 was used as the refrigerant in a 2-stage pumped system.*

Detailed information on each store is presented in the section 11.

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[31] Foster, A.M., Reinholdt, L.O., Brown, T., Hammond, E.C. and Evans, J.A., 2016. Reducing energy consumption in cold stores using a freely available mathematical model. *Sustainable Cities and Society*, 21, pp.26–34. https://doi.org/10.1016/j.scs.2015.11.006

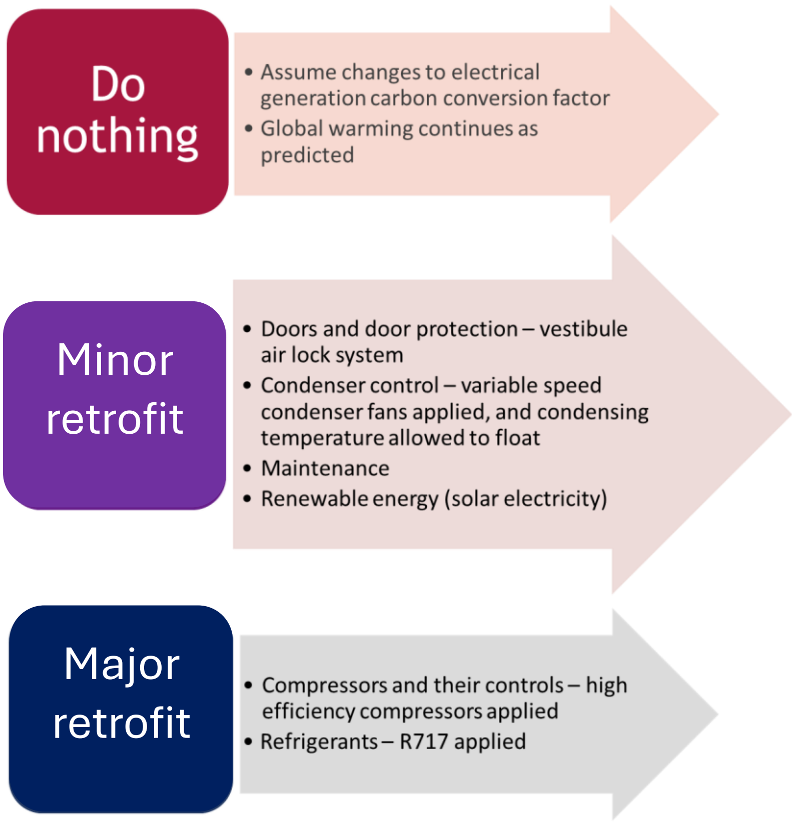
[32] IPCC, 2014. *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC.

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

7.1.2 Minor retrofit

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

1. Door protection – move to vestibule air lock system.
2. Condenser – More efficient fan motor and condenser floating temperature.
3. Maintenance – reduce energy consumption by 5%.
4. Renewable energy (solar electricity) – assumed that solar panels cover 65% of the roof of the cold store.



7.1.3 Major retrofit

Some technologies would require a major retrofit. These technologies were applied in addition to the 'do nothing' and 'minor-retrofit' scenarios and considered energy consumption and carbon emissions for the cold store types through to 2050. The technologies applied were:

1. Compressors– high efficiency compressors.
2. Refrigerants – R717 (only chilled store as freezer was already R717).

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

7.2 How to interpret the results

Predicted GHG emission savings were integrated over time. This showed accumulated GHG emissions reductions. Although there are ambitions to reduce GHG emissions to zero by 2050, the rate at which this is achieved is also important. The earlier that GHG emissions are reduced, the less overall emissions occur, which is a significant factor in reducing global warming. For the 3 scenarios, we calculated the GHG savings that can be achieved from 2025 to 2050 and the impact of accelerating the move to climate friendly technologies. The accumulated GHG emissions from 2025 to 2050 in Aberdeen (**Error! Reference source not found.**) would be:

Do nothing: 1952 tCO_{2e}

Minor retrofit: 1519 tCO_{2e}

Major retrofit: 420 tCO_{2e}

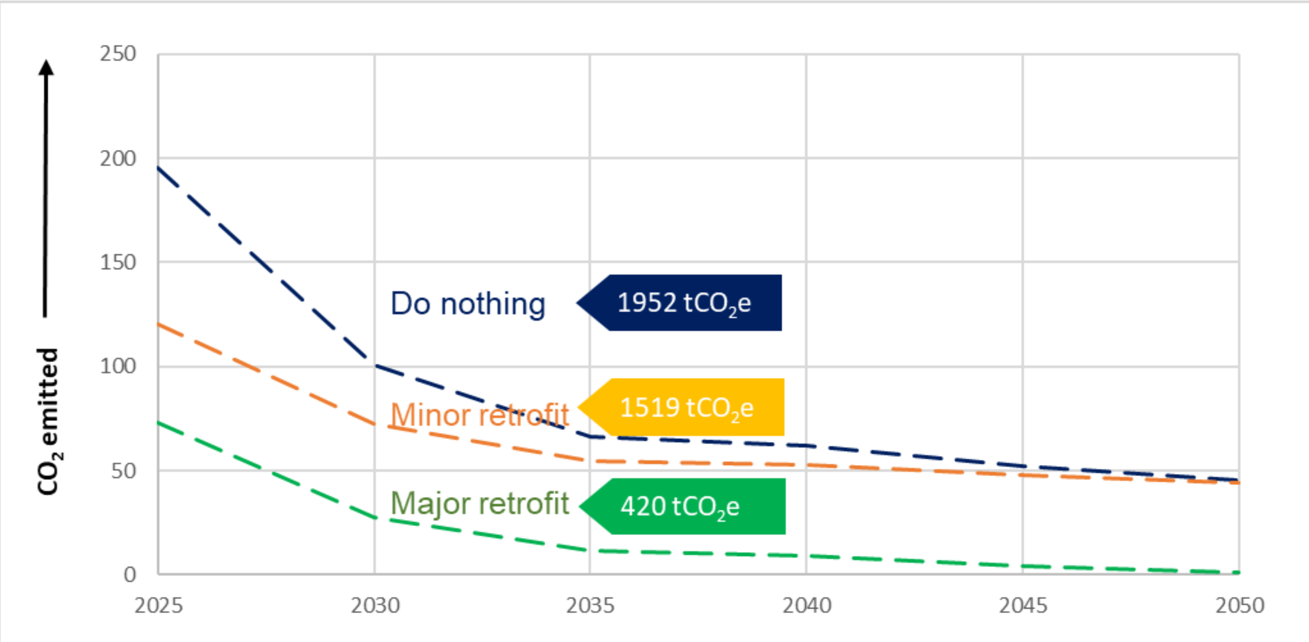


Figure 15. Diagram showing impact on accumulated carbon of when technologies are applied in a cold store chilled in Aberdeen

Other options were modelled to assess impacts of when changes are made on accumulated carbon savings (**Error! Reference source not found.**). For example:

- If the facility did nothing until 2030 and then carried out a major retrofit, the accumulated carbon emissions would be 889 tCO_{2e} (option 1).
- If they did nothing until 2025, then applied a minor retrofit and in 2035 carried out a major retrofit, the accumulated carbon emissions would be 869 tCO_{2e} (option 2).

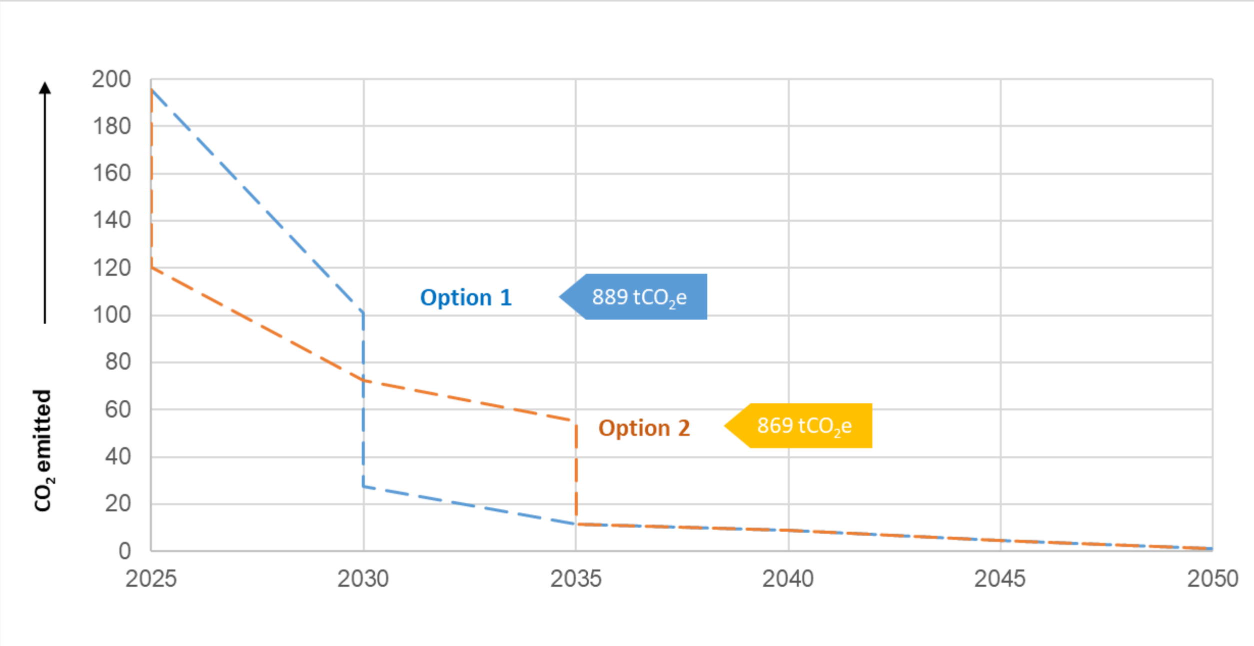


Figure 16. Diagram showing impact of when minor and major retrofit are applied in different years in the Aberdeen chilled cold store

7.3 Assumptions applied in the modelling

The ice-e model was used to simulate performance of cold stores. Complete information on the modelling approach is described in Section 11.

The modelling was based on two typical cold stores. The inputs to the model are shown in Section 11.

7.4 Scenario 1: do nothing

The impact of climate change and grid electricity carbon intensity were considered individually to assess impact and the benefit in additive impacts.

Impact of climatic temperature change: Error! Reference source not found. (chilled store) and **Error! Reference source not found.** (frozen store) shows the impact of climatic temperature change on energy consumption for the 2 locations in 2025 and 2050. The Figures present information divided into the electrical loads (compressor, condenser and evaporator fans, defrosts, lights and other loads).

Overall differences between energy consumed in 2025 and 2050 were small (maximum of 2.7% for the chilled and 2.5% for the frozen store). This was because the mean temperature increased between 2025 and 2050 was relatively small (0.5 K).

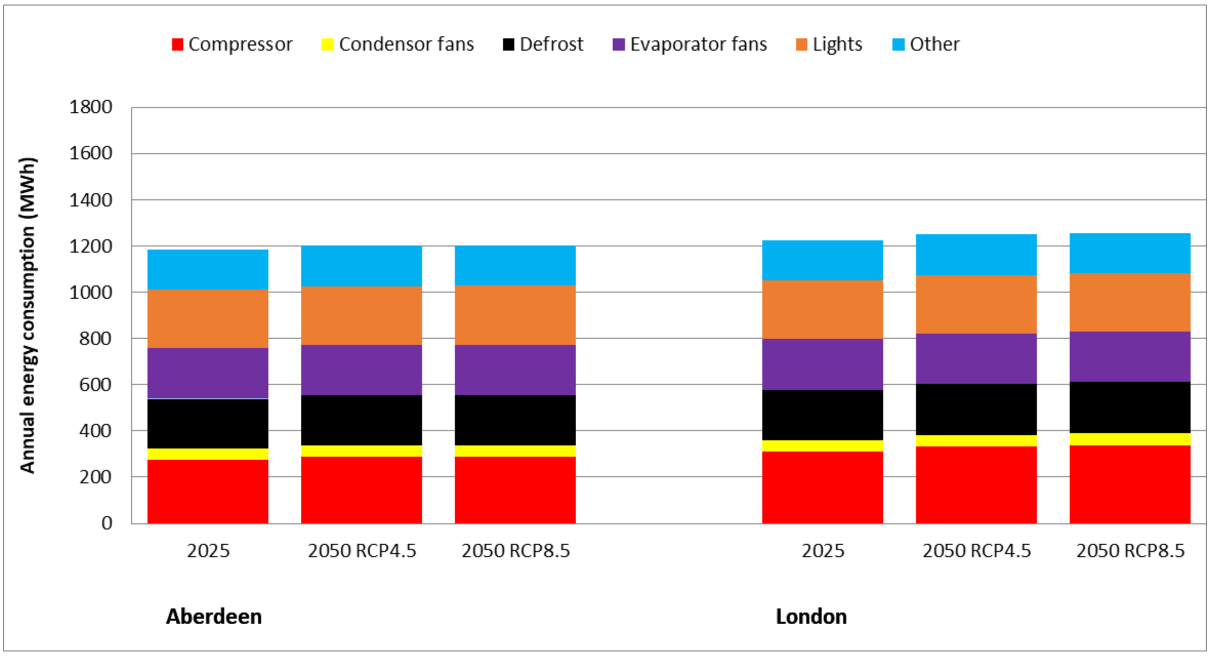


Figure 17. Impact of climatic temperature change on energy consumed between 2025 and 2050 for the chilled store in the 2 locations studied.

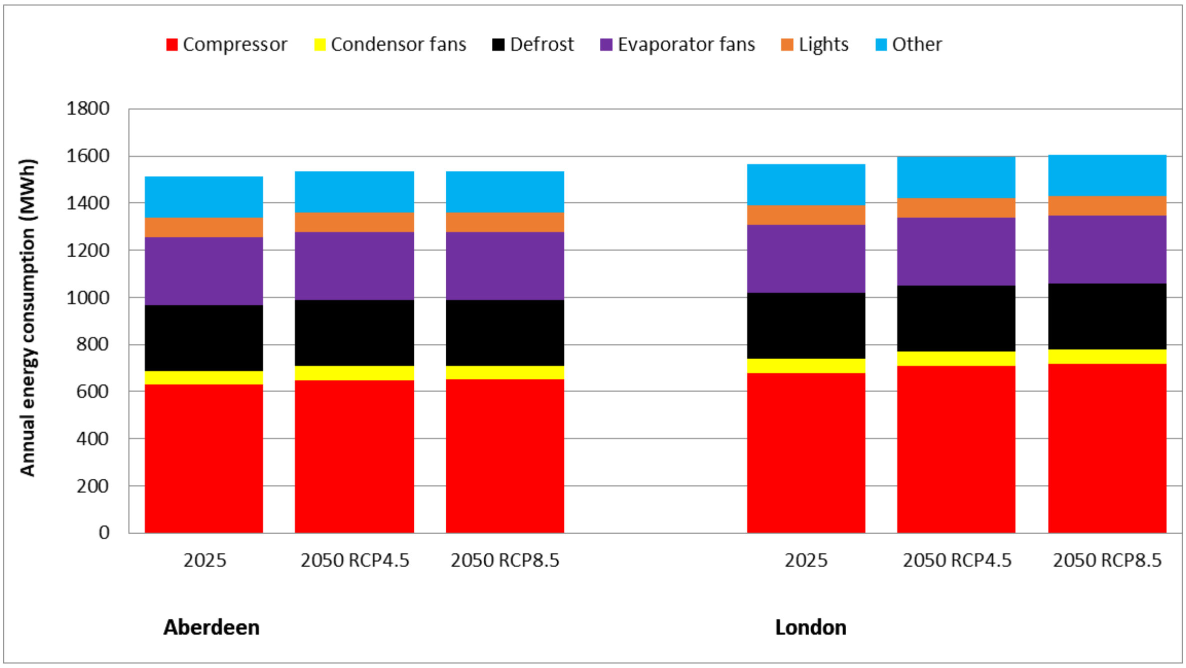


Figure 18. Impact of climatic temperature change on energy consumed between 2025 and 2050 for the frozen store in the 2 locations studied.

Impact of changes to electrical grid carbon intensity

Over time the carbon intensity of the electricity grid in the UK is predicted to decrease considerably and reach almost zero by 2050 [33].

The significant changes to carbon intensity over time had a major impact on emissions for the cold stores studied. **Error! Reference source not found.** presents the GHG emissions for the chilled store and **Error! Reference source not found.** presents the GHG emissions for the frozen store in the two locations.

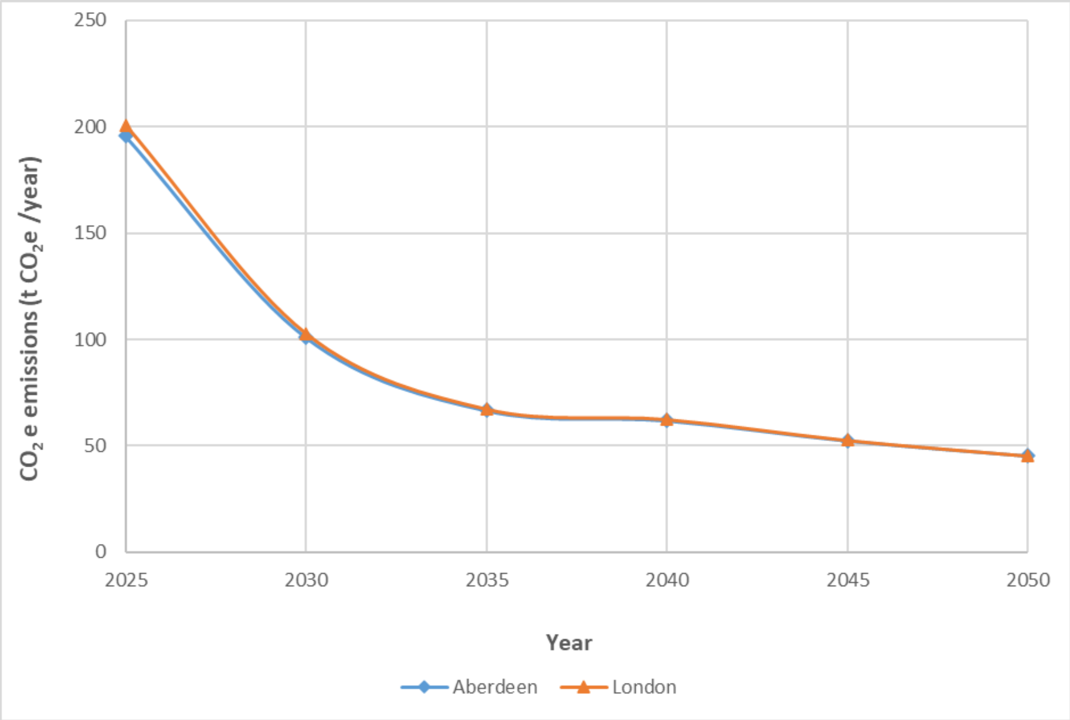


Figure 19. Impact of grid carbon emission intensity change on total GHG emissions in the 'do nothing' scenario by the chilled store in the 2 locations studied.

[33] Department for Energy Security and Net Zero (DESNZ), 2024. *Energy and emissions projections: 2023 to 2050*. London: UK Government. Available at: https://www.gov.uk/government/publications/energy-and-emissions-projections-2023-to-2050

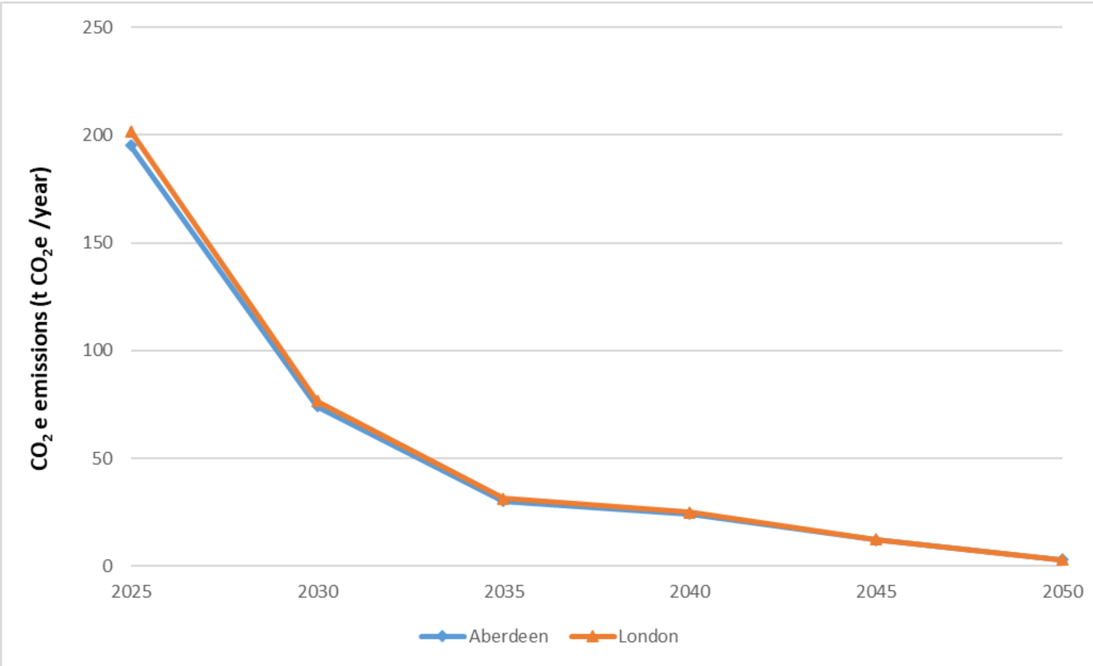


Figure 20. Impact of grid carbon emission intensity change on total GHG emissions in the 'do nothing' scenario by the frozen store in the 2 locations studied.

The accumulated carbon emitted between 2025 and 2050 for the 'do nothing' scenario are presented in **Error! Reference source not found.** for the chilled and frozen stores.

Table 3. Accumulated GHG emissions between 2025 and 2050 for Aberdeen and London, for the do-nothing scenario.

	Accumulated tCO_2e emitted between 2025 and 2050	
	Chilled store	Frozen store
Aberdeen	1952	1124
London	1983	1163

DO NOTHING SCENARIO

In the cold store case studies (assuming no operational changes between 2025 and 2050), only the frozen store using R717 refrigerant can approach net zero. The chilled store, which uses an HFC refrigerant, cannot reach net zero even when the grid carbon intensity is close to zero. Retrofit measures are required to improve efficiency and reduce electricity-related emissions in both chilled and frozen cold stores.

7.5 Scenario 2: minor retrofit

Initially each retrofit technology was applied individually to the 2 stores (chilled/frozen) and the impact assessed to 2050 in addition to the changes in the 'do nothing' scenario. The following assumptions were made:

Vestibule: an air-lock vestibule was simulated by increasing the effectiveness of the door protection from 0 to 0.97. This meant that 97% less air exchanged between inside and outside of the store through the doorway, when it was open.

More efficient condenser and fans: the temperature difference across the condenser was reduced from 15 to 10 K. Additionally the fans energy ratio (proportion of maximum cooling duty to fan power ratio) was increased from 30 to 110.

Improved maintenance: 5% reduction in total electrical consumption of the cold store due to better maintenance.

RES (solar): solar panel area was equal to 65% of the area of the roof and 20% solar panel efficiency.

The impact of the retrofit options (alone and in combination) is shown in **Error! Reference source not found.** and 22 for energy consumption and Figure 23 and **Error! Reference source not found.** for GHG emissions.

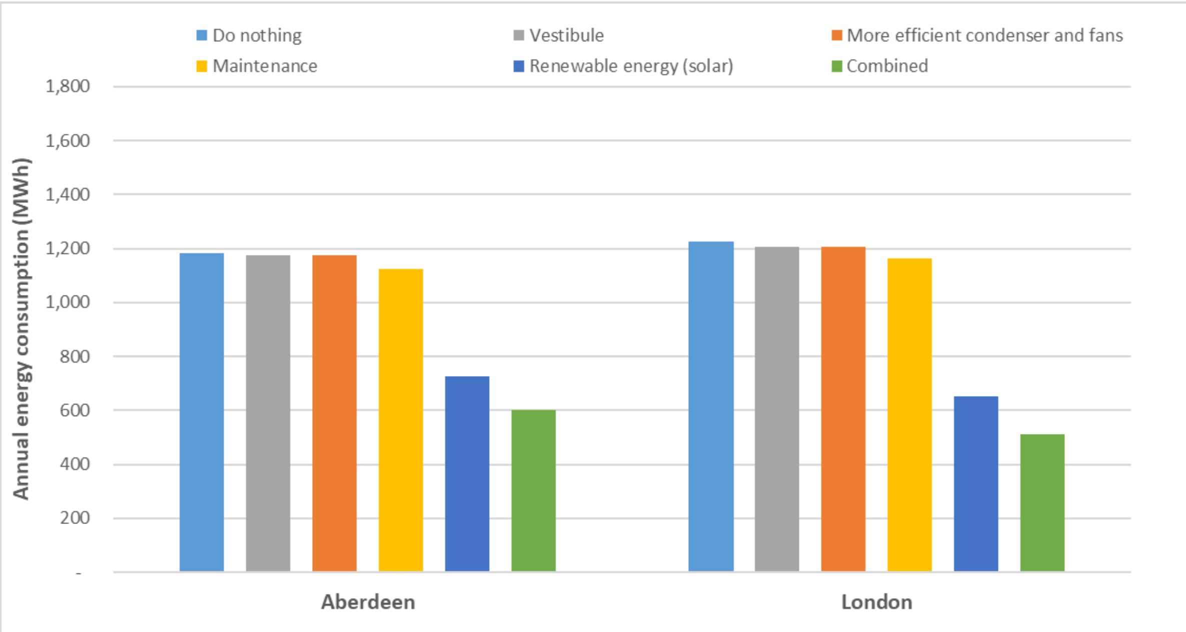


Figure 21. Impact on energy consumption of minor retrofit options individually and together for the chilled store in the 2 locations.

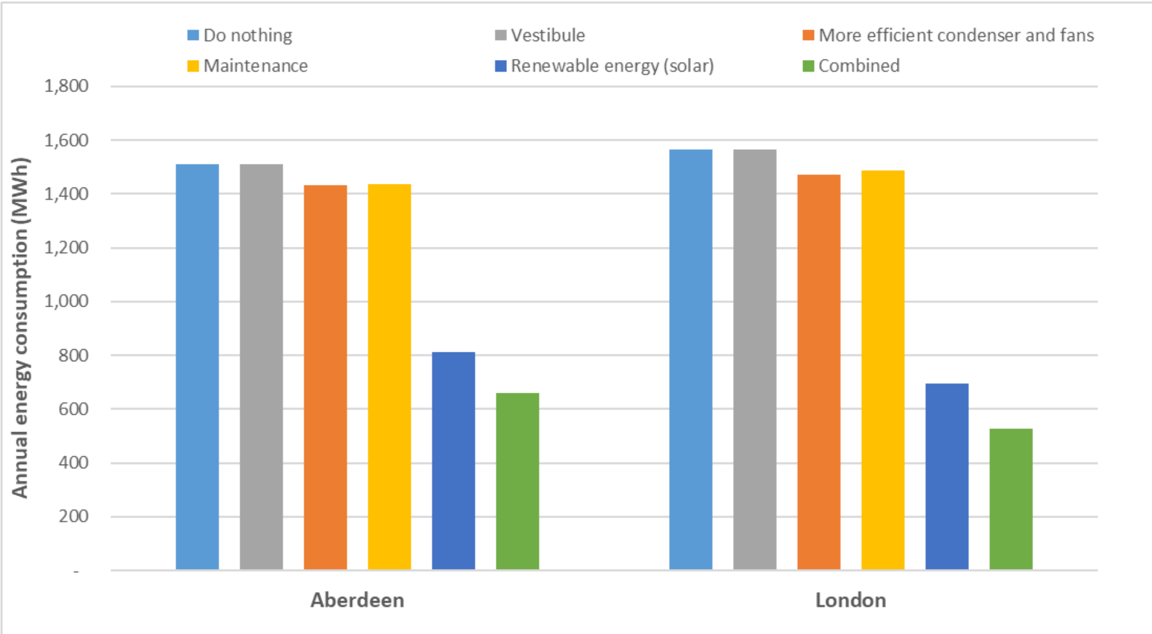


Figure 22. Impact of energy consumption minor retrofit options individually and together for the frozen store in the 2 locations.

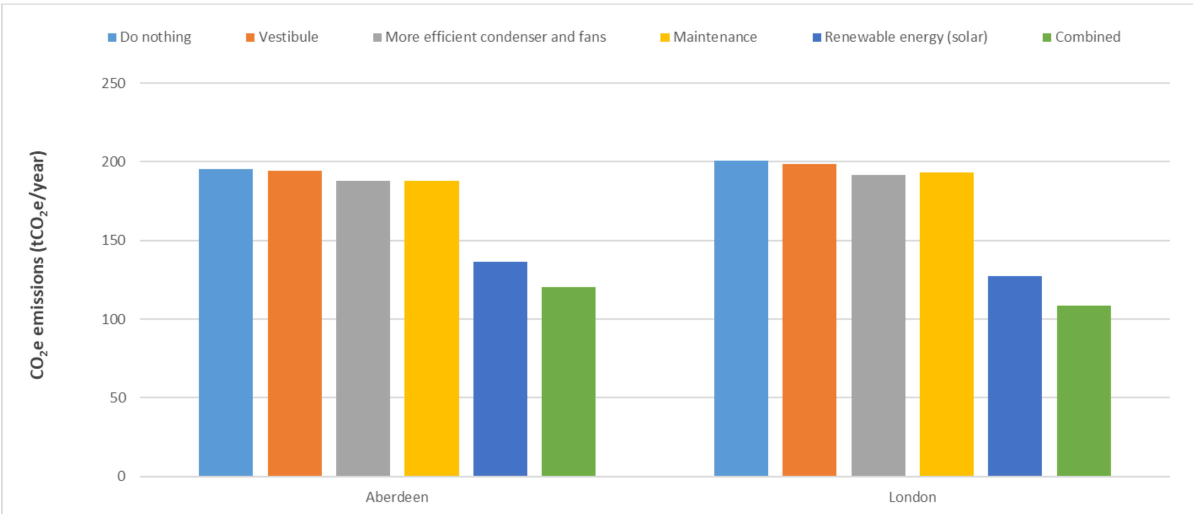


Figure 23. Impact on carbon emissions of minor retrofit options individually and together for the chilled store in the 2 locations.

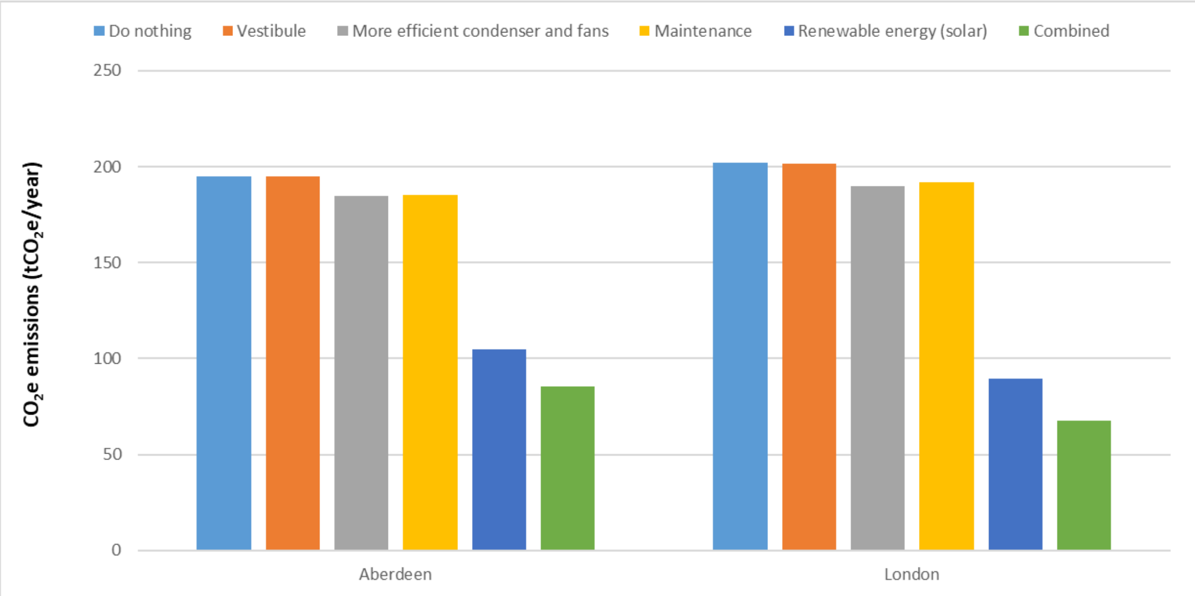


Figure 24. Impact on carbon emissions minor retrofit options individually and together for the frozen store in the 2 locations.

Vestibule:

ELECTRICAL CONSUMPTION: adding a vestibule had minimal impacts on energy savings for both chilled (1%) and frozen cold stores (0.1%). The frozen store was automated (modelled as medium traffic and 20 x 15 s door openings per day and infiltration was a small proportion of the overall heat load) and already has extremely efficient door protection (strip curtains with effectiveness of 0.77).

GHG EMISSIONS: % GHG emission savings were also negligible for both chilled and frozen cold stores.

More efficient condenser and fans:

ELECTRICAL CONSUMPTION: energy savings of up to 5 - 6% were predicted for the chilled and frozen stores for Aberdeen and London respectively. Greater benefits were seen in locations with higher ambient temperature e.g. London, where a higher heat is extracted by the condenser and thus a more efficient condenser has more impact.

GHG EMISSIONS: for the chilled store, the ghg emissions were dominated by refrigerant leakage (R134a refrigerant with a GWP of 1430). This was not the case in the frozen store with R717 (GWP of 0). In reality, a more efficient condenser would likely be larger in size and contain more refrigerant. Leakage of refrigerant may therefore be increased which would increase the carbon emissions (for the chiller). This was not considered in the modelling.

Improved maintenance:

ELECTRICAL CONSUMPTION: The percentage savings assumed were identical across all cold stores and locations.

GHG EMISSIONS: carbon emission reductions of 4 and 5% were obtained for both locations for chilled and frozen stores respectively.

RES (solar PV):

ELECTRICAL CONSUMPTION: Solar PV had significant impacts on energy savings, between 39% and 56%. Greatest savings were seen in London as it has more sunshine than Aberdeen.

GHG EMISSIONS: These varied between 30 and 56%.

Electrical energy and GHG emissions in 2025 for each scenario are presented in Table 9.

Table 4. Energy use and carbon emissions for retrofit scenarios in 2025.

Scenarios modelled	Electrical energy use and GHG emissions	Chilled store		Frozen store	
		Aberdeen	London	Aberdeen	London
Do nothing	MWh	1,184	1,225	1,513	1,565
	tCO_2e	196	201	195	202
Vestibule	MWh	1,174	1,208	1,512	1,564
	% reduction	1	1	0.1	0.1
	tCO_2e	194	199	195	202
	% change	1	1	0.1	0.1
More efficient condenser and fans	MWh	1,123	1,153	1,434	1,473
	% change	5	6	5	6
	tCO_2e	188	192	185	190
	% change	4	5	5	6
Maintenance	MWh	1,125	1,164	1,437	1,487
	% change	5	5	5	5
	tCO_2e	188	193	185	192
	% change	4	4	5	5
Solar PV	MWh	726	654	813	693
	% change	39	47	46	56
	tCO_2e	137	127	105	89
	% change	30	37	46	56
Combined	MWh	601	510	662	526
	% change	49	58	56	66
	tCO_2e	120	109	85	68

Scenarios modelled	Electrical energy use and GHG emissions	Chilled store		Frozen store	
		Aberdeen	London	Aberdeen	London
	% change	38	46	56	66

The impact on GHG emissions of the combined technologies to 2050 are shown in **Error! Reference source not found.** for the chilled store and **Error! Reference source not found.** for the frozen store.

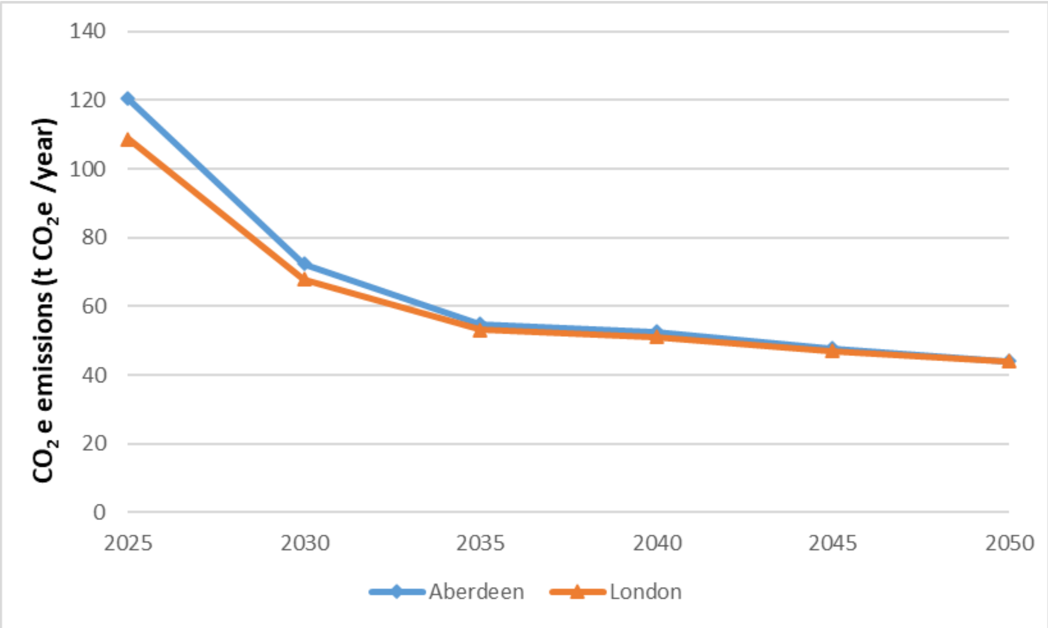


Figure 25. Impact of grid carbon emission factor change on total carbon emitted in the 'combined retrofit' scenario in the chilled store in the 2 locations studied.

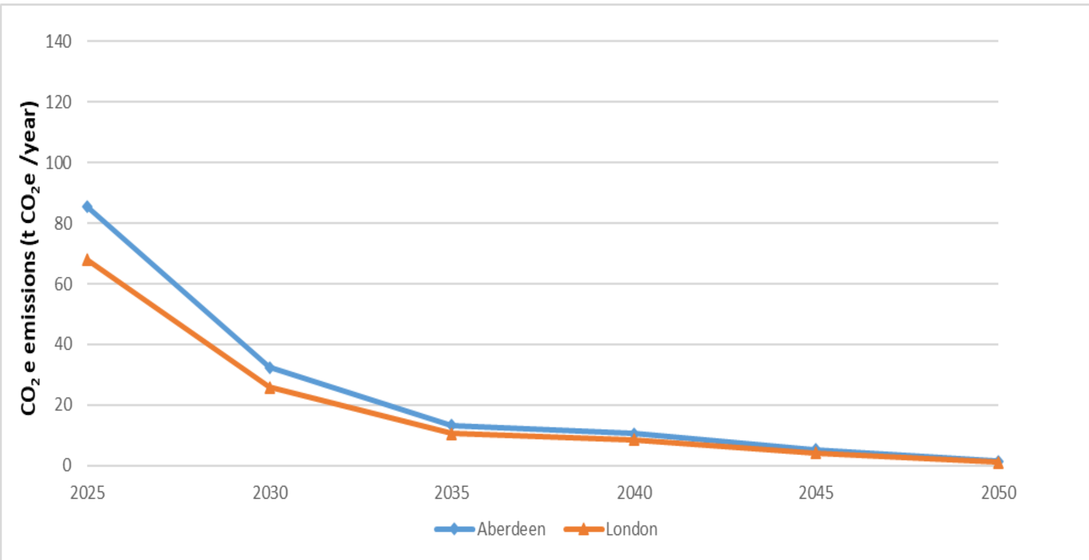


Figure 26. Impact of grid carbon emission factor change on total carbon emitted in the 'combined retrofit' scenario in the frozen store in the 2 locations studied.

Combined impact

GHG EMISSIONS: overall GHG savings of 60% were predicted for the chilled store and up to 98% for the frozen store.

Table 10 shows the cumulative GHG emissions between from 2025 to 2050 when implementing the 'combined minor retrofit' scenario for the two cold stores (chilled and frozen).

Table 5. Accumulated GHG emissions between 2025 and 2050 for Aberdeen and London, for the combined retrofit scenario.

	Accumulated GHG emissions between 2025 and 2050 (tCO_2e)	
	Chilled store	Frozen store
Aberdeen	1519	492
London	1452	391

7.6 Scenario 3: major retrofit

Each major retrofit technology was applied individually to the combined retrofit scenario for the 2 stores (chilled/frozen) and the impact assessed to 2050 so that the stores continued to be operated in the same manner throughout this period. The following assumptions were made:

High efficiency compressors: the isentropic efficiency of the compressors were increased from 0.5 to 0.7.

Natural refrigerant (chilled store only): the R134a refrigerant was replaced by R717.

The impact of the major retrofit options (alone and in combination) is shown in **Error! Reference source not found.** and 28 for energy consumption and **Error! Reference source not found.** and 30 for GHG emissions.

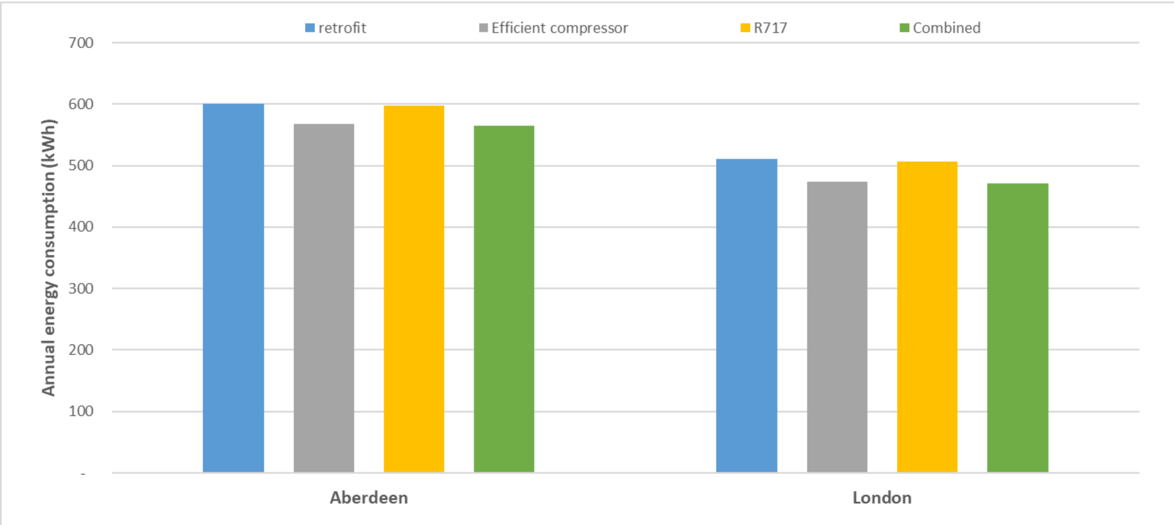


Figure 27. Impact on electrical energy consumption on major retrofit options applied individually and together for the chilled store in the 2 locations.

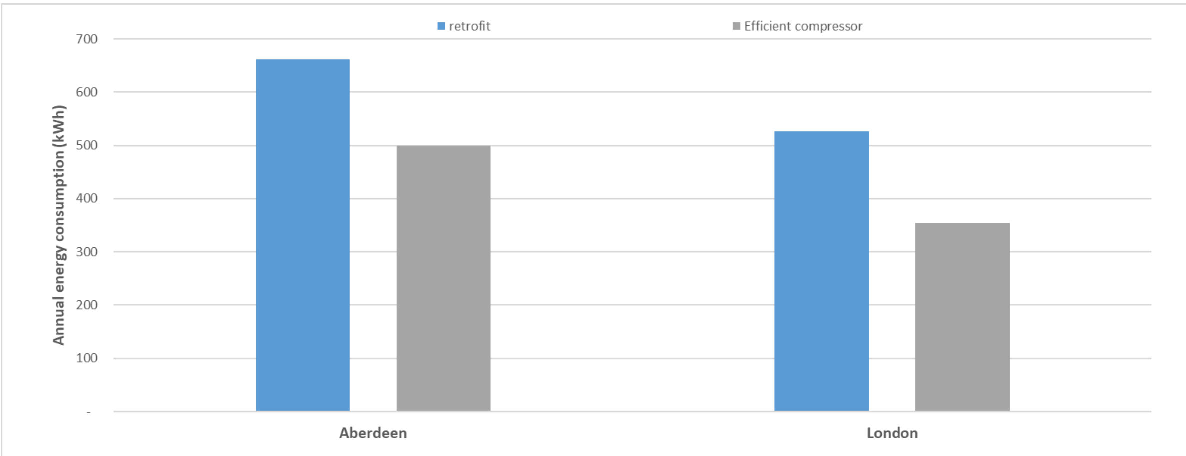


Figure 28. Impact on electrical energy consumption of major retrofit options applied individually and together for the frozen store in the 2 locations.

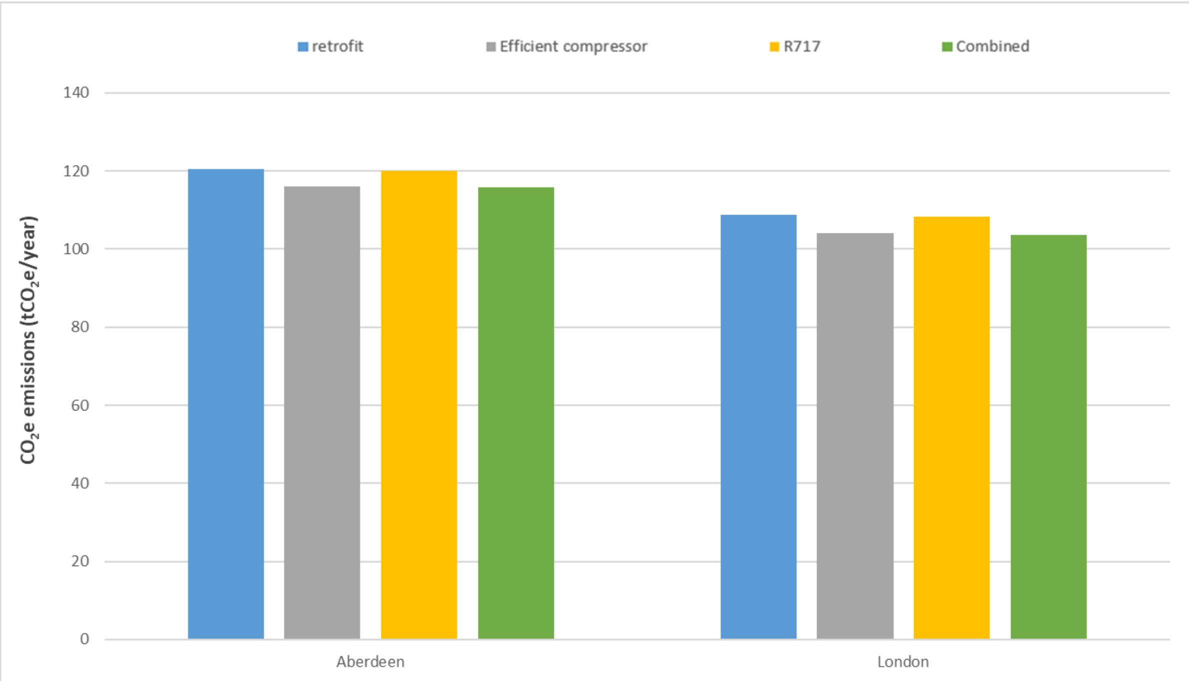


Figure 29. Impact on GHG emissions of major retrofit options applied individually and together for the chilled store in the 2 locations.

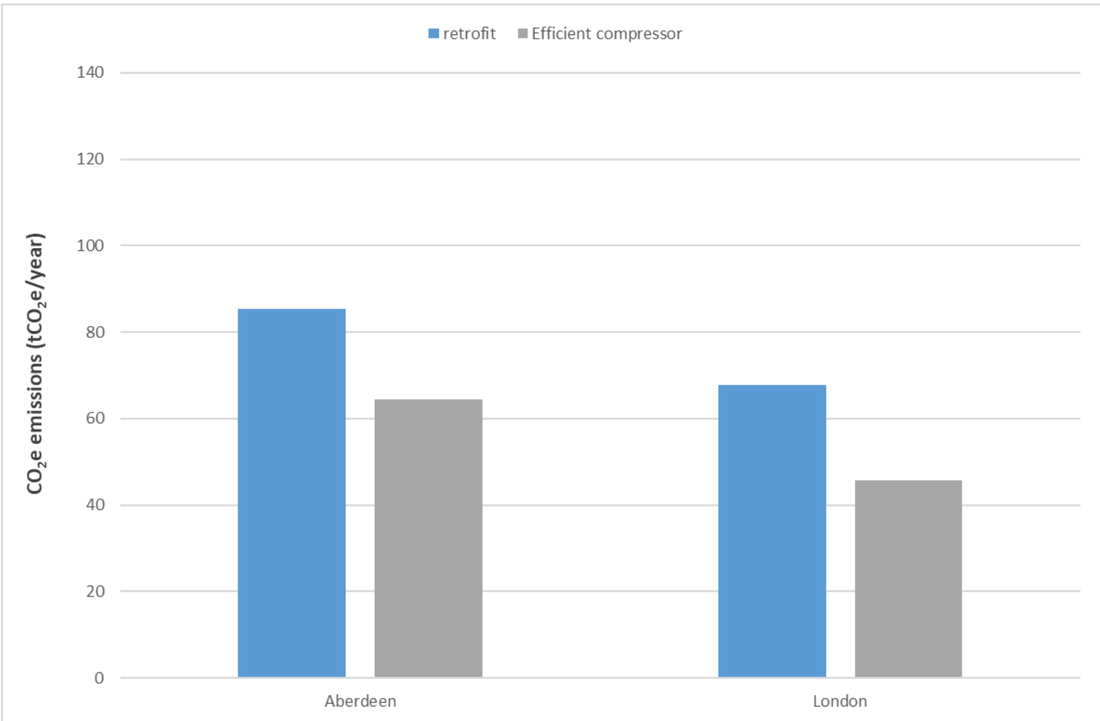


Figure 30. Impact on GHG emissions of major retrofit options applied individually together for the frozen store in the 2 locations.

High efficiency compressor

ELECTRICAL ENERGY: applying a high efficiency compressor had more impact on the freezer store and greatest impact in London, saving up to 33% of the energy.

GHG EMISSIONS: For the chiller store, percentage savings were lower than those for the freezer store, as a large proportion of the emissions were from refrigerant leakage. Savings were approximately 4% for the chilled store and up to 33% for the freezer store. A more efficient compressor would reject less heat, and thus if installing a new system, a smaller condenser could be used reducing refrigerant charge and emissions from refrigerant leakage. This was not considered in the modelling.

R717 (chilled store only)

ELECTRICAL ENERGY: changing refrigerant in the chilled store had a small impact on energy consumption, saving 1% in both Aberdeen and London.

Electrical energy and GHG emissions for each scenario are presented in **Error! Reference source not found.**.

Table 6. Electrical energy use and GHG emissions for the major retrofit scenarios in 2025.

Scenarios modelled	Electrical energy use and GHG emissions	Chilled store		Frozen store	
		Aberdeen	London	Aberdeen	London
Do nothing	MWh	601	510	662	526
	tCO2e	120	109	85	68
High efficiency compressors	MWh/year	568	474	500	354
	% reduction	5	7	24	33
	tCO2e/year	116	104	64	46
	% change	4	4	24	33
Refrigerant (R717)	MWh/year	598	507	N/A	N/A
	% change	1	1	N/A	N/A
	tCO2e/year	120	108	N/A	N/A
	% change	0.3	0.4	N/A	N/A
Combined	MWh/year	565	471	500	354
	% change	6	8	24	33
	tCO2e/year	116	104	64	46
	% change	4	5	24	33

The impact of the combined technologies to 2050 are shown in **Error! Reference source not found.** for the chilled store and **Error! Reference source not found.** for the major retrofit scenario.

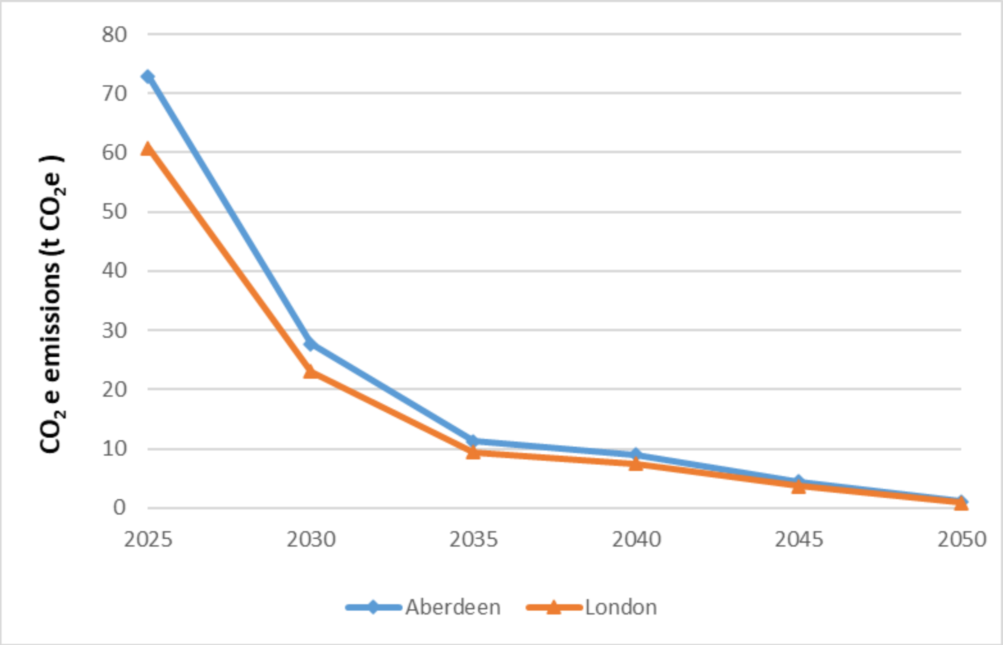


Figure 31. Impact of grid carbon emission factor change on GHG emissions in the 'combined major retrofit' scenario for the chilled store in the 2 locations studied.

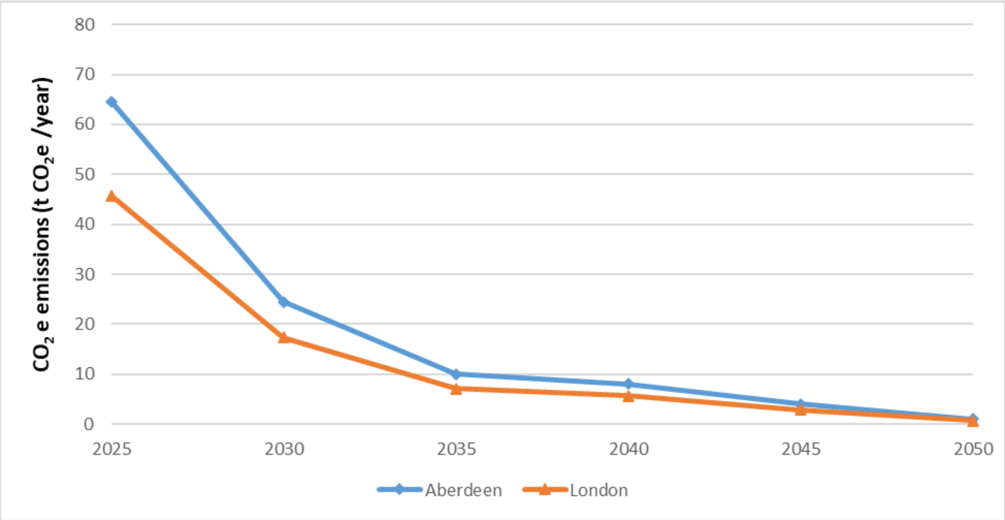


Figure 32. Impact of grid carbon emission factor change on GHG emissions in the 'combined major retrofit' scenario for the frozen store in the 2 locations studied.

Combined impact

GHG EMISSIONS: changing the refrigerant to a low GWP option combined with high efficiency compressor resulted in significant GHG savings in the chilled store (up to 98%).

Error! Reference source not found. displays the accumulated GHG emissions from 2025 to 2050 for the 'combined major retrofit' scenario for the two cold store configurations.

Table 7. Accumulated GHG emissions between 2025 and 2050 for Aberdeen and London, for the combined major retrofit scenario.

	Accumulated GHG emissions between 2025 and 2050 (tCO_2e)	
	Chilled store	Frozen store
Aberdeen	420	372
London	350	263

7.6.1 Overall impact of making changes

The impact of all retrofit options is presented in Table 8. Significant GHG emission reductions were predicted, ranging from 41% to 77%. Electrical energy savings of up to 77% were achieved in the London frozen cold store. These GHG emission reductions resulted from the transition to a zero-GWP refrigerant and from a substantial proportion of electricity being supplied by rooftop solar PV.

Table 8. Electrical energy use and GHG emissions for all interventions (do nothing, minor and major retrofit combined) in 2025.

Scenarios modelled	Electrical energy use and GHG emissions	Chilled store		Frozen store	
		Aberdeen	London	Aberdeen	London
Do nothing	MWh	1,184	1,225	1,513	1,565
Combined (minor + major retrofit)	MWh	565	471	500	354
	% reduction	52.3	61.5	66.9	77.4
Do nothing	tCO2e/year	196	201	195	202
	tCO2e/year	116	104	64	46

Scenarios modelled	Electrical energy use and GHG emissions	Chilled store		Frozen store	
		Aberdeen	London	Aberdeen	London
Combined (minor + major retrofit)	% change	40.8	48.4	66.9	77.4

7.6.2 Impact on GHG emissions of making changes

The total GHG emitions between 2025 and 2050 for the chilled and frozen store in Aberdeen and London are shown in **Error! Reference source not found.** and 34 respectively. The charts compare cumulative emissions across three scenarios: do nothing, minor and major retrofit. Other options were modelled to assess impacts of when changes are made on accumulated carbon savings as follows:

- Option 1: If the facility did nothing until 2030 and then carried out a major retrofit,
- Option 2: If they did nothing until 2025, then applied a minor retrofit and in 2035 carried out a major retrofit.

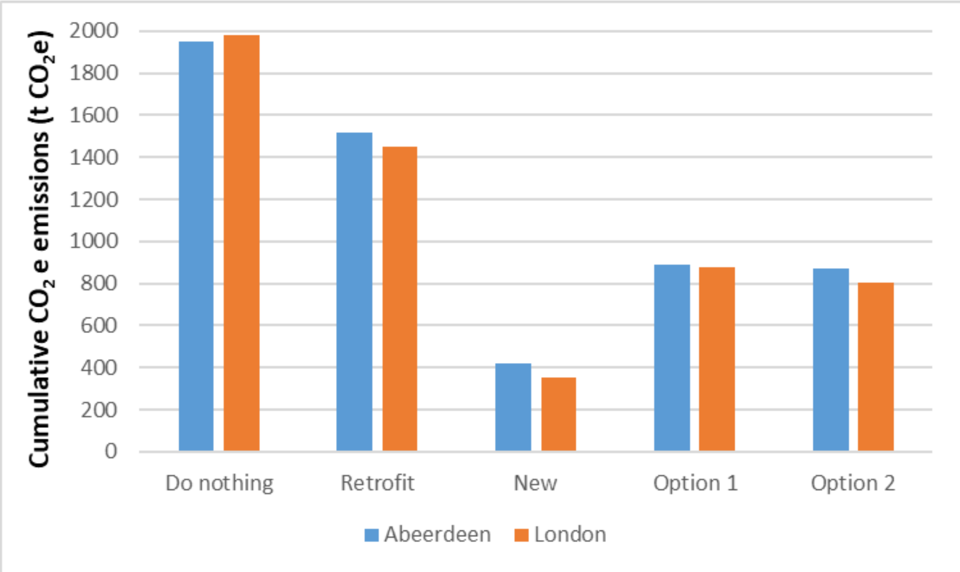


Figure 33. Carbon emitted by the chilled store in Aberdeen and London from 2025 to 2050.

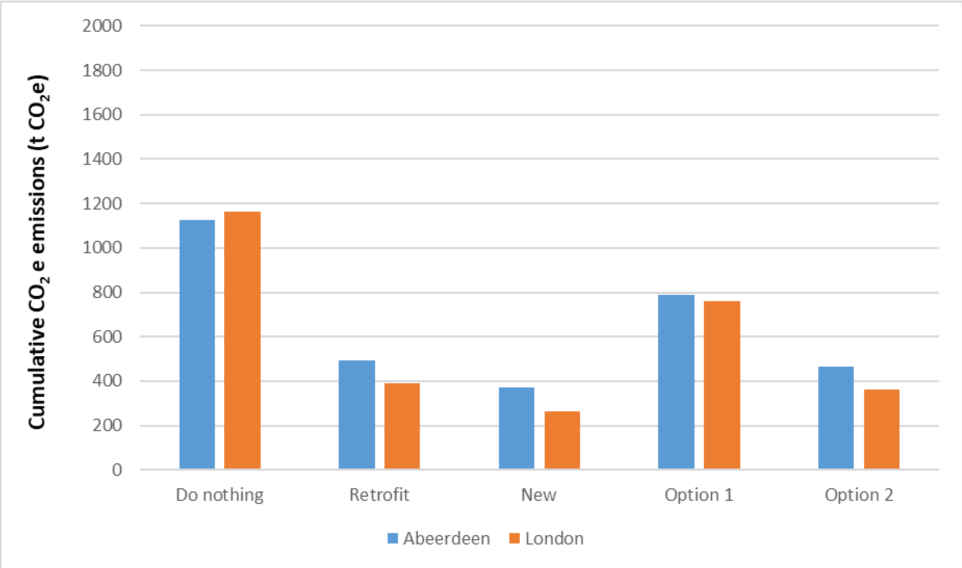


Figure 34. Carbon emitted by the frozen store in Aberdeen and London from 2025 to 2050.

8 Recommendations

The modelling provided a direct comparison between the impact of each intervention in each location.

A great deal of decarbonisation should occur naturally (without intervention from the cold store sector) through reduction in the UK electrical grid carbon conversion factor, which is predicted to reach almost zero by 2050.

Decarbonisation of the electrical grid has a huge impact on carbon emission from cold stores. In 2050 the emissions after all the modelled interventions were applied meant that the both the chilled and frozen stores were almost carbon neutral in London and Aberdeen. To decarbonise earlier would require additional interventions. One opportunity is to apply a greater number, or more efficient solar panels. This would have a greater impact in sunnier locations where there is more direct solar radiation (the prediction assumed the entire roof area had solar panels; therefore, off-roof solar panel would be required). This may

OUR RECOMMENDATIONS

- *Apply technological interventions as rapidly as possible to ensure cumulative carbon emissions are maximised.*
- *Always apply low GWP refrigerants, if possible, in major retrofits and new cold store applications.*
- *Check operation of plant through regular auditing, maintenance and automated monitoring.*
- *Always purchase the most efficient equipment that is available on the market. In particular efficient compressors.*
- *Consider the use of renewable energy resources (especially solar in sunnier climates).*

become more relevant as one issue which was not covered in the road map was the potential need to charge refrigerated electric vehicles at cold stores in the future. Logically it makes sense to have charging available for such vehicles at cold stores. However, this would mean an additional energy load which would need to be mitigated.

The road map investigated the options which were assessed as being most economic. Some technologies may develop in the next few years and provide greater energy savings. These could include more efficient compressors, advanced control systems, greater levels of automation (and the associated reduction in energy required for defrost, lighting etc.). There is also greater emphasis being placed on operation practices, maintenance and controls. Use of digital twins which simulate the design performance of a store are becoming available to highlight divergences between design and actual operation. Much of the savings in the future may come from these initiatives which rapidly identify operational issues and enable rapid remedial action and correction.

The opportunities to change main components (such as compressors) are limited to major retrofits and changes to the construction of a store are primarily limited to new stores. Most larger cold stores are designed to operate for 20 - 30 years and so opportunities to benefit from these options have limitations. Efficient initial design is an essential component in the road to net zero. However, purchasing decisions are based around initial cost. Greater emphasis needs to be placed on energy efficiency and maintaining energy efficiency over the life of the store.

Overall, one clear outcome from the modelling was that not all interventions had the same impact. It should also be noted that the stores modelled were example facilities and that results would be different in facilities with different designs, operational practices, and locations. It is essential to assess each cold store individually to ascertain the most beneficial interventions. Good auditing by an experienced engineer has been shown to identify energy savings on average in the region of ~30% [34] and should be one of the first steps in the road map to reducing energy use.

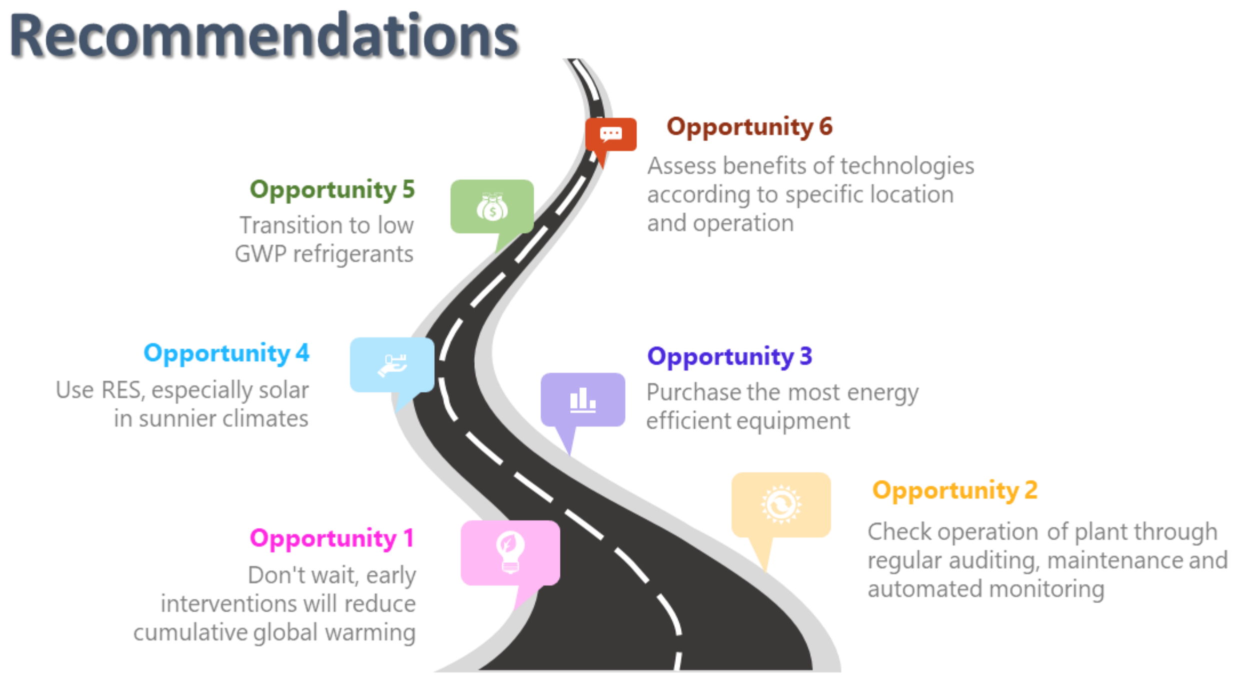
To achieve near net zero carbon emission in cold stores will require a range of initiatives. Operators themselves are incentivised to reduce energy costs and are keen to project a green and environmental image. Policy and legislation are driving the change to low GWP refrigerants and energy is a major part of the operational cost of a cold store.

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

[34] Evans, J.A. and Hammond, E.C., 2014. Assessment of methods to reduce the energy consumption of food cold stores. Applied Thermal Engineering, 62, pp.697–705.

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 cold stores exists and is feasible. The diagram below shows what we consider to be the priority areas for cold stores to focus on.



9 Detailed technology/strategy reviews

9.1 Automation

Automation of handling tasks can offer various routes to more energy efficient operation of cold storage facilities. It can:

- remove the need for some or all of the personnel normally present in the warehouse
- speed up loading, stacking and unloading of goods
- enable the use of smaller access doors instead of full-size loading doors
- allow use of faster opening and closing doors with reduced opening duration
- reduce the space required for handling aisles
- allow greater stacking density
- facilitate greater heights of racking, leading to better building configurations
- in unstaffed operation it can remove the need for lighting
- depending on the equipment used it can replace less efficient forklifts and reduce heat loads from the handling equipment.

While the benefits can be significant, there is a lack of published data particularly in the academic journals. However, its increasing use is reported widely in the trade press and by numerous equipment suppliers and warehouse construction companies. Although these typically quote unsubstantiated figures, some examples are as follows:

https://www.ajot.com/premium/ajot-new-technology-in-cold-storage

This describes automated storage and retrieval systems (AS/RS) consisting of elevators, conveyor belts and driverless stacker cranes, capable of use in tall buildings. Trucks are unloaded inside the temperature-controlled environment, which is claimed by the company to save 50% of the energy costs of traditional cold storage warehouses. The split of where these energy savings occur is however not clear. The same source describes a particular warehouse which is operated by only five workers who remotely control the AS/RS, and the inside of the building is operated in the dark.

In another example, an automated facility with 8,000-10,000 or more pallet positions is claimed by an AS/RS supplier to allow 50-75 percent savings in labour costs and 60-80 percent savings in energy expenditure, as well as a 40-50 percent reduction in footprint. Again however, it is not clear where the energy savings occur, although a significant proportion could be due to reduced usage, less infiltration and reduced lighting levels.

https://supplychaindigital.com/supply-chain-risk-management/cold-chain-future

Scope 1 emissions savings (% or another quantifiable metric)	Not quantified in the sources reviewed, although more efficient stacking may reduce the number of cold stores and thus refrigeration plants needed.
Quality of scope 1 emissions information	Not applicable
Scope 2 emissions savings (% or another quantifiable metric)	From 50 to 80% reduction in energy use based on the above sources, but this will be very dependent on specific store circumstances.
Quality of scope 2 emissions information	Low – basis is trade press / online company information, not refereed publications.
Availability barriers	Initial costs are higher than traditional builds, but availability is good.
TRL level	8-9 (dependant on how quality of information above is perceived)
Maintainability issues	Increasing automation may increase the need for maintenance.

Legislative concerns	Nothing specific.
Payback time (years)	Installing automation can be a significant cost and is only suitable (currently) for large stores. Assuming a relatively efficient cold store (~30 kWh/m^3) with automation then applied paybacks of 3-5 years would be anticipated.

9.2 CO_2 scrubbers

Most fruits and vegetables are refrigerated and stored under normal air conditions for relatively short periods. But fruit like apple and pear, on the other hand, are stored for several months. For these products, in addition to cool storage, the storage atmosphere is also changed by so-called ultra-low oxygen (ULO) storage systems. The oxygen concentration is reduced from 21% in normal air to a few percent in ULO. The carbon dioxide concentration will be slightly increased in this storage atmosphere (0.7-3%), compared to normal air where very little carbon dioxide is present 1s (0.03%). The respiration of the fruit is so further inhibited and a better and longer storage with minimal loss of quality is possible. While respiration is inhibited, it is not completely stopped. The fruit is a living organism and will therefore continue to consume oxygen and produce carbon dioxide. To maintain the ULO storage atmosphere, a control system will regularly remove the carbon dioxide produced with a carbon dioxide scrubber, by means of an adsorption system. However, this requires energy. Oxygen is supplemented from the outside air, either passively through the leaks in the cell or actively by opening a valve. However, not all cells are equally leak-tight and sometimes too much oxygen will leak in. This is flushed out with nitrogen made with a nitrogen separator. This again requires energy.

An energy cost model was previously developed by KU Leuven and VCBT to determine the additional cost of realizing a controlled atmosphere compared to normal cold storage for pome fruit (apple and pear).[35] Starting from the specific respiration properties of the product, it will determine how much carbon dioxide the product will produce under the given storage conditions. On the basis of scrubber properties, the energy cost required to remove this produced quantity of carbon dioxide from the operating atmosphere is then can be calculated. In the energy cost model, the costs are expressed per ton of product and per day of storage. Here we use the model to calculate the emissions.

The model works as follows. After cooling the fruit, most of the oxygen is flushed out through a process called "burning" (N_2 injection) of the cells. This process is largely independent of the type of product present in the cold store and more dependent on the degree of filling and the efficiency of the nitrogen separator used. This is calculated as an average 'burning cost' per weight unit of fruit, independent of the fruit type. After setting the atmosphere, the energy required to maintain this atmosphere will depend on the stored product. The model is valid

[35] Verlinden, B., 2002. Adviesopdracht GMO-koelkostberekeningen. *Vlaams Centrum voor Bewaring van Tuinbouwproducten*, Belgium

when kept in equilibrium. It can be assumed that during the setting of the atmosphere at the beginning of storage more carbon dioxide will be produced as the respiration of the fruit has not yet completely slowed down. However, given that this set-up period is short compared to the total storage time, this additional cost was neglected. N_2 injection may be repeated during the storage to compensate for leaks. To translate the used energy into a CO_2 emissions, the conversion factor for Belgium in 2019 (198 gCO_2eq/kWh) was used.

The respiratory properties of the different apple and pear varieties were obtained from the scientific literature.[36] [37] [38] A complete parameter set could not be found for all varieties important for Belgium. Missing respiratory parameters were supplemented with the values of related varieties that were available. Minor changes in respiration characteristics due to the slow ripening of the fruits during storage were neglected.

Operating characteristics of carbon dioxide gas scrubbers were looked up in information from various manufacturers (Isolcell, Storex, Van Amerongen). From this an average scrubber model was characterized. Also, an error analysis was performed to assess the effects of error/uncertainty margins on the different parameters, such as the conversion factor, the respiration rate, the efficiency of the scrubber and the nitrogen injection energy use. Tables 1 and 2 provide the emissions for the scrubber energy use for scrubbers with a nominal and double efficiency. The emissions are calculated for different apple and pear fruit cultivars with different respiration behavior and different optimal ULO conditions. With respect to the energy use for cooling (also given in the table for the different fruits) the scrubbers are responsible for 2-11% (Table 9, nominal efficiency) and 2-6% (Table 10, double efficiency) of the total emissions. Potential emission savings resulting from an improved CO_2 scrubber efficiency are limited to 1 to 5% depending on the fruit type. Different methods for CO_2 scrubbing exist with different energy use, but commercially available systems from different manufacturers are today quite comparable in terms of methodology and performance.

[36] Peppelenbos, H.W., Tijskens, L.M.M. & van 't Leven, J. 1996, *Modelling oxidative and fermentative carbon dioxide production in fruits and vegetables*, Postharvest Biology and Technology, vol. 9, pp. 283–295, DOI: 10.1016/S0925-5214(96)00029-4.

[37] Lammertyn, J., Franck, C., Verlinden, B.E. and Nicolaï, B.M., 2001. Comparative study of the O_2, CO_2 and temperature effect on respiration between 'Conference' pear cell protoplasts in suspension and intact pears. *Journal of Experimental Botany*, 52(362), pp.1769–1777. https://doi.org/10.1093/jexbot/52.362.1769

[38] Hertog, M.L.A.T.M., Peppelenbos, H.W., Evelo, R.G. and Tijskens, L.M.M., 1998. A dynamic and generic model of gas exchange of respiring produce: the effects of oxygen, carbon dioxide and temperature. *Postharvest Biology and Technology*, 14(3), pp.335–349. https://doi.org/10.1016/S0925-5214(98)00058-1

Indirect emissions savings from investment into a new scrubber are also expected from reduced leaks in the scrubber system, leading to less N_2 injection actions. These are estimated to be in the order of 1-2%.

Finally, an optimally functioning scrubber system maintains optimal CO_2 levels in the storage rooms, leading to improved quality and shelf life of the fruits and reduced fruit losses from CO_2 disorders. Savings by reduced losses are difficult to estimate roughly.

Table 9. CO_2 emissions from scrubbers for ULO storage of pome fruit for a CO_2 scrubber reference efficiency of 3.3×10^{-7} kg CO_2/J at 3% CO_2.

Fruit	ULO storage temperature	ULO storage O_2 concentration	ULO storage CO_2 concentration	CO_2 emissions for scrubbing	+/- error estimate	CO_2 emissions for cooling
	°C	%	%	gCO_2eq/ton fruit.day	gCO_2/ton fruit.day	gCO_2eq/ton fruit.day
Jonagold	1.2	1	2.5	5.4	7.0	225.6
Conference	-1	3	0.7	11.0	7.6	233.1
Golden	1	1	2.5	5.4	7.0	225.6
Elstar	2	2.5	1	18.1	8.4	225.6
Cox	3.5	2.5	0.8	29.2	10.0	225.6
Boskoop	3.5	2.5	0.8	29.2	10.0	225.6
Doyenné	0	2.5	0.7	14.8	8.0	233.1

Table 10. CO_2 emissions from scrubbers for ULO storage of pome fruit for a CO_2 scrubber reference efficiency of 6.6×10^{-7} kg CO_2/J at 3% CO_2.

Fruit	ULO storage temperature	ULO storage O_2 concentration	ULO storage CO_2 concentration	CO_2 emissions for scrubbing	+/- error estimate	CO_2 emissions for cooling
	°C	%	%	gCO2eq/ton fruit.day	gCO2/ton fruit.day	gCO2eq/ton fruit.day
Jonagold	1.2	1	2.5	3.7	6.8	225.6
Conference	-1	3	0.7	6.5	7.1	233.1
Golden	1	1	2.5	3.7	6.8	225.6

Elstar	2	2.5	1	10.0	7.4	225.6
Cox	3.5	2.5	0.8	15.6	8.1	225.6
Boskoop	3.5	2.5	0.8	15.6	8.1	225.6
Doyenné	0	2.5	0.7	8.4	7.3	233.1

Scope 1 emissions savings (% or another quantifiable metric)	1-5% CO_2eq for replacing an old scrubber by a more efficient scrubber.
Quality of scope 1 emissions information	Calculated based on a cooling and scrubber model for ULO storage of fruit, using available literature and industry data for product and scrubber parameters.
Scope 2 emissions savings (% or another quantifiable metric)	Reduced leaks: 1-2% CO_2eq Reduced fruit losses: difficult to quantify
Quality of scope 2 emissions information	Reduced leaks with a new system reduce the need for N_2 injection to control O_2 levels. Calculated based on a cooling and scrubber model for ULO storage of fruit, using available literature and industry data for product and scrubber parameters.
Availability barriers	Commercial systems available from different suppliers.
TRL level	9
Maintainability issues	Automated recovery of adsorber material and maintenance to avoid leaks. Especially entrance of oxygen should be avoided in the scrubber system as this may increase the need for N_2 injection and consequent energy use.
Legislative concerns	None
Payback time (years)	Considering only for savings on direct emissions, the payback time of a typical scrubber installation (for 10 storage rooms with a capacity of 150 ton of Conference pears, investment ~ 30000 Euro (personal communication), electricity price 0.24€/kWh) is 30 y. The financial benefits of the investment lie more in improved control of fruit quality, extended storage and shelf life and eventual better price of the product.

9.3 Compressors and their controls

Compressor types

There are five main types of compressors which are used in refrigeration applications, with their selection depending on capacity and performance as well as other aspects such as cost.

Reciprocating compressors are positive displacement compressors that use pistons driven by a crankshaft to pressurise the refrigerant vapour.

Screw compressors use either one or two helical screws rotating at high speed to compress the refrigerant vapour. The twin-screw configurations consist of matched rotors that mesh closely in a common housing.

Scroll compressors compress vapour by use of radial movement in two entwined scrolls, often with one stationary and the other orbiting eccentrically within it. While they are efficient close to their design operating conditions, they lose efficiency at other conditions, and they are typically small in capacity.

Rotary vane compressors employ a bladed shaft which rotates within a graduated cylinder to circulate and compress the refrigerant vapour. Rotary lobe compressors similarly use two sets of intermeshing lobes. While simple in design, they are also limited in capacity.

Centrifugal compressors rely on kinetic energy developed by a rotating impeller to increase the vapour pressure. As the impeller rotates, it exerts centrifugal force on the vapour, thereby pressurizing it. Although the volume flow in such compressors is high, the force created by a single impeller is relatively low, so it is common for several impellers to be employed in series. Their use for lower temperature applications is restricted by the large pressure differentials required.

For larger scale refrigeration systems such as those used in cold storage application, the use of reciprocating or screw compressors is most common.[39]

<u>Part load operation</u>

Ekman, McGlasson and Golding[40] suggested that energy use of reciprocating compressors can be reduced by 15 to 40% using an inverter to vary compressor speed according to cooling demand. Similarly, Australian Institute of Refrigeration, Air Conditioning and Heating[41] (AIRAH, 2020) stated that variable capacity control achieves much narrower storage temperature

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[39] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

[40] Ekman, J.H., Golding, J.B. and McGlasson, W.B., 2005. Innovation in cold storage technologies. *Stewart Postharvest Review*, 1(3), pp.1–14

[41] AIRAH., 2020. DA12 energy efficiency in cold rooms. *Design Application Manual*, 73pp. Available at: https://www.airah.org.au/DA_Manuals/2020_releases/DA12.aspx

bands, which delivers energy savings of up to 25 per cent and higher product quality preservation.

Nigro & Goossen[42] provided wide-ranging advice on control strategies for compressor sets, which they stated typically operate at part load. To maintain efficiency, they recommended use of compressor staging, loading and unloading, and also use of variable frequency drives (VFDs). Reciprocating compressors with cylinder unloading were said to have very good part-load efficiency, with staging and unloading being used to help manage suction pressure. Compressor staging (multi-compressor systems) and unloading strategies help manage suction pressure, and proper staging strategies can reduce annual system energy usage by 5% to 15%. For screw compressors, which have poor part load performance, they advised that slide valve capacity control is not efficient at low loads and can be improved by use of VFDs. Screw compressors using slide valves should be base-loaded most of the time if possible.

Sequencing strategies should be designed to match load with all but the last compressor operating at or near full load. In systems with both screw and reciprocating compressors, screw compressors should be base loaded as much as possible, and screw compressors with VFDs should be used as "trim" compressors. Operating multiple screw compressors (without VFDs) at partial load is the least efficient approach.

The authors also suggested decreasing compressor 'lift' to enhance operating efficiency, with options being to increase suction pressure and use floating head pressure control. Reduction of suction pressure drop can be achieved by selection of larger evaporator coils and careful consideration of suction piping size and pressure drop. Annual system energy savings of up to around 10% can be achieved.

Further useful information on compressor types and operation is given in IOR 2020.[43]

Scope 1 emissions savings (% or another quantifiable metric)	Refrigerant leakage is unlikely to markedly differ due to the choice of compressor and controls.
Quality of scope 1 emissions information	Not applicable

[42] Nigro, R. and Goossen, K., 2020. Energy efficiency opportunities in industrial refrigeration. *University of Delaware Industrial Assessment Center with US EPA Webinar*. Available at: https://www.epa.gov/sites/default/files/2020-10/documents/p2webinar_energy_ind_refrig_061720.pdf

[43] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

Scope 2 emissions savings (% or another quantifiable metric)	Variable speed/capacity control offers energy savings of 15 to 40% (Ekman et al 2005). Similarly (Nigro et al 2020) suggest energy savings of up to 25%. Proper staging can reduce energy consumption by 5 to 15%.[44]
Quality of scope 2 emissions information	Actual savings will be system dependant, but the referenced sources provide indicative ranges of savings.
Availability barriers	None.
TRL level	9
Maintainability issues	Nothing specific.
Legislative concerns	None.
Payback time (years)	No financial information included in references. Additional costs in a new system would indicate short paybacks.

9.4 Condenser control

Head pressure control

Efficient operation of condensers can be achieved by decreasing discharge pressure.[34]

Refrigeration systems typically 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 (TEVs) 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, there is scope to reduce the condenser head pressure. According to Davies[45] minimum condensing temperatures for UK supermarkets running on R440A are typically 30°C with a temperature difference between ambient and condensing temperature of 10 K.

Annual system energy savings will vary, and it is worth nothing that some systems require minimum compressor discharge pressures for defrost, liquid injection oil cooling, and other requirements and that condenser fan energy consumption will increase. Nevertheless, annual

[44] Nigro, R. and Goossen, K., 2020. Energy efficiency opportunities in industrial refrigeration. *University of Delaware Industrial Assessment Center with US EPA Webinar*. Available at: https://www.epa.gov/sites/default/files/2020-10/documents/p2webinar_energy_ind_refrig_061720.pdf

[45] Davies, T.W., 2003. A universal floating head system. *International Congress of Refrigeration*, ICR0079, Washington DC

system energy savings of between 5% and 12% can be achieved. Davies[39] predicted energy savings of 23% with an evaporating temperature of -30°C over a year in the UK.

Condenser fan motors

Use of VFDs on larger evaporative condenser fans and cooling towers in conjunction with floating head pressure control can offer up to 3% annual system energy savings.[46]

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)	Floating head pressure saves 5 to 12% of system energy consumption.[37] Added to this, fan speed control using VFDs can offer a further 3% saving. [37]
Quality of scope 2 emissions information	Good but figures above are from one source only.
Availability barriers	None.
TRL level	9
Maintainability issues	None.
Legislative concerns	None.
Payback time (years)	Not included in available information but as technology relies on changes to controls the savings achieved would indicate that paybacks would be less than 1 year.

9.5 Defrosts and defrost controls

Defrost types

[46] Nigro, R. and Goossen, K., 2020. Energy efficiency opportunities in industrial refrigeration. *University of Delaware Industrial Assessment Center with US EPA Webinar*. Available at: https://www.epa.gov/sites/default/files/2020-10/documents/p2webinar_energy_ind_refrig_061720.pdf

For cold storage applications with large duty medium and low temperature evaporators, the most common type of defrosting technique is electric, typically using arrays of heater elements embedded in the evaporator coils (see for example Danfoss https://www.danfoss.com/en-gb/service-and-support/case-stories/dcs/refrigeration-controllers/). Electric defrosting is however prone to 'overheating', and in addition the evaporator fans are turned off during defrosting to avoid heat being blown away from the evaporator into the room.

Off-cycle defrosting can be used for chilled temperature applications, but it is not an option for low temperature evaporators and is not an efficient option for chilled cold stores due to the need for extended periods in which the evaporator is doing no cooling of the store, leading to temperature rises in the stored products.

Another alternative to electric is hot gas defrosting, which introduces compressor discharge gas downstream of the 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 system to work, the compressor needs to run whilst an evaporator is defrosting, but for cold stores with multiple evaporators this is not an issue.

Hot gas defrosts are more thermodynamically efficient than electric heaters. The coefficient of performance (COP) of the refrigeration system during defrost was found to be between 4.1 and 4.5 in a study by Zahid[47] 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. Efficiency is however still low, for example Cole[48] showed that typical hot gas defrosts are only about 20% efficient (based on the proportion of energy melting the ice). 60% of the energy escapes into the ambient air and 20% heats the metal.

Although gas defrost uses less energy than electric defrost, it requires valving that increases head pressure and consequently requires a higher refrigerant charge. The Pacific Gas and Electric Company[49] assumed an increased charge size up to 10% for a retail refrigeration 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. Although figures were given for expected emissions impacts, these were specific to retail systems with multiple small evaporators using HFCs rather than natural refrigerants.

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[47] Zahid, S., 2013. Investigation of electric and reverse-cycle hot-gas defrosting for evaporators in refrigeration systems. *ASHRAE Transactions*, 119, pp.1W

[48] Cole, R.A., 1989. Refrigeration loads in a freezer due to hot gas defrost and their associated costs. *ASHRAE Transactions*, 95(CONF-890609-)

[49] Pacific Gas and Electric Company., 2011. *Supermarket refrigeration codes and standards enhancement initiative (CASE): 2013 California building energy efficiency standards*. PG&E Report

With a small experimental cold store setup, Abdulla et al.[50] used liquid line refrigerant heat to defrost each of two evaporators in turn. While one of the evaporators cooled the room, the other sub-cooled the refrigerant before it entered the cooling evaporator. The sub-cooling process provided defrosting heat for the second evaporator. When the cooling evaporator required defrosting, a four-way valve reversed the cycle, and the roles of the two exchangers reversed. In comparison with an electric defrost in the same experimental chamber, the liquid defrosting process required no external power and at the same times improved refrigeration efficiency by 12%. To balance this, two evaporators and a 4-way valve were required, adding additional capital cost and potential for leakage.

Guangpeng et al.[51] proposed use of heat recovered from refrigerant vapour at the compressor discharge, transferred to the evaporator using glycol, to replace electric defrosting. Theoretical energy savings of 20 to 30% for small frozen stores and 10 to 20% for medium and large frozen stores were claimed.

Other options have been reported for defrosting typically smaller evaporators (for example in supermarket display cabinets), such as phase change material (PCM) thermal heat stores, ultrasonic defrosting and electrohydrodynamic defrosting. Information on potential improvements to energy efficiency is not readily available for these systems for the scale of operation in large cold stores.

<u>Defrost on demand</u>

Regardless of the defrost method, a key objective is to minimize defrosting frequency and duration. This can be achieved using on demand defrosting, controlled by various means. Liquid run-time controls measure the amount of time an evaporator is in cooling mode and adjust frequency of defrosting to be less frequent during low demand periods. Another option is frost sensors measuring frost build-up directly to initiate and terminate defrosting. Actively managing defrost frequency and duration can reduce annual system energy usage by approximately 3%.[52]

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[50] Abdulla, M.O.A., Deniz, E., Karagöz, M. and Gürüf, G., 2021. An experimental study on a novel defrosting method for cold room. *Applied Thermal Engineering*, 188, p.116573. https://doi.org/10.1016/j.applthermaleng.2020.116573

[51] Guangpeng, L., Yanrui, Z. and Liwen, S., 2021. Application research on energy saving technology of waste heat recovery and defrosting for low temperature cold storage. *E3S Web of Conferences*, 245, p.01038

[52] Nigro, R. and Goossen, K., 2020. Energy efficiency opportunities in industrial refrigeration. *University of Delaware Industrial Assessment Center with US EPA Webinar*. Available at: https://www.epa.gov/sites/default/files/2020-10/documents/p2webinar_energy_ind_refrig_061720.pdf

Scope 1 emissions savings (% or another quantifiable metric)	Hot gas: 5% increase in refrigerant leakage (note - based on typical retail system rather than cold storage) Reverse cycle: 5% increase in refrigerant leakage (note – as above) Liquid: 0%
Quality of scope 1 emissions information	Limited in scope
Scope 2 emissions savings (% or another quantifiable metric)	Hot gas: 100% reduction of electric defrost heat load. Reverse cycle: 75% reduction of electric defrost heat load. Liquid: 100% reduction of electric defrost heat load. Defrost on demand can save 3% of system energy use.
Quality of scope 2 emissions information	Hot gas: L Reverse cycle: L Defrost on demand: L/M
Availability barriers	None
TRL level	Hot gas: TRL8-9 Reverse cycle: TRL8-9 Warm and hot liquid: TRL5-7 Defrost on demand: TRL8 or 9.
Maintainability issues	Some options require additional equipment and valving, with greater risk of leakage.
Legislative concerns	None
Payback time (years)	Lack if quantified information. Technology likely to be only applied to new plant where additional costs are likely to significant. Therefore, paybacks of <3 years anticipated.

9.6 Demand side response (DSR)

Demand side response (DSR) is one of the energy management strategies that can relieve the strain on power grid by balancing the energy consumption and production. It aims to increase the flexibility of end-user demands by changing their electricity profiles from their usual consumption patterns. Cold storage facilities, due to the high thermal inertia contained in stored products, is a promising solution for applying DSR. Different DSR strategies can be considered: stopping evaporator fans or stopping the refrigeration machine, producing more cooling power during off peak hours or using green energy supply and reducing the cooling operation during on peak hours, etc. However, these strategies need to be carefully applied to respect the temperature regulation to maintain food quality and safety. Moreover, DSR application might lead to an increase of power demand when restarting the cold machine or an over-consumption of energy for the recovery of the temperature level before DSR period.

Green energy supply adapted strategies aim to link the control system of the cooling infrastructure to the availability of green energy. One concept is that cooling takes place when electricity is very cheap, for example due to a large production as a result of wind energy; when energy is expensive, cooling is delayed until a critical temperature is exceeded. Similarly, one can consider periods when solar energy supply is available on site. This, of course, requires that the control system has access to the hourly price of the electricity and is also adjusted accordingly. Simulations based on a simplified dynamic model of a cold store, implemented in Matlab Simulink, were used to investigate which savings are possible and whether this has consequences for the product temperature that needs to be maintained in specific margins for quality and safety assurance.[53] Historical climate data were used in the preconditions of the model (energy losses through walls/ceiling) as well as historical electricity costs. The simulations were performed for an apple cold store at the auction (10.5 m × 7.55 m × 7.9 m, BelOrta, Borgloon), with 315 pallet boxes or about 116 tons of apple fruit stored at 1°C. It was assumed that the room operated with 24 cooling actions per day (1 per hour) with an outlet temperature of the evaporator set at -1.0°C. The cooling actions last 3 min and there is 5 min of post-ventilation. The rest of the time the fans are off. The model only calculated the average temperatures in the cold store for the products and the air. The respiration heat, heat ingress (outside temperature of 15°C) and fan heat were taken into account. For cooling based on energy price, the energy price of the period 21 April to 4 May 2017 was assumed in this study. It was investigated what is needed to compensate for the loss of cooling hours and thus prevent extreme temperature fluctuations. The following situations were compared in the table below:

Reference: fixed cooling actions 24/24h

[53] Schenk, M., Hertel, J., Wessam, M., Fiedler, F. and Müller, D., 2018. Energy saving potential of cold storage facilities: a simulation-based study using a simplified dynamic model. *Proceedings of the 5th IIR International Conference on Sustainability and the Cold Chain*, 6–8 April 2018, Beijing, China. International Institute of Refrigeration

Cooling at fluctuating electricity price if price is lower than 0.08 €/kWh, assuming then abundant supply of green wind energy

Cooling at fluctuating electricity price as above, with upper limit on product temperature

Cool to 1°C if product temperature >= 1.7°C

Cooling at fluctuating electricity price in combination with cooling during availability of solar energy

Scenario	Total grid energy use		% Energy savings w.r.t reference	Mean product temperature (°C)
	Yearly* (kWh/year/ton)	Yearly* (kWh/year/m³)		
Reference	150.8	28.2		1
Control based on hourly electricity price	101.7	19.0	32.5	1.5 (with max up to 2°C)
Control based on hourly electricity price with temperature limit	132.7	24.8	12.0	1.3
Control based on hourly electricity price with temperature limit and solar energy supply on site	114.1	21.3	24.3	1.3

* extrapolated from 14 days simulation

Energy savings appear possible at the expense of less tight temperature control. Still, by using a similar lumped-model analysis on another storage unit but also for apples, East et al. showed that avoiding cooling during peak price hours and concentrating cooling during off-peak hours may result in a 40% cost reduction, but does not save on actual energy use while allowing (slightly) more temperature fluctuations.[54] The reference system was based on 4 min of run

[54] East, A., Smale, N.J. and Trujillo, F., 2013. Potential for energy cost savings by utilising alternative temperature control strategies for controlled atmosphere stored apples. *International Journal of Refrigeration*, 36, pp.1109–1117

time occurring every 23 min throughout the 24 h period and all scenarios had less fluctuations than that explored by Schenk, et al.[55]

By reducing the working time of the fans with the specific on/off cycling regime according to availability of solar energy during the day and not night, Ambaw et al. found, using computational fluid dynamic, that there was a significant decrease in heat load with respect to that of control strategies with continuous fan operation, also showing promising possibilities for energy reduction in apple storage.[56] Under a 16 h off/8 h on cycle scenario, refrigeration load was reduced by 55% compared to constant cooling at 1 °C. Fans would operate only 33% of the time in this scenario. In another study using computational fluid dynamics, allowing larger temperature fluctuations did not negatively impact product quality (apple firmness) but did not reduce energy use in apple storage.[57]

DSR in cold storage has also been studied experimentally.[58] In this study, the effects of DSR (compressor turning off while maintaining the fans) on the air and product temperatures and the energy consumption were evaluated. The impacts of various parameters: load presence, set point temperature, outside temperature and DSR duration were analyzed. It is shown that thermal inertia, the increase of the set point temperature or the reduction of the DSR duration could reduce the air and product temperature rise due to DSR application. Limited impact on stored product was observed: a maximum increase of 1.1 °C at the product core after 3 days of DSR application with a frequency of one DSR per day. However, a cumulative effect of DSR applications on product core temperature was noticed. An increase in power demand after DSR application was found for all scenarios. Compressor energy consumption can be reduced thanks to DSR applications in some scenarios. However, this reduction needs to be considered with caution as the energy stored in the product is not the same after DSR applications. To predict the risk of temperature abuse, these authors have proposed a novel concept using deep learning approaches to forecast temperature changes and power demands due to the application of DSR (Hoang, et al. 2021).

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[55] Schenk, M., Hertel, J., Wessam, M., Fiedler, F. and Müller, D., 2018. Energy saving potential of cold storage facilities: a simulation-based study using a simplified dynamic model. *Proceedings of the 5th IIR International Conference on Sustainability and the Cold Chain*, 6–8 April 2018, Beijing, China. International Institute of Refrigeration

[56] Ambaw, A. et al., 2016. Analysis of the spatiotemporal temperature fluctuations inside an apple cool store in response to energy use concerns. *International Journal of Refrigeration*, 66, pp.156–168

[57] Gruyters, W. et al., 2018. A numerical evaluation of adaptive on-off cooling strategies for energy savings during long-term storage of apples. *International Journal of Refrigeration*, 85, pp.431–440

[58] Akerma M., Hoang H-M., Leducq D. & Delahaye A., 2020. *Experimental characterization of demand response in a refrigerated cold room*, *International Journal of Refrigeration*, vol. 115, pp. 256–265, DOI: 10.1016/j.ijrefrig.2020.02.006.

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)	The direct grid energy savings when accounting for a maximum product temperature bound were found to be 12% (when using only green grid energy) to 24% (when combined with onsite green energy), depending on the allowed temperature increase.
Quality of scope 2 emissions information	Estimated based on dynamic model simulations.
Availability barriers	In Belgium, for example, purchasing at an hourly electricity rate is currently only possible for large consumers (via Belpex) and not automatically (linked to a control system), but it is reasonable to assume that this will be possible in the future. Operators may hesitate to relax temperature control in storage as it may adversely affect product quality, although it has been shown to be minor in the different studies.
TRL level	8-9
Maintainability issues	May require tools to predict risk of temperature abuse during off-cooling periods.
Legislative concerns	Food safety only potential issue.
Payback time (years)	Savings are predominantly based on cost reduction by arbitrage.

9.7 Doors and door protection

Infiltration of warm, moist air through open doorways is often one of the major heat loads on cold stores, particularly where frequent loading and unloading is required. A typical heat load proportion due to infiltration of 32% of total load was given by Cold Chain Federation 2020. However, there is huge variability due to factors such as opening frequency, protection, traffic and outside ambient conditions. This is illustrated by the example of Alves et al 2014 who found that infiltration was responsible for up to 68.2% of the thermal load on a small chilled dairy store. For frozen stores, additional energy input is required for heating of door frame/mating faces to prevent water vapour freezing and jamming of the doors.[59]

[59] Institution of Professional Engineers New Zealand (IPENZ)., 2009. *Coldstore engineering in New Zealand*. Practice Note 15. Wellington: IPENZ. ISSN 1176–0907. Available at: https://iifiir.org/en/fridoc/cold-store-engineering-in-new-zealand-version-1-0-3891

Cold Chain Federation 2020 suggested several measures aimed at reducing infiltration and the associated heat load. Door opening area should be kept as low as possible, and high-speed doors used to reduce the door open time. Conveyorized loading of products into the store from the loading bay can further reduce door opening, and air locks around the conveyorized opening can limit the volume of air entering the store. Dehumidification of the loading bays can reduce the moisture content of the air entering the store, although the energy they require should be carefully considered. IPENZ[50] also emphasized the need for effective vapour seals, either wiper type or compression type, and avoidance of conduction paths.

Automatic sensing for opening and timed closing can greatly reduce the duration of opening times, as can rapid opening and closing sliding or roller doors. The power required for such systems must be considered but it is usually a small fraction of the energy related to infiltration.

A simple method of door protection which has been commonly used in the cold storage industry is the suspension of flexible PVC strips inside the door, to provide a barrier to airflow when the door opens. An advantage is that they do not require any energy input, but they are not without issues, Ligtenburg and Wijjfels[60], for example, described them as unsafe, not particularly efficient, unhygienic and requiring a lot of maintenance. An alternative is the air curtain, which requires energy to drive one or more fans, but which does not block vision or impede traffic. Foster et al 2006 and 2007 combined measurements in 2D and 3D with Computational Fluid Dynamics modelling to study the effectiveness of an air curtain system. While the initial installation only achieved an effectiveness of 0.31 for a 30 second door opening (on a scale where 0 is totally open 1 and is totally blocked), optimisation of the air jet increased effectiveness to 0.71 for the same opening duration. Design and operating conditions for air curtains in doorways were described by Craxton[61], who suggested that compared with open doorways, specialised air curtains could reduce energy infiltration by 65%, and in cases where door opening is frequent and / or extended, the resultant payback can be as low as 2 years.

For loading bay doors which open to the outside ambient to allow transports to back onto them, it is common to have rubber flaps or soft, compressible seals or cushions around the openings. These require frequent checking and maintenance to avoid damage and resultant leaks. Inflatable versions of the seals allow more flexibility to cover varying gaps due to different vehicle sizes and can function better than normal flap protection (for example, Sarabia Escriva

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[60] Ligtenburg, P.J.J.H. and Wijjfels, D.J., 1995. Innovative air curtains for frozen food stores. *Proceedings of the 19th International Congress of Refrigeration*, 20–25 August 1995, The Hague, Netherlands, pp.420–437. International Institute of Refrigeration. Available at: https://iifiir.org/en/fridoc/innovative-air-curtain-for-frozen-food-stores-13863

[61] Craxton, M., 2021. Energy saving at coldstore doorways by means of specialist air curtains. *IOR Annual Conference*. Available at: https://ior.org.uk/public/downloads/odOK8/Paper%20ID%2004%20-M.%20Craxton.pdf

et al.[62] found that inflatable seals reduced the energy related to infiltration by up to 88% compared with simple flap operation in cold warehouses in Spain).

The scope for energy and emissions savings related to door and door opening improvements is highly dependent on the specific circumstances and operating patterns of each store. Evans et al.[63] carried out detailed energy audits on 38 European cold stores and found that 13 of them had problems with high infiltration rates through doorways. Comparison of measured data with modelling of improved door operation and protection indicated that on average 6% of total store energy consumption could be saved for these stores, with an average payback time of under 2.5 years. It should be stressed however that this was based on the simple application of a better door protection effectiveness in the model, rather than specific physical measures.

A further consideration in reducing infiltration loads is dehumidification of the air entering the doorway. How this is done will depend on the measures used to protest the doorway. If air curtains are employed, the air circulated in the curtain can be dehumidified. If there is a refrigerated loading bay adjacent to the doorway, temperatures in the bay should be maintained low enough to minimise heat ingress to the store but high enough such that moisture condenses on the loading bay evaporators and the condensate is easily drained away.[64]

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)	Very dependent on particular store and usage patterns. Examples of savings are:

62 Sarabia Escriva, E.J., Soto Francés, V. and Pinazo Ojer, J.M., 2020. Comparison of annual cooling energy demand between conventional and inflatable dock door shelters for refrigerated and frozen food warehouses. *Thermal Science and Engineering Progress*, 15, p.100386. https://doi.org/10.1016/j.tsep.2019.100386

63 Evans, J.A., Foster, A.M., Huet, J.-M., Reinholdt, L., Fikiin, K., Zilio, C., Houska, M., Landfeld, A., Bond, C., Scheurs, M. and Van Sambeeck, T.W.M., 2014. Specific energy consumption values for various refrigerated food cold stores. *Energy and Buildings*, 74, pp.141–151. https://doi.org/10.1016/j.enbuild.2014.01.019

64 Stoecker, W.F., 1998. *Industrial refrigeration handbook*. New York: McGraw-Hill. ISBN 9780070616233

	• Optimisation of air curtain improved effectiveness from 0.31 to 0.71.[65] [66] This was however for a particular air curtain in a test environment and may not translate to real life conditions. • Typical reduction of infiltration energy achieved by specialised air curtains is 65%, but highly dependent on specific circumstances of the store and its use.[67] • Use of inflatable flexible loading bay seals reduced energy associated with infiltration by up to 88%.[68] • Rectification of excessive infiltration issues found on a selection of European cold stores could save 6% of total store energy consumption.[69] • Data for savings due to sensing and rapid opening/closing were not readily available.
Quality of scope 2 emissions information	Good but limited and specific to application.
Availability barriers	None
TRL level	8-9
Maintainability issues	Dependent on option – for example door seals and strip curtains can be damaged, high speed roller doors can require high maintenance, air curtains require careful installation and optimisation. However, stopping moisture from entering can reduce maintenance elsewhere in the stores.
Legislative concerns	None

[65] Foster, A.M., Swain, M.J., Barrett, R., D'Agaro, P. and James, S.J. 2006. *Effectiveness and optimum jet velocity for a plane jet air curtain used to restrict cold room infiltration*. International Journal of Refrigeration, 29(5), pp. 692–699.

[66] Foster, A.M., Swain, M.J., Barrett, R., D'Agaro, P., Ketteringham, L.P. and James, S.J. 2007. *Three-dimensional effects of an air curtain used to restrict cold room infiltration*. Applied Mathematical Modelling, 31(6), pp. 1109–1123.

[67] Craxton, M., 2021. Energy saving at coldstore doorways by means of specialist air curtains. *IOR Annual Conference*. Available at: https://ior.org.uk/public/downloads/odOK8/Paper%20ID%2004%20-M.%20Craxton.pdf

[68] Sarabia Escriva, E.J., Soto Francés, V. and Pinazo Ojer, J.M., 2020. Comparison of annual cooling energy demand between conventional and inflatable dock door shelters for refrigerated and frozen food warehouses. *Thermal Science and Engineering Progress*, 15, p.100386. https://doi.org/10.1016/j.tsep.2019.100386

[69] Evans, J.A., Foster, A.M., Huet, J.-M., Reinholdt, L., Fikiin, K., Zilio, C., Houska, M., Landfeld, A., Bond, C., Scheurs, M. and Van Sambeeck, T.W.M., 2014. Specific energy consumption values for various refrigerated food cold stores. *Energy and Buildings*, 74, pp.141–151. https://doi.org/10.1016/j.enbuild.2014.01.019

Payback time (years)	Not much information. Evans et al 2014 suggested improvements to door protection would typically pay back in under 2.5 years, with air curtains being more effective but more expensive than strip curtains. Craxton 2021 suggested that for stores with frequent and / or extended door opening, air curtains compared with open doorways can offer payback with 2 years.

9.8 Dynamic control atmosphere storage systems

Climacteric fruits, including apple and pear, exhibit a ripening phase strongly associated with an increase in respiration and ethylene production. To counteract this ripening and the associated loss of quality, most commercial storage facilities try to reduce respiration. This is done by storing fruit at a low temperature in combination with high CO_2 (carbon dioxide) and low O_2 (oxygen). As a result, oxygen consumption and CO_2 production will decrease. In ULO, the atmosphere with modified oxygen and carbon dioxide is set based on experience and advice. If due to lack of oxygen the aerobic respiration of the fruit stops, fermentation will start. This can lead to fruit damage. When the fruit gets too little oxygen, this is referred to as oxygen stress. The lowest oxygen percentage at which CO_2 production is minimal is called the oxygen stress point (ACP). With the new storage technique of DCA (dynamically controlled atmosphere storage), this ACP is determined by measuring the oxygen stress of the fruits and the atmosphere is adjusted just above this stress point. This way fermentation is avoided, and oxygen level can be kept as low as possible to prevent loss of quality. Because the stress point is not fixed in advance and can have a different value for each batch, and can change during storage, we speak of storage with a 'dynamic' controlled atmosphere.

Available systems on market

Different systems are available to determine this stress point (ACP) and these systems are available on the market.

Ethanol measurement: Measurement in the cold store air of the volatile ethanol from the fruits is possible with sensitive specific gas sensors. Fruits are producing this ethanol while going into fermentation below their ACP. Since the concentrations in the air are low (< 1 ppm), these sensors must have a high accuracy and sensitivity, and must not be affected by the presence of other volatile components in the air. Commercial system: DCS-Pro, Storex, NL https://www.storex.nl/our-portfolioquick-overview-of-our-products-dcs-pro.html

Chlorophylfluorescence measurement: the functioning of the leaf green of top fruit changes under oxygen stress. When you illuminate fruits in a controlled manner and measure the fluorescence of the chlorophyll, you can observe a sharp change in the signal in fruits that evolve from no oxygen stress to oxygen stress. The low oxygen concentration at which this occurs is taken as a stress point to set the conditions in the cold store to a safe value. The measurement is done on a number (4 to 6) fruits that are placed in a small measuring box with lighting and a fluorescence sensor. This measuring box can be placed in a bin.

Commercial systems:

HarvestWatch, Isolcell, IT https://storage.isolcell.com/en/isostore-dca-cf/

FruitObserver, Besseling, NL https://besseling-group.com/nl/fruit-observer/

Respiration quotient (RQ) measurement is measuring the ratio of the CO_2 production rate to the O_2 consumption rate of the fruits. This RQ has a value close to 1 during normal respiration: the fruit then produces as much carbon dioxide as it consumes oxygen. RQ shows a strong increase when O_2 concentrations are reduced during oxygen stress, because CO_2 production increases, while oxygen consumption decreases. RQ can be determined based on the measurement of the changes in gas concentrations in the storage room as a result of the respiration of the fruits. As long as the RQ value is close to 1, the oxygen concentration in the room can be further reduced. As soon as a significant increase in the value is observed, this is an indication that the fruits are going to ferment. Then the oxygen concentration must be actively increased. If RQ is measured regularly, the gas conditions during the course of storage can be dynamically adjusted to the changing respiration of the fruits.

Commercial systems:

- OptiControl, Optiflux, BE http://optiflux.world/
- ACR, Van Amerongen, NL https://www.van-amerongen.com/nl/control-systems
- SafePod, SCS, VK https://www.storagecontrol.com/products/safepod-system/
- Storefresh, Isolcell, IT https://storage.isolcell.com/en/storefresh-dca-rq/

CO_2 production

At the oxygen stress point (ACP), the CO_2 production of the fruits is lowest. Both higher respiration or fermentation provide more CO_2 in the cool room. By only accurately measuring the changes in CO_2, one can therefore also do DCA storage.

Commercial system: FruitAtmo, https://www.jdcooling.com/cooling/fruitatmo/

Primary energy savings and GHG emission reduction

The primary energy consumption for cooling of the various systems with their respective CO_2 emissions and reduction compared to the reference system is shown in

Table 11

Table 11. Primary energy consumption for cooling of various systems with respective CO_2 emissions

	kWh/ tonnes	For storage room of 200 tonnes in kWh	in MJ	in CO_2 eq[1, 2]	Relative reduction in %
Reference storage (2013)					
Standard ULO R22 (with 1-MCP)	126	25272	90979	7107	
Alternative systems					
Standard ULO R717 (with 1-MCP)	114	22745	81881	6396[1]	10%
Standard DCA R717	120	24008	86430	6752	5%
Bioteelt					
Reference organic growing					
Bio ULO R22 (no 1-MCP)	140	28080	101088	7897	
Alternative systems organic growing					
Bio ULO R717	126	25272	90979	7107	9%
Bio DCA R717	120	24008	86430	6752	14%

[1] The climate impact only concerns that of electricity consumption and not that of the installation itself. Similarly, the climate impact of the refrigerant is not considered.

[2] The calculation was made for medium voltage electricity.

Assuming that a DCA system costs about 8000 to 10000 euro per cool room, the ROI is about 4 to 6 years. In some countries subsidies are given for energy saving investments, like in Belgium. With these subsidies, the ROI is about 3 to 5 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)	5 to 14 %
Quality of scope 2 emissions information	Good, calculations and measurements in own research
Availability barriers	L
TRL level	TRL 8-9
Maintainability issues	Little, sensors not more than reference system. Cool rooms need to be very airtight
Legislative concerns	none
Payback time (years)	4 – 6 years

9.9 Electronic Expansion Valves

A common type of expansion device used in cold storage applications is the thermostatic expansion valve (TEV). TEVs provide good superheat control with reasonably stable load conditions.

An improved expansion device, the electronic expansion valve (EEV) serves the same function as TEVs but requires an electronic controller. EEVs offer greater potential to optimise refrigeration system performance and enhance efficiency.

Mechanical TEVs generally need a minimum pressure difference of 6 bar whereas electronic expansion valves can operate with a minimum pressure difference of around 4 bar. Findings from recent studies further indicate that those commissioning these systems often do not optimise the expansion valve operation; they tend to control the condensing pressure at a higher level than that required to ensure reliable operation of the expansion valves (IOR, 2020).

There are two types of EEVs:

- Pulse valves, which modulate the refrigerant flow by Pulse Width Modulation (PWM). Pulse valves are simple and robust, and self-close in the case of an interruption to power.
- Stepper valves, which modulate the flow by stepwise rotation based on electrical pulses from the controller to open or close an orifice. Stepper valves are more sophisticated, but less robust. They are also not self-closing and additional measures such as liquid line solenoid valves or battery back-up are required to ensure closing of the refrigerant line in the event of a power failure.

The advantages offered by EEVs include adjusting to varying working conditions such as changing condensing and evaporating pressures and feeding refrigerant to the evaporator at low pressures. This makes them suitable for energy-saving strategies such as floating head pressure or adaptive suction) pressure.

Some electronic controllers offer so-called ‘adaptive superheat control algorithms’ that maintain maximum evaporator efficiency at varying load conditions. In a multiple-evaporator system with a common compressor rack, such controllers combined with adaptive evaporation technology can yield efficiency improvements of up to 10%.[70]

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)	EEVs with adaptive superheat control can achieve 10% efficiency improvements[61]
Quality of scope 2 emissions information	General in nature, peer reviewed studies tend to be on smaller retail applications.
Availability barriers	None
TRL level	9
Maintainability issues	None identified
Legislative concerns	None
Payback time (years)	No quantified data but savings and paybacks are obviously variable and very dependent on application.

9.10 Energy storage (thermal and electrical)

Energy storage systems for refrigerated warehouses include thermal storage and electrical storage. Both can shift the electrical energy consumption of the refrigeration plant, allowing peak shaving and shifting of refrigeration plant operation to more efficient ambient periods.

[70] AIRAH., 2020. *DA12: Energy efficiency in cold rooms*. Design Application Manual, 73pp. Australian Institute of Refrigeration, Air Conditioning and Heating. Access may require AIRAH membership or login. Available at: https://www.airah.org.au/site/resources/da-manuals

Zhu et al.[71] presented modelled results for examples of both systems in a chilled storage warehouse, with cold energy storage in sodium chloride brine and electrical storage in batteries. Cold energy storage reduced electricity consumption by 4.3% and operational cost by 20.5%, while the battery system increased the electricity consumption by 3.9% but reduced the operational cost by 18.7%. At the time of the study, payback periods were in the order of 7 years for the battery system and just under 4 years for the cold storage system. The reducing cost of batteries and increases in peak electricity costs were predicted to greatly reduce these periods.

Another form of energy storage was reported by Altwies and Reindl[72], who used the frozen food in four warehouses to allow operating times for the refrigeration plant to be shifted. Although they reported savings in operating costs and the conclusion that product temperature rises during off periods would not affect quality, they did not at the time consider potential carbon emissions reductions due to shifting demand to periods met by renewables. Similarly, Ambaw et al.[73] investigated use of on-off control of an apple storage cooling system and fans, with one approach being to run cooling and fans during cheaper night-time periods and turn them off during more expensive day-time periods. They concluded that reducing the duration of fan operation had a significant effect on reducing energy consumption, and at the same time that the night-day on-off strategy could successfully load shift and reduce energy costs without major detriment to product quality.

A more recent study by Yang et al.[74] used water as a phase change material (PCM) in panels attached to the insulated walls of a chilled food warehouse. These were successfully used to shift demand from peak to off-peak periods with acceptable temperature rises, although the 'warehouse' chosen was actually a very small experimental chamber. A payback period of 2.7 years was calculated for this specific case.

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[71] Zhu, K., Li, X., Campana, P.E., Li, H. and Yan, J., 2018. Techno-economic feasibility of integrating energy storage systems in refrigerated warehouses. *Applied Energy*, 216, pp.348–357. https://doi.org/10.1016/j.apenergy.2018.01.079

[72] Altwies, J.E. and Reindl, D.T., 2002. Passive thermal energy storage in refrigerated warehouses. *International Journal of Refrigeration*, 25(1), pp.149–157. https://doi.org/10.1016/S0140-7007(00)00080-3

[73] Ambaw, A., Defraeye, T., Opara, U.L. and Verboven, P., 2016. Analysis of the spatiotemporal temperature fluctuations inside an apple cool store in response to energy use concerns. *International Journal of Refrigeration*, 66, pp.156–168. https://doi.org/10.1016/j.ijrefrig.2016.02.010

[74] Yang, T., Wang, C., Sun, Q. and Wennersten, R., 2017. Study on the application of latent heat cold storage in a refrigerated warehouse. *Energy Procedia*, 142, pp.3546–3552. https://doi.org/10.1016/j.egypro.2017.12.243

Scope 1 emissions savings (% or another quantifiable metric)	None.
Quality of scope 1 emissions information	Not relevant.
Scope 2 emissions savings (% or another quantifiable metric)	Cold energy storage reduced electrical consumption by 4.3% Electrical energy storage increased electrical consumption by 3.9%.
Quality of scope 2 emissions information	Results published in refereed journal, caveats – specific to example chosen, based on economics in China.
Availability barriers	Cold energy storge M – seeing increasing application. Electrical energy storage M/L but impact on emissions was not studied.
TRL level	7
Maintainability issues	Nothing specific.
Legislative concerns	No concerns.
Payback time (years)	Based on market in China in 2017: Just under 4 years for cold energy storage 7 years for battery storage but no emissions advantage

9.11 Evaporative and adiabatic condensers

The use of evaporative condensers with wetted heat exchange surfaces is recommended for larger refrigeration systems (typically more than 500 kW heat rejection capacity) such as those serving large cold storage facilities.[75] Harby et al.[76] reviewed the state of the art of evaporative

[75] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

[76] Harby, K., Gebaly, D.R., Koura, N.S. and Hassan, M.S., 2016. Performance improvement of vapor compression cooling systems using evaporative condenser: an overview. *Renewable and Sustainable Energy Reviews*, 58, pp.347–360. https://doi.org/10.1016/j.rser.2015.12.313

condensers on refrigeration systems ranging from 3 to 3000 kW and found that in suitable circumstances energy savings of up to 58% could be achieved compared with dry 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[77] 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.

Rey Martínez et al.[78] 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.

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[77] Baltimore Aircoil Company., n.d. *Trillium series adiabatic products*. Baltimore Aircoil Company. Available at: https://www.baltimoreaircoil.com/products/hybrid-adiabatic/trilliumseries-adiabatic-products

[78] Rey Martínez, F.J., San José Alonso, J.F., Velasco Gómez, E., Tejero González, A., Esquivias, P.M. and Rey Hernández, J.M., 2020. Energy consumption reduction of a chiller plant by adding evaporative pads to decrease condensation temperature. *Energies*, 13(9), p.2218

The cooling systems in a large office building were surveyed using the REAL Zero methodology.[79] 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.[80] 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 et al.[81] 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.

[79] Rodway, M., 2009. REAL ZERO case study 2 – industrial. *Institute of Refrigeration*. Available at: https://ior.org.uk/public/downloads/eAxZk/casestudy2INDUSTRIAL.pdf

[80] Wallace, K., 2013. Supermarkets for the future: natural refrigeration and heat recovery. *CIBSE Conference Paper*

[81] Scott, D., Bellon, T. and Chappell, C., 2019. Adiabatic condensers for refrigerated warehouses and commercial refrigeration – final report. Available at: http://title24stakeholders.com/wp-content/uploads/2017/09/2019-T24-CASE-Report_Adiabatic-Condensers_Final_September-2017-1.pdf

Quality of scope 1 emissions information	Some sources 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)	0 to 30% dependant on climatic conditions and design of condenser.
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.
Availability barriers	L
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

9.12 Evaporator fans and fan speed controls

Fan motors

Common practice for many years was the use of shaded pole fixed speed electric induction motors to drive evaporator fans. However, these can have efficiencies as low as 20%.[82]

A slightly more efficient type of induction motor, the permanent split capacitor (PSC) motor can operate at typically up to 29% efficiency, with capital costs being between those of shaded pole and expensive but efficient electronically commutated (EC) motors.

EC fans not only have high operating efficiencies but can modulate output speed from 10 to 100 per cent without an external drive. EC evaporator fans can deliver energy savings of

[82] Fricke, B.A. and Becker, B.R., 2018. Permanent magnet synchronous motors for commercial refrigeration. *Oak Ridge National Laboratory*. https://doi.org/10.2172/1482222

around 40 per cent compared to fixed-speed AC fans.[83] Efficiency of EC fan motors can be up to 66%, which compares very favourably with shaded pole motors.[84]

IOR 2020 suggests best practice is the use of EC fans for all air coolers. EC motors are also known as Brushless DC Motors (BLDC) and are synchronous electric motors powered by direct-current. They combine AC and DC voltages, bringing the best of both technologies: the motor runs on a DC voltage, but with a normal AC supply. An EC motor developed for one specific application may not be suitable for use in other applications. The specific requirements must be understood in order to select the appropriate EC motor for a given application.

A more recently developed option for some applications is the selection of Permanent Magnet Synchronous (PMS) motors.[75] Although typically small in capacity, these have significantly higher power factors (resulting in lower current draw) and can operate at even greater efficiencies of up to 75%. A series of retrofit results were reported by the authors, mostly based on retail refrigeration applications, but with some walk-in chillers and freezers included.

Evaporator fan speed controllers

IOR[85] stipulates that design of efficient operation of refrigeration systems includes provision of an adaptive fan control system allowing continuous variable speed fans to match capacity with demand. Use of the most efficient motors, coupled with use of Variable Frequency Drives (VFDs) where possible, can offer up to 2% annual system energy savings.[86]

The benefits of using VFDs for evaporator fans (particularly in facilities used to cool warm incoming products) were described by Ekman et al.[87] For evaporator fans they allow speed to be reduced by as much as 50% once the products have reached the desired storage temperature. This can reduce energy consumption by as much as 85%[88] while not compromising temperature distribution and control. On top of this, the heat produced by the fans inside the room is greatly reduced, offering further energy savings due to reduced load

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[83] AIRAH., 2020. *DA12: Energy efficiency in cold rooms*. Design Application Manual, 73pp. Australian Institute of Refrigeration, Air Conditioning and Heating. Access may require AIRAH membership or login. Available at: https://www.airah.org.au/site/resources/da-manuals

[84] Fricke, B.A. and Becker, B.R., 2018. Permanent magnet synchronous motors for commercial refrigeration. *Oak Ridge National Laboratory*. https://doi.org/10.2172/1482222

[85] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

[86] Nigro, R. and Goossen, K., 2020. Energy efficiency opportunities in industrial refrigeration. *University of Delaware Industrial Assessment Center with US EPA Webinar*. Available at: https://www.epa.gov/sites/default/files/2020-10/documents/p2webinar_energy_ind_refrig_061720.pdf

[87] Ekman, J.H., Golding, J.B. and McGlasson, W.B., 2005. Innovation in cold storage technologies. *Stewart Postharvest Review*, 1(3), pp.1–14

[88] Morton, R.D. and McDevitt, M.L., 2000. Evaporator fan variable frequency drive effects on energy and fruit quality. *16th Annual Postharvest Conference*, Yakima, WA, pp.14–15

on the compressor.[89] This was estimated by Hilton[90] to offer another 20 to 50% in direct fan-energy savings.

As well as basing speed control on temperature measurements, simpler two-speed (or more) control with EC evaporator fans can be more cost-effective and is considered an acceptable control strategy, as often an air flow of only around 70% maximum is required in order to achieve the desired air throw in the cold store. Alternatively, the evaporator fan could use high speed when the evaporator is cooling and switch to low speed when the evaporator is off, consuming less energy but still mixing and circulating the air sufficiently inside the cold store. Another simple option pulse operation of single-speed fans during evaporator off periods, which can save some energy without affecting the temperature profile in the room.[91]

Minimum acceptable speed should be determined by the room configuration and the need for acceptable air movement. In general, most cold stores can be operated at substantially reduced fan speed with no increase in temperature stratification or the appearance of 'hot spots'. Setting a maximum speed also provides a number of advantages. A coil operating at 80% fan speed still produces 90% of rated capacity, while at the same time reducing fan power to nearly 50%. In addition, a maximum fan speed helps reduce utility peak demand charges. (https://www.focusondrives.com/using-vfds-refrigeration-cold-storage-applications-4/).
Payback in a typical cold room when installing VSDs to replace fixed speed drives operating at full design speeds was stated to be 1.3 years (Hilton[81] cited in https://studylib.net/doc/18093987/refrigeration-%E2%80%93-variable-evaporator-fan-speed).

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)	Depends on whether old inefficient fan motors are being replaced by better types. In new installations, better types are likely to be specified anyway.

89 Wilcox, M.H., 1998. The evaporator fan VFD initiative. *Proceedings of the 14th Annual Postharvest Conference*, 3–4 March 1998, Yakima, WA, pp.10–11. Washington State University

90 Hilton, G., 2013. Reducing energy use in the cold storage industry – a case study. *EcoLibrium*, pp.44–50

91 AIRAH., 2020. *DA12: Energy efficiency in cold rooms*. Design Application Manual, 73pp. Australian Institute of Refrigeration, Air Conditioning and Heating. Access may require AIRAH membership or login. Available at: https://www.airah.org.au/site/resources/da-manuals

	Efficiencies are roughly ranked as follows: Shaded pole 20%, PSC 29%, EC 66%, PMS 75% but not all options suit all applications. AIRAH 2020 suggest 40% energy saving using EC fans Fan speed control can offer up to 50% energy savings on fan power in facilities which are also used to cool or freeze warm incoming product.
Quality of scope 2 emissions information	Good but fairly general in nature, benefits will vary in practice.
Availability barriers	Costs of efficient motors are higher than less efficient types.
TRL level	8-9
Maintainability issues	Nothing extraordinary.
Legislative concerns	None.
Payback time (years)	Data not found for different motor types,]. 1.3 years for VSDs replacing fixed speed operation in facilities also used for cooling warm incoming products.

9.13 Free cooling

For chilled storage of commodities such as fruits and vegetables, it is possible to introduce ambient air during periods when it is colder outside the chilled store than it is inside and use this instead of the refrigeration system to remove heat loads such as respiration from the produce. By turning off the refrigeration compressor and evaporator fans at times when the outside air is cooler than inside and replacing it with ducted (fan-driven) outside ambient air, significant energy savings may be achieved in some circumstances. These savings are however seasonal, with cold winter months offering the greatest potential for savings.

Use of free cooling is widely reported for applications such as building air conditioning and data centre cooling, but less so for food storage. Al-Salaymeh and Abdelkader[92] used mathematical modelling to study the use of free cooling for storage of potatoes, lemons and

[92] Al-Salaymeh, A. and Abdelkader, M.R., 2011. Efficiency of free cooling technique in air refrigeration systems. *Jordan Journal of Mechanical & Industrial Engineering*, 5(4)

tomatoes. Being based in Jordan, the ambient temperatures used in the model were less suitable for free cooling than those which would be found in countries like the UK, but the target storage temperature was relatively high at 15°C and this afforded significant opportunity for free cooling. The reported energy cost savings ranged from 83% in winter months to only 5% in summer months. Payback times for the three products for installing the ducting, fans and dampers were around 1 year.

Sáenz-Baños et al.[93] included free cooling in a selection of cooling demand reduction measures for a potato cold store in Spain and found that day-night variations in ambient temperature could also be exploited at certain times of year. The resultant reduction in energy demand was however modest at 0.94%, compared for example with a measure to improve the efficiency of the refrigeration plant, which reduced energy demand by 6.2%.

A more generic study including free cooling in the supply of chilled water for an industrial application was reported by Canova et al.[94] who found that annual energy savings of up to 6 to 7% could be achieved in an Italian location even with a water temperature as low as 7°C, which could be useful in cooling of chilled produce stores.

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)	Only applicable for some chilled storage applications. Dependant on storage facility factors, as well as weather, with location and seasonal as well as day-night variance. Energy cost savings varied from 5 to 83% over a year in Jordan,[95] but annual energy demand reduction was only 0.94% in Spain.[84] Use of free colling for chilled water supply at 7°C saved 6-7% of

[93] Sáenz-Baños, M., Latorre-Biel, J.I., Martínez-Cámara, E., Jiménez-Macías, E., Longo, F. and Blanco-Fernández, J., 2022. Methodology for energy demand reduction of potato cold storage process. *Journal of Food Process Engineering*, 45(10), e14127. https://doi.org/10.1111/jfpe.14127

[94] Canova, A., Cirio, D., Giordano, D., Spertino, F. and Tartaglia, M., 2019. Exploitation and optimal management of free cooling for industrial refrigeration. *Energy Conversion and Management*, 198, p.111815. https://doi.org/10.1016/j.enconman.2019.111815

[95] Al-Salaymeh, A. and Abdelkader, M.R., 2011. Efficiency of free cooling technique in air refrigeration systems. *Jordan Journal of Mechanical & Industrial Engineering*, 5(4)

	annual refrigeration energy for an Italian industrial application (Canova et al 2019).
Quality of scope 2 emissions information	Quality is reasonable but limited in quantity.
Availability barriers	None.
TRL level	9
Maintainability issues	Additional ducting, fans and dampers require some additional maintenance, and sensing and control is required.
Legislative concerns	None.
Payback time (years)	1 year reported in Jordan.[96]

9.14 Heat reclaim/recovery

The amounts and 'quality' (or in other words the temperatures) of heat which can be recovered from refrigeration systems are typically quite low in quality[97] but can be high in terms of quantity. Water cooling of reciprocating compressors and oil cooling of screw compressors (in the ranges 30-35°C and 50-70°C depending on low or high stage rejection) are generally considered ineffective for most heating demands. Recovery of heat from condensing refrigerant is also of low quality (typically from 16-38°C) but in greater amounts. De-superheating of refrigerant can offer much higher temperatures (in the range of 80-90°C and 95-115°C for low and high stage reciprocating but only 50-60°C and 65-75°C for screws) but is typically in low amounts, at around 10 to 15% of total heat rejected. However, Xia et al.[98] reported that use of phase change materials to recover heat between the compressor and condenser in a cold storage refrigeration system was capable of recovering heat at around 80°C, a temperature suitable for supplying domestic hot water. In addition to the benefit of recovered heat, in multi-stage compression systems, de-superheating vapour from the low-stage compression reduces the load on the high stage.

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[96] Al-Salaymeh, A. and Abdelkader, M.R., 2011. Efficiency of free cooling technique in air refrigeration systems. *Jordan Journal of Mechanical & Industrial Engineering*, 5(4)

[97] Stoecker, W.F., 1998. *Industrial refrigeration handbook*. New York: McGraw-Hill. ISBN 9780070616233

[98] Xia, M., Yuan, Y., Zhao, X., Cao, X. and Tang, Z., 2016. Cold storage condensation heat recovery system with a novel composite phase change material. *Applied Energy*, 175, pp.259–268. https://doi.org/10.1016/j.apenergy.2016.05.001

Guangpeng et al.[99] (2021) proposed use of heat recovered from refrigerant vapour at the compressor discharge, transferred to the evaporator using glycol, to replace electric defrosting. Theoretical energy savings of 20 to 30% for small frozen stores and 10 to 20% for medium and large frozen stores were claimed.

Matching the needs for heating to these supplies is of course critical, with underfloor heating for frozen stores being easiest due to its low temperature requirement (10-15°C). Space heating and reheat for humidity control are next requiring temperatures in the 30s and 40s, while most challenging is pre-heating of wash water and boiler feed water, which require temperatures up to approximately 50°C (Stoecker, 1998).

Profiles of heat recovery and use should be considered, with matching supply and demand being ideal and thermal storage possibly being required if profiles do not match.

Nigro and Goossen[100] confirmed the above, suggesting consideration of compressor heat recovery for underfloor heating, boiler make-up feedwater pre-heating, and hot water for cleaning, which in general were said to offer up to 4% annual system energy savings.
The temperatures available from heat recovery can by boosted using heat pumps. For example, Singh and Dasgupta[101] used a trans-critical CO_2 heat pump coupled to an ammonia refrigeration plant in a dairy application, with the heat being used to pre-heat boiler water. They reported reduction in total CO_2 emissions for the process to be 45.7% and payback to be around 40 months. In another example, Li et al.[102] proposed using condenser heat boosted by a heat pump to meet the needs of an associated food drying process.

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

[99] Guangpeng, L., Yanrui, Z. and Liwen, S., 2021. Application research on energy saving technology of waste heat recovery and defrosting for low temperature cold storage. *E3S Web of Conferences*, 245, p.01038

[100] Nigro, R. and Goossen, K., 2020. Energy efficiency opportunities in industrial refrigeration. *University of Delaware Industrial Assessment Center with US EPA Webinar*. Available at: https://www.epa.gov/sites/default/files/2020-10/documents/p2webinar_energy_ind_refrig_061720.pdf

[101] Singh, S. and Dasgupta, M.S., 2017. CO_2 heat pump for waste heat recovery and utilization in dairy industry with ammonia-based refrigeration. *International Journal of Refrigeration*, 78, pp.108–120

[102] Li, M., Li, Z., Jiang, X. and Ye, B., 2011. Design and performance analysis of the heat pump-based condensing heat of cold storage recovery drying equipment. *2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring*, pp.158–161

Scope 2 emissions savings (% or another quantifiable metric)	Up to 4% system energy.[103] 45.7% reduction in CO_2 emissions for a dairy application.[104]
Quality of scope 2 emissions information	Figure given by Nigro and Goossen[94] is not backed up with referenced data. Other sources are peer-reviewed journal or conference papers.
Availability barriers	None.
TRL level	9
Maintainability issues	Adds additional components and pipework.
Legislative concerns	None.
Payback time (years)	Payback time for the addition of heat pump to a diary application around 40 months.[95]

9.15 High temperature CA storage

Maintaining quality of apple and pear during storage is mainly achieved by storing at low temperature just above freezing conditions resulting in a metabolism that is as low as possible. For apple these non-freezing temperatures are around 1°C but pear with a high amount of sugars can be kept at -1°C without freezing. Metabolism, including respiration, is further lowered by applying controlled atmosphere (CA) conditions with elevated CO_2 (carbon dioxide) and low O_2 (oxygen) concentrations. The particular modified oxygen and carbon dioxide concentrations are set based on experience and advice and depend on the stored cultivar. In general respiration will by lower at lower oxygen concentrations.[105] However, if due to lack of oxygen the aerobic respiration of the fruit is too low to provide enough energy for maintenance, fermentation will start which can lead to fruit damage and loss of fruit quality.

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[103] Nigro, R. and Goossen, K., 2020. Energy efficiency opportunities in industrial refrigeration. *University of Delaware Industrial Assessment Center with US EPA Webinar*. Available at: https://www.epa.gov/sites/default/files/2020-10/documents/p2webinar_energy_ind_refrig_061720.pdf

[104] Singh, S. and Dasgupta, M.S., 2017. CO_2 heat pump for waste heat recovery and utilization in dairy industry with ammonia-based refrigeration. *International Journal of Refrigeration*, 78, pp.108–120

[105] Hertog, M.L.A.T.M., Peppelenbos, H.W., Evelo, R.G. and Tijskens, L.M.M., 1998. A dynamic and generic model of gas exchange of respiring produce: the effects of oxygen, carbon dioxide and temperature. *Postharvest Biology and Technology*, 14(3), pp.335–349. https://doi.org/10.1016/S0925-5214(98)00058-1

In the first instance, it could seem that increasing the storage temperature would result in lower energy use for the cooling of the storage rooms however because of the higher temperature the stored fruit would produce more respiration heat[106]. As respiration increases exponentially with temperature one ends up needing even more energy for cooling the storage room at a higher temperature. Only when wall losses are a main component of the heat load, cooling at a higher temperature would be more energy efficient as one gains more because of the decreased heat load through the walls than the increase in respiration heat. In any case this would be undesirable as fruit quality will be compromised because of higher metabolism. Bad wall insulation should be dealt with by installing proper wall insulation.

Things might be different when dynamically controlled atmosphere (DCA) storage is applied. In classical CA storage safety margins are built in as the stress levels for low oxygen vary from batch to batch and from season to season.[107] With this new storage technique, the lowest possible oxygen concentration is determined by measuring the oxygen stress of the fruits and the atmosphere is adjusted just above this stress point.[108] This way fermentation is avoided, and oxygen level can be kept as low as possible to prevent loss of quality and have a respiration rate as low as possible and so decreasing de production of respiration heat. Some of this decrease in respiration might be traded for a small increase in storage temperature, say stored at 2 to 3°C instead of 1°C. Wendt et al.[109] showed that DCA stored Gala apples maintained even better quality after nine months of storage when a varying storage temperature between 0.5 and 3°C was carried out in comparison with a constant 0.5°C storage temperature. However much more research is needed to generalise this to other cultivars and take into account batch and seasonal effects. Because of the higher storage temperature respiration heat production will increase but there might be a net gain as the wall loads will be smaller. Bxchele et al.[110] concluded in their research that because the extremely low oxygen levels slowed down fruit metabolism to a minimum, DCA allowed room temperatures to be

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[106] Hertog, M.L.A.T.M., Peppelenbos, H.W., Evelo, R.G. and Tijskens, L.M.M., 1998. A dynamic and generic model of gas exchange of respiring produce: the effects of oxygen, carbon dioxide and temperature. *Postharvest Biology and Technology*, 14(3), pp.335–349. https://doi.org/10.1016/S0925-5214(98)00058-1

[107] Bessemans, N., Verboven, P., Verlinden, B.E. and Nicolaï, B.M., 2016. RQ-based dynamic controlled atmosphere storage of apple fruit. *Acta Horticulturae*, 1194, pp.729–736. https://www.actahort.org/books/1194/1194_97.htm

[108] Bessemans, N., Verboven, P., Verlinden, B.E. & Nicolaï, B.M. 2018, *RQ-based dynamic controlled atmosphere storage of apple fruit*, *Acta Horticulturae*, vol. 1194, pp. 681–687, DOI: 10.17660/ActaHortic.2018.1194.97. Available at: https://lirias.kuleuven.be/1715970

[109] Wendt, L.M., Ludwig, V., Rossato, F.P., Berghetti, M.R.P., Schultz, E.E., Thewes, F.R. and Both, V., 2022. Combined effects of storage temperature variation and dynamic controlled atmosphere after long-term storage of 'Maxi Gala' apples. *Food Packaging and Shelf Life*, 31, p.100770

[110] Büchele, F., Pristavka, L., Neuwald, D.A., Ulrich, D., Geyer, M. and Herppich, W.B., 2023. Dynamic control of atmosphere and temperature based on fruit CO_2 production: practical application in apple storage and effects on metabolism, quality, and volatile profiles. *Food and Bioprocess Technology*, pp.1–14. https://doi.org/10.1007/s11947-023-03091-2

raised and energy consumption from cooling machines to be reduced. They found a reduced energy use for cooling (energy use for compressor, evaporator fans and defrosting) of 18% for DCA with varying storage temperature between 1 and 3°C, based on carbon dioxide production, compared to DCA at 1°C. However, it is not very clear how temperature needs to be varied based on the carbon dioxide production and will depend on the stored cultivar as well. The rate of quality loss will increase which as well means the fruit will reach marketability thresholds faster making it not suitable for long storage. The energy saving tests were run in a 11 ton room which is about 10 times smaller than a typical commercial storage room making the wall losses comparably large in the experimental setup.

Scope 1/3 emissions savings (% or another quantifiable metric)	Fruit losses will in the best case be the same. However, because of season and batch variability fruit might not cope with elevated storage temperatures and fruit losses might be higher.
Quality of scope 1/3 emissions information	Peer reviewed scientific papers
Scope 2 emissions savings (% or another quantifiable metric)	Depending on storage room size overall energy savings for cooling will range from 10% (large commercial rooms) to 18% (small research rooms)
Quality of scope 2 emissions information	Peer reviewed scientific papers
Availability barriers	L
TRL level	TRL5-7: applying different operational parameters on an existing DCA equipment but high risk on fruit losses. TRL1-4: improved technology incorporating measures of fruit suitability.
Maintainability issues	Fruit quality maintenance is an important issue as storage temperature has a major impact on it. Energy savings have been demonstrated in particular cases for particular cultivars however there is still too little information to make it general applicable.
Legislative concerns	n/a
Payback time (years)	No. As the technology consists of applying different operational parameters on an existing DCA equipment.

9.16 Humidification

Humidification can help reduce post-harvest losses of high moisture content perishable products such as fruit and vegetables but also, among others, meat products: creating a high humidity environment during storage minimizes water loss from the food to the surroundings. Water loss leads to weight loss and could induce quality deterioration due to shrivelling, texture loss and colour changes and eventually decreases the remaining shelf life. A high relative humidity in cooled storage at temperatures close to freezing does not necessarily require additional humidification. The low temperature environment and moist product generally create a high relative humidity environment in a passive way, especially when the temperature difference between the air and cooling coils of the evaporator is kept small. Only for products that are very sensitive to water loss or when suboptimal storage temperatures are applied, additional humidification can be beneficial to prevent excessive weight loss, maintain quality and extend shelf life.[111] [112]

Humidification systems using spray nozzles or fogging of microscopic droplets are generally preferred as a more energy-efficient alternative to injection of steam, which is created in a boiler at higher temperature than that in the storage room. Microdroplets also assist cooling of the storage air by evaporative cooling, albeit generally to a minor extent as only low rates of humidification are required at low temperatures typical for storage (unless in dedicated evaporative cooling systems.[113] Spray nozzles (creating droplet diameters from 7 to 18 μm) generally create larger droplets than ultrasonic humidifiers (droplet sizes 1-5 μm).[102] [114] The larger the droplets, the higher the risk for condensation due to uncomplete evaporation with consequent risks for microbial growth and quality decay. Also, in case of non-zero temperatures frost formation can cause problems related to airflow and temperature conditions in the room and energy consumption.[102] Therefore, careful optimization of the spray and airflow in cool stores is required for the humidification system to operate correctly.[102]

It could be considered that the evaporative cooling effect due to humidification provides a means for saving mechanical cooling energy in a cool store; however, in a steady state closed cooling room system, added moisture is also condensed on the evaporator cancelling out this effect. Therefore, it is argued that additional humidification for increasing relative humidity in

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[111] Delele, M.A. et al., 2009. Evaluation of a chicory root cold store humidification system using computational fluid dynamics. *Journal of Food Engineering*, 94(1), pp.110–121

[112] Brown, T., Corry, J.E. and James, S.J., 2004. Humidification of chilled fruit and vegetables on retail display using an ultrasonic fogging system with water/air ozonation. *International Journal of Refrigeration*, 27(8), pp.862–868

[113] Lal Basediya, A., Samuel, D.V.K. and Beera, V., 2013. Evaporative cooling system for storage of fruits and vegetables – a review. *Journal of Food Science and Technology*, 50(3), pp.429–442. https://doi.org/10.1007/s13197-011-0311-6

[114] Fabbri, S., Olsen, S.I. and Owsianiak, M., 2018. Improving environmental performance of post-harvest supply chains of fruits and vegetables in Europe: potential contribution from ultrasonic humidification. *Journal of Cleaner Production*, 182, pp.16–26

cool store systems will not lead to direct emissions savings. On the contrary, the operation of the humidifier will add to the energy use balance by its own energy consumption, and by increasing refrigeration due to the increased amounts of water condensing or freezing onto the evaporator.[115]

Based on the work of Delele et al.[116], it is estimated that the energy cost of humidification amounts to 0.07 kWh/ton/day for applications in long term storage rooms, which a high load ratio, for fruit or vegetables operating a low optimal temperature (typically -2 to 3°C, depending on product type), which would account for approximately 5% of the total energy use.[117] In using humidification in shorter term storage of perishable products in less tightly controlled conditions and lower load ratios, the specific energy consumption may raise to values up to 2.81 kWh/ton/day.[118] In a display cabinet study, the increased refrigeration was found to be on average 0.2 to 0.4 kW (1.5-12% increase) compared to a nominal ('dry') situation consuming on average 3.4 kW to maximally 12.6 kW (Brown, Corry and James, 2004).

In the life cycle assessment (LCA) of the impact of humidification in supply chains of strawberry, peach, grape and asparagus,[109] it has also been quantified that the main benefit of humidification is in reducing food losses, while the system operation itself adds to the impact. The importance of reducing food losses is demonstrated by the fact that, in the LCA scenarios with zero efficiency of humidifiers (i.e., when losses are not reduced), humidification slightly increases environmental burdens. Based on the LCA analysis of these highly perishable foods, the environmental performance of the humidification system improves as losses are reduced. Even a modest improvement is evident when humidifiers operate with low efficiency, i.e., by reducing losses by 20% at each stage of application. If the efficiency increases, to reduce losses by 50%, the climate change impact is 5 to 20% in emissions savings, depending on the product category and inherent quality level of specific batches (expressed as their sensitivity to losses).[109]

Payback time of the technology depends on the food loss reduction that can be achieved, and the production value of the respective crop being stored. For low value crops and low loss reduction, humidification has a high payback time. For high value more perishable crops, the payback time is short.

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[115] Brown, T., Corry, J.E. and James, S.J., 2004. Humidification of chilled fruit and vegetables on retail display using an ultrasonic fogging system with water/air ozonation. *International Journal of Refrigeration*, 27(8), pp.862–868

[116] Delele, M.A. et al., 2009. Evaluation of a chicory root cold store humidification system using computational fluid dynamics. *Journal of Food Engineering*, 94(1), pp.110–121

[117] Verlinden, B., 2002. Adviesopdracht GMO-koelkostberekeningen. *Vlaams Centrum voor Bewaring van Tuinbouwproducten*, Belgium

[118] Fabbri, S., Olsen, S.I. and Owsianiak, M., 2018. Improving environmental performance of post-harvest supply chains of fruits and vegetables in Europe: potential contribution from ultrasonic humidification. *Journal of Cleaner Production*, 182, pp.16–26

<table>
<tr><td>Scope 1/3 emissions savings (% or another quantifiable metric)</td><td>Reduction of food losses leading to, on average, 0.1 kg CO2eq/kg</td></tr>
<tr><td>Quality of scope 1/3 emissions information</td><td>LCA analysis in peer reviewed journal article[119]</td></tr>
<tr><td>Scope 2 emissions savings (% or another quantifiable metric)</td><td>No direct savings, humidification may add 5% to total energy use during long term storage.</td></tr>
<tr><td>Quality of scope 2 emissions information</td><td>Based on peer reviewed research works.</td></tr>
<tr><td>Availability barriers</td><td>None</td></tr>
<tr><td>TRL level</td><td>9</td></tr>
<tr><td>Maintainability issues</td><td>Careful design needed to avoid condensation and hot spots.</td></tr>
<tr><td>Legislative concerns</td><td>-</td></tr>
<tr><td>Payback time (years)</td><td>
Storage room load (ton): 100
Humidification investment (€): 5000
Nominal food loss: 20%
<table>
<tr><td>Relative food loss reduction by humidification:</td><td>10%</td><td>20%</td><td>50%</td></tr>
<tr><td>Production value of crop (€/kg)</td><td colspan="3">Payback (yr)</td></tr>
<tr><td>0.5</td><td>5</td><td>2.5</td><td>1</td></tr>
<tr><td>1</td><td>2.5</td><td>1.25</td><td>0.5</td></tr>
<tr><td>2</td><td>1.25</td><td>0.625</td><td>0.25</td></tr>
<tr><td>5</td><td>0.5</td><td>0.25</td><td>0.1</td></tr>
</table>
</td></tr>
</table>

9.17 Insulation

The relative importance of transmission of heat through cold storage insulation varies depending on the use of the store and the other consequent loads. The Cold Chain

[119] Fabbri, S., Olsen, S.I. and Owsianiak, M., 2018. Improving environmental performance of post-harvest supply chains of fruits and vegetables in Europe: potential contribution from ultrasonic humidification. *Journal of Cleaner Production*, 182, pp.16–26

Federation[120] presented typical relative proportions of heat loads on cold stores operated by their members, with 22% being the typical transmission heat load for stores with high throughput and cooling of product which arrived warm. By comparison, Alves et al.[121] found that in modelling of heat loads on a chilled dairy storage room, transmission of heat through the insulation accounted for just 12.8% of the total energy consumption. Nevertheless, in new installations, insulation with low thermal conductivity should be chosen, with sufficient thickness to achieve high resistance to heat transfer, as reflected by the R-value (thickness/conductivity). R-values for some typical insulation materials used in cold storage applications were presented in AIRAH,[122] arranged from best on the left to worst on the right:

General properties Core	PIR Polyurethane modified isocyanurate foam	PUR Rigid polyurethane foam	XPS Rigid board of extruded polystyrene	EPS (including EPS-FR) Molded block formed from beads of polystyrene	MRF Structural grade mineral rock fiber
Thermal conductivity ($W\ m^{-1}K^{-1}$)	0.020	0.022	0.028	0.038	0.043
Panel thickness/	R-value (m^2K/W)				
50 mm	2.50	2.27	1.79	1.32	1.16
75 mm	3.75	3.41	2.68	1.97	1.74
100 mm	5.00	4.55	3.57	2.63	2.33
125 mm	6.25	5.68	4.46	3.29	2.91

[120] Cold Chain Federation., 2020. *Energy efficiency in cold stores: a practical guide*. Cold Chain Federation. Available at: https://www.coldchainfederation.org.uk/download/energy-efficiency-in-cold-stores-a-practical-guide/

[121] Alves, O., Brito, P., Lopes, P. and Reis, P., 2014. Optimization of energy consumption in cold chambers in the dairy industry. *Energy Procedia*, 50, pp.494–503. https://doi.org/10.1016/j.egypro.2014.06.060

[122] AIRAH., 2020. *DA12: Energy efficiency in cold rooms*. Design Application Manual, 73pp. Australian Institute of Refrigeration, Air Conditioning and Heating. Access may require AIRAH membership or login. Available at: https://www.airah.org.au/site/resources/da-manuals

General properties Core	PIR Polyurethane modified isocyanurate foam	PUR Rigid polyurethane foam	XPS Rigid board of extruded polystyrene	EPS (including EPS-FR) Molded block formed from beads of polystyrene	MRF Structural grade mineral rock fiber
150 mm	7.50	6.82	5.36	3.95	3.49
200 mm	10.00	9.09	7.14	5.26	4.69

The same source recommended that as a minimum for walk-in cold rooms, insulation panels for walls, ceilings and doors should have an R-value equivalent to 100 mm polyurethane isocyanurate (PIR) on chilled stores, and thicker than 150 mm PIR on freezers. In addition, the minimum thermal insulation rating on floors should be at least 4.9m²K/W.

On a simplistic level, based on the above table 150mm PIR saves 33.3% of the transmission load compared with 100 mm. If this is combined with the typical 22% transmission load reported by CCF 2020, the saving would be 33.3% of 22%, or in other words 7.7%.

Cost effectiveness of different types of cold storage insulation has been assessed in studies based in various countries and regions. For example, Soylemez and Unsal[123] studied capital and operating costs for stores with different types and thicknesses of insulation at a range of locations in the USA. Similarly, Kxçxktopcu et al.[124] assessed cost effectiveness at 4 locations in Turkey, while Batiha et al.[125] conducted a similar study for 4 locations in Jordan. Although conclusions varied, it is clear that determining the optimum type and thickness of insulation is not only dependant on the specifics of the cold stores and the location and weather but also on the price of insulation and energy, both of which change over time.

For cold storage applications, increasing the thickness of insulation generally does not have a large impact on the useable volume of the store as it would on for example a domestic refrigerator with fixed outside dimensions and relatively small internal volume. This means that

123 Söylemez, M.S. and Ünsal, M., 1999. Optimum insulation thickness for refrigeration applications. *Energy Conversion and Management*, 40(1), pp.13–21

124 Küçüktopcu, E., Cemek, B. and Simsek, H., 2022. Application of spatial analysis to determine the effect of insulation thickness on energy efficiency and cost savings for cold storage. *Processes*, 10(11), p.2393

125 Batiha, M.A. et al., 2019. A study on optimum insulation thickness of cold storage walls in all climate zones of Jordan. *Case Studies in Thermal Engineering*, 15, p.100538

the more traditional materials above can be used in greater thickness if required, rather than selecting more novel and expensive insulation technology such as vacuum insulation panels or aerogel material. While these novel types of insulation could be used on cold stores, their lower cost effectiveness and questionable robustness make them less attractive than materials such as PIR.

For retrofitting or repair of existing cold stores with replacement of old poor quality or damaged insulation, energy savings can be achieved, particularly where the damage has allowed ingress of moisture into the panels. Evans et al 2014 identified that inadequate insulation was a source of unnecessary heat load on 13 of 38 surveyed cold stores, due to damage or breakdown of the insulation, insufficient thickness, or use of chilled stores as frozen stores. Estimated energy savings after addressing these issues were on average 8% for large stores and 14% for small stores, but payback times were long (18 to 20 years). Recent increases in energy costs will have reduced the payback time for these examples.

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)	Dependent on specifics of store and usage patterns. For new stores it is likely that adequate thicknesses of the best performing traditional insulation (PIR) will be used anyway, but for retrofitting or repair of older stores, the performance of the insulation being replaced could be far worse due to poor materials, damage and moisture ingress. In these circumstances, Evans et al.[116] estimated energy savings of 8% for large stores and 14% for small stores. From simplistic calculation using AIRAH[126] and CCF[127] figures, a saving of 7.7% of total energy can be achieved by increasing PIR thickness from 100 to 150mm.

[126] AIRAH., 2020. *DA12: Energy efficiency in cold rooms*. Design Application Manual, 73pp. Australian Institute of Refrigeration, Air Conditioning and Heating. Access may require AIRAH membership or login. Available at: https://www.airah.org.au/site/resources/da-manuals

[127] Cold Chain Federation., 2020. *Energy efficiency in cold stores: a practical guide*. Cold Chain Federation. Available at: https://www.coldchainfederation.org.uk/download/energy-efficiency-in-cold-stores-a-practical-guide/

Quality of scope 2 emissions information	Good but specific to application.
Availability barriers	None
TRL level	9
Maintainability issues	Requirements are similar for all traditional types of insulation.
Legislative concerns	None
Payback time (years)	Depends on type and thickness – price of panels and energy vary over time. Evans et al.[128] suggested improvements to poorly insulated cold stores would have long payback (18 to 20 years), although recent increases in energy costs will have reduced this.

9.18 Internal loading and unloading bays

Some cold stores have been constructed with loading and unloading bays inside their main structure. Instead of backing up transport vehicles against openings in the outside walls, the transport containers are taken inside climate-controlled areas of the store. This reduces the risk of ingress of warm ambient air around imperfect loading bay seals, thereby reducing the load on the store as a whole and avoiding exposure of the product to undesirable temperatures.

Sources of information on energy savings are scarce, with no peer-reviewed publications being found. Online journalism does however mention the use of internal loading and unloading in https://www.ajot.com/premium/ajot-new-technology-in-cold-storage, which discusses automation and high-level racking in conjunction with trucks being unloaded inside the temperature-controlled environment. The latter alone is claimed to save 50% of the energy costs of traditional cold storage warehouses, but no data are presented to substantiate this.

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

[128] Evans, J.A., Foster, A.M., Huet, J.-M., Reinholdt, L., Fikiin, K., Zilio, C., Houska, M., Landfeld, A., Bond, C., Scheurs, M. and Van Sambeeck, T.W.M., 2014. Specific energy consumption values for various refrigerated food cold stores. *Energy and Buildings*, 74, pp.141–151. https://doi.org/10.1016/j.enbuild.2014.01.019

Scope 2 emissions savings (% or another quantifiable metric)	Trade press articles suggest possible energy savings of 50%.
Quality of scope 2 emissions information	Poor, no data presented, just the claimed saving.
Availability barriers	None
TRL level	9
Maintainability issues	Vehicle access doors are required instead of loading bays, but maintenance issues are probably similar.
Legislative concerns	None
Payback time (years)	No data.

9.19 Lighting and light controls

Types of lighting

Energy consumption of lighting in refrigerated warehouses is determined by several factors, including the type of lights used, the level of lighting which is maintained in the warehouse and loading bays and whether or not the lights are sensor controlled such that they switch off or dim when not required.

For some time, Light Emitting Diode (LED) lighting has been the accepted choice for most lighting applications, and cold storage can benefit from it in two ways. It can use less than half of the energy for similar levels of lighting compared with more traditional types of lights (particularly halogens, see for example IOR 2020 which gives the following guidance: a conventional lighting system may be expected to consume 10 to 12 $W.m^{-2}$ of floor area, while modern systems could reduce this to around 5 $W.m^{-2}$. LEDs also adds far less heat to the cold store, thereby reducing refrigeration energy consumption.

Although more efficient than fluorescents and particularly halogen lights, LEDs may not offer significant amounts of saved energy, depending on the store and its use. For example, Alves et al.[129] found that use of LEDs had a negligible impact on a dairy store's energy use compared

[129] Alves, O., Brito, P., Lopes, P. and Reis, P., 2014. Optimization of energy consumption in cold chambers in the dairy industry. *Energy Procedia*, 50, pp.494–503. https://doi.org/10.1016/j.egypro.2014.06.060

with fluorescents but was an improvement on the use of halogens due to their high operating temperatures.

Evans et al.[130] reported that payback on replacing old inefficient lights in several larger cold stores surveyed in Europe was typically around 4 years.

Light controls

The energy consumption and heat generation of lighting can be reduced considerably by use of automatic controls such as motion sensors to dim or switch off lights depending on occupancy. In some circumstances it may be possible to apply lighting only to the aisles.[131]

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)	Approximately half of the lighting energy consumption can be saved by using LEDs instead of older lighting. However, the lighting energy consumption may not be a large part of the total energy consumption.
Quality of scope 2 emissions information	Mostly general in nature, measured data are scarce.
Availability barriers	None
TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	Typically, 4 years (Evans et al 2020)

[130] Evans, J.A., Foster, A.M., Huet, J.-M., Reinholdt, L., Fikiin, K., Zilio, C., Houska, M., Landfeld, A., Bond, C., Scheurs, M. and Van Sambeeck, T.W.M., 2014. Specific energy consumption values for various refrigerated food cold stores. *Energy and Buildings*, 74, pp.141–151. https://doi.org/10.1016/j.enbuild.2014.01.019

[131] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

9.20 Maintenance

The importance of careful, planned maintenance is stressed by industry documents such as IOR 2020. Not only does this help to ensure correct operating temperatures, it prevents gradual degradation of energy efficiency. Particular aspects which maintenance should be focussed on include regular checking of set points, refrigeration plant operating parameters, refrigerant leak testing and also cleaning of heat exchangers to maintain their performance.

Evaporators, air coolers and condenser heat exchangers must be kept free of dirt and other contaminants. Dirt on air type heat exchangers (condensers) such as leaves, and plastic can significantly affect the air flow through the finned area reducing their heat transfer effectiveness.[132]

When dirt is removed from air cooled condensers or non-condensable gases are vented from condensers, the electrical consumption reduces between 10 to 15%.[122]

Servicing, maintenance and monitoring was identified by Evans et al.[133] as being an aspect of cold store management which could result in energy savings. However, only 3 % of surveyed stores were identified as having issues with maintenance, but for the larger stores that did, the mean energy savings were around 5%. Payback on improved maintenance measures was said to be typically 2 years, although detail on exact measures was not given.

Scope 1 emissions savings (% or another quantifiable metric)	Identification and rectification of refrigerant leaks is part of maintenance, but potential savings are unclear.
Quality of scope 1 emissions information	No quantitative data.
Scope 2 emissions savings (% or another quantifiable metric)	Difficult to assign a value, as saving depends greatly on specific store circumstances. According to the Evans et al.[123] survey, the vast majority of stores (97% of those surveyed) did not have issues caused by lack of maintenance. For those that did, energy savings of around 5% could be made.

[132] Cold Chain Federation., 2020. *Energy efficiency in cold stores: a practical guide*. Cold Chain Federation. Available at: https://www.coldchainfederation.org.uk/download/energy-efficiency-in-cold-stores-a-practical-guide/

[133] Evans, J.A., Foster, A.M., Huet, J.-M., Reinholdt, L., Fikiin, K., Zilio, C., Houska, M., Landfeld, A., Bond, C., Scheurs, M. and Van Sambeeck, T.W.M., 2014. Specific energy consumption values for various refrigerated food cold stores. *Energy and Buildings*, 74, pp.141–151. https://doi.org/10.1016/j.enbuild.2014.01.019

Quality of scope 2 emissions information	Information is scarce and rather general in nature.
Availability barriers	None.
TRL level	9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	For large stores in Evans et al 2014, surveyed examples had paybacks around 2 years, but it is not clear what measures were involved and whether monitoring was included.

9.21 Monitoring

Monitoring per se does not save carbon. However, the assessment and scrutiny of the monitored data does potentially allow emissions to be reduced. Monitoring enables changes in the performance of a store to be highlighted and early intervention can be implemented to repair or identify the reason for changes in performance. Companies such as Star Refrigeration have created digital twins of cold stores where they can predict the energy that should be used by a store and compare it to the actual energy consumption. Through this they can identify faults at an early stage which can be repaired before they become a significant problem.[134]

Companies have also used monitoring of store temperature to better control the temperature. In these cases, control algorithms control the speed of evaporator fans to optimise the refrigeration systems efficiency.

Scope 1 emissions savings (% or another quantifiable metric)	Very limited quantified evidence but savings could be very similar to those from better maintenance.
Quality of scope 1 emissions information	L
Scope 2 emissions savings (% or another quantifiable metric)	Very limited quantified evidence but savings could be very similar to those from better maintenance.

[134] Pearson, A., 2022. Beyond refrigeration: next steps for the future of low carbon RACHP. *IOR Annual Conference – Beyond Refrigeration*, December 2022, Institute of Refrigeration

Quality of scope 2 emissions information	L
Availability barriers	None
TRL level	5-7
Maintainability issues	None identified.
Legislative concerns	May enable end users to better comply with f-gas regulations through early identification of refrigerant leakage.
Payback time (years)	Very limited quantified evidence but savings could be very similar to those from better maintenance.

9.22 Orientation and aspect ratio of store, and outside cladding

The orientation of a building relative to the sun and its aspect ratio will impact on the solar heat gain it experiences, affecting its thermal performance and energy efficiency. In addition, the exposure of doors to prevailing winds can greatly impact heat loads from infiltration. Published literature has tended to focus on occupied buildings and thermal comfort rather than large refrigerated cold stores, but Singh et al.[135] discussed the subject as part of a survey of Indian potato cold stores (albeit at relatively warm storage temperatures). The data presented was limited to 10 cold stores, which had a range of specific energy consumption between 9 kWh/tonne and 15 kWh/tonne. The variability was attributed partly to orientation and aspect ratio, as well as building materials and colours, but also to operational parameters such as loading, and to store size. Due to the variability and limited numbers no conclusions on optimum aspect ratio or other parameters were presented.

The application of automation to cold storage warehouses often includes the use of high bay enclosures which are more easily and quickly accessed by automated loading and retrieval units (see section on automation). While they are occasionally referred to as energy efficient configurations, the impact of aspect ratio on energy consumption is not differentiated from that of the automation and store configuration combined.

Regardless of the orientation of a building to the sun, the colour and solar reflectance of its external walls or cladding can have a significant impact on solar heat gain and subsequent transmission heat loads. IOR[136] illustrated this (see **Error! Reference source not found.**),

[135] Singh, R., Lazarus, I.J. and Singh, S.P., 2014. Impact of building and refrigeration system's parameters on energy consumption in the potato cold storage. *Energy and Environment Research*

[136] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

which shows the typical impact of the varying solar reflectance of different coloured cladding on the exposed surface temperature.

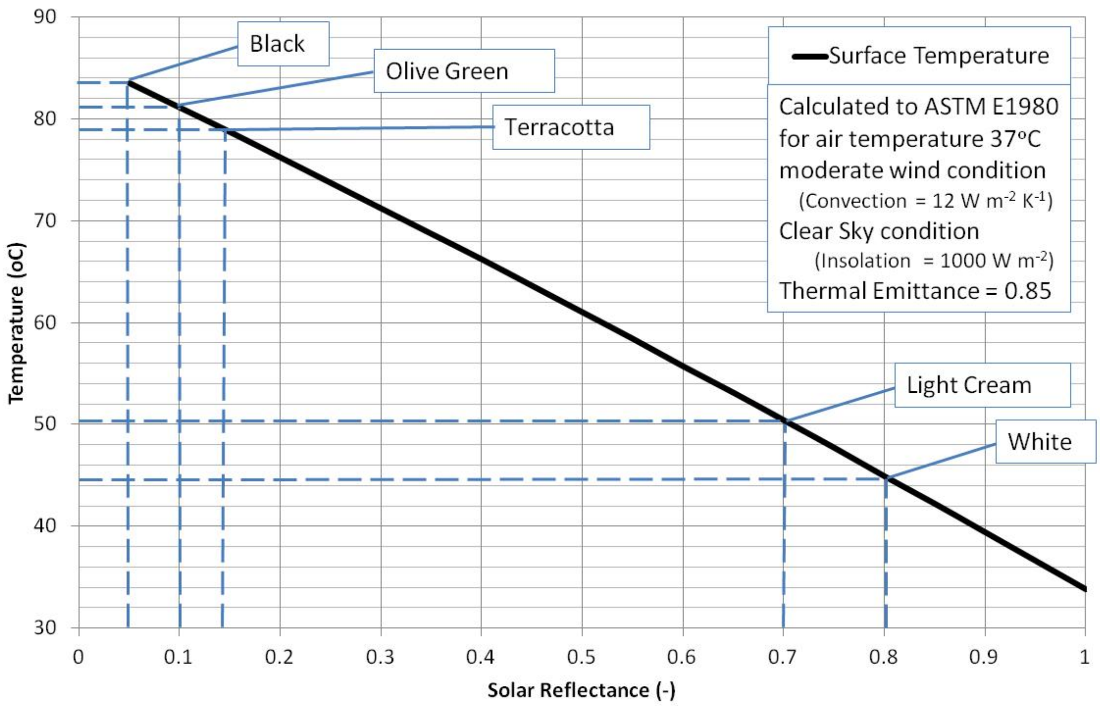

Figure 35. Roof surface temperatures for different cladding colours.

Reducing the outside cladding temperature by using a white or cream colour is an obvious and inexpensive way to reduce the transmission heat gains through the walls and ceilings, which are directly proportional to the temperature differences across them. Despite this, published studies including cladding colour are typically focussed on the housing sector in hotter climates rather than cold storage in the food chain.

In addition to orientation and cladding colour, solar shading can be employed to reduce heat gains. This can be achieved with additional panels blocking the incident solar heat or using an array of photovoltaic panels on the roof of the facility. Again however, while use of such techniques has seen received considerable attention in publications relating to the housing and retail sectors, information relating to cold storage is scarce.

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)	Logically the orientation and aspect ratio of a store will impact on its energy consumption and therefore indirect emissions, but before and after comparisons are not possible unless a store is physically re-configured or demolished and replaced. Cladding colour and solar shading can also reduce heat load on cold stores, but published data is extremely scarce for the cold storage sector. Use of mathematical models such as the ICE-E model can provide useful insights into the impact of variable orientation and aspect ratio at different locations. Depending on the transmission load on the store the impact of surface colour and shading can have variable impacts. Using the model to assess annual energy consumption indicates that the impact on shading and colour is less than 5%.
Quality of scope 2 emissions information	No data available.
Availability barriers	None, part of normal design considerations.
TRL level	9
Maintainability issues	None.
Legislative concerns	None.
Payback time	Very limited information. Energy savings indicate that only feasible if part of original design at limited additional cost.

9.23 Postharvest treatments

The treatment that has most impact on energy consumption of fruit and vegetable storage is the treatment with 1-MCP (1-methylcyclopropene). 1-MCP is thought to occupy ethylene receptors such that ethylene cannot bind and elicit action. Sisler and Serek[137] proposed.

A model of how 1-MCP reacts with the ethylene receptor. The affinity of 1-MCP for the receptor is approximately 10 times greater than that of ethylene.[138] The product is registered in Europe

[137] Sisler, E.C. and Serek, M., 1997. Inhibitors of ethylene responses in plants at the receptor level: recent developments. *Physiologia Plantarum*, 100(3), pp.577–582

[138] Blankenship, S.M. and Dole, J.M., 2003. 1-methylcyclopropene: a review. *Postharvest Biology and Technology*, 28(1), pp.1–25

since the early 2000's. Main crops are apple and pear. Extensive research has been done to establish correct application protocols for all different produce.[139]

Energy saving:

1-MCP is not applied as an energy saving treatment as such. It is a quality saving component that has indirect energy saving actions. By blocking the ethylene action, fruits will not ripen and respiration will be kept on a low level. Hence, also the respiration heat will be lower and less cooling is needed. A lower respiration leads also to lower CO_2-production that will reduce the need of actions of the CO_2-scrubber.

Fruits that are treated with ethylene can be stored at higher temperature without quality loss.

Available systems on market

Different 1-MCP formulations are available on the market. They all have the same active ingredient 1-methylcyclopropene. Their application mode can be slightly different.

- Smartfresh, Fruitsmart (is a 1-MCP powder where the 1-MCP is encapsulated in cyclodextrine. Dissolving of the powder in water will release the a.i.
- https://www.agrofresh.com/solutions/smartfresh/
- https://en.innvigo.com/plnat-growth-regulators/

Fysium is a tree component system where the gas 1-MCP is formulated in situ.

- https://www.janssenpmp.com/what-we-offer/crop-management/fysiumr-1-mcp

Energy savings and GHG emission reduction

In one study, Gala apples were stored with 1-MCP technology at 4°C, while the control apples were stored at the standard temperature of 1.5°C. The 1-MCP storage room used 35% less energy than the control storage room. A sensorial study carried out after storage clearly showed consumers' preference for SmartFresh quality apples.[140]

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[139] Watkins, C.B., 2008. Overview of 1-methylcyclopropene trials and uses for edible horticultural crops. *HortScience*, 43(1), pp.86–94

[140] McCormick, R., Neuwald, D.A. and Streif, J., 2010. A case study: potential energy savings using 1-MCP with 'Gala' apples in commercial CA storage. *Kompetenzzentrum Obstbau-Bodensee (KOB), Germany*. Available at: https://www.researchgate.net/publication/268216295

Thewes et al.[141] reports respiration reduction around 40% when Gala of different maturity stages is treated with 1-MCP. Xuan and Streif[142] published a reduction of about 40% respiration of Jonagold thanks to 1-MCP. This is confirmed by the findings of the Flanders Centre of Postharvest Technology for Jonagold apples and Conference pears (data not published).

The reduced respiration rate leads to a reduction of respiration heat and scrubber activity, less need for ventilation etc. The Flanders Center of Postharvest Technology developed a calculation tool that calculates the energy consumption of storage rooms for fruits and vegetables. When these reduced respiration rates etc. are taken into account this leads to a certain reduction of energy consumption that is mentioned in Table 12.

Table 12. Energy savings based on reduced respiration rate thanks to the treatment with 1-MCP (1-methylcyclopropene)

Respiration rate (%)	Reduction in heat production (cooling) (%)	Savings of the CO2 scrubber (%)	Total reduction in energy use of the storage room (%)*	Payback time*
100	0	0	0	-
80	7.3	20	8.3	6 years
70	10.9	30	12.5	4 years
60	14.6	40	16.7	3 years

1-MCP (Smartfresh, Fysium) costs approximately 1.5 à 2.5 €cent/kg fruit/vegetables.

ULO storage of fruit for about 9 months costs about 4 €cent/kg.

Saving of the energy thanks to 1-MCP = 16.7%*0.04 = 0.0067€/kg per year

Payback = saving/cost = 0.02/0.0067 = 3 years, see Table 12

<u>Summary table: 1-MCP technology</u>

[141] Thewes, F.R., Brackmann, A., de Oliveira Anese, R., Ludwig, V., Schultz, E.E., Dos Santos, L.F. and Wendt, L.M., 2017. Effect of dynamic controlled atmosphere monitored by respiratory quotient and 1-methylcyclopropene on the metabolism and quality of 'Galaxy' apple harvested at three maturity stages. *Food Chemistry*, 222, pp.84–93

[142] Xuan, H. and Streif, J., 2004. Effect of 1-MCP on the respiration and ethylene production as well as on the formation of aroma volatiles in Jonagold apple during storage. *V International Postharvest Symposium*, 682, pp.1203–1210

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	12.5 – 16.7% reduction of the energy use for the whole store
Quality of scope 2 emissions information	H
Availability barriers	L
TRL level	TRL 8-9
Maintainability issues	-
Legislative concerns	Legally registered in EU for most crops
Payback time (years)	1MCP is a yearly quality treatment with energy saving effects, not an investment

9.24 Refrigerants

For larger low temperature refrigeration systems such as those used in food cold stores, the use of natural refrigerants (ammonia R717 with a GWP of 0 and to a lesser extent carbon dioxide R744 with a GWP of 1 in the low temperature circuit of a cascade) has largely replaced previously widespread use of fluorinated refrigerants. Emissions are therefore related much more to energy efficiency than leakage.

The general performance of some of these refrigerants were indicated as COPs by IOR[143] (**Error! Reference source not found.**).

[143] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

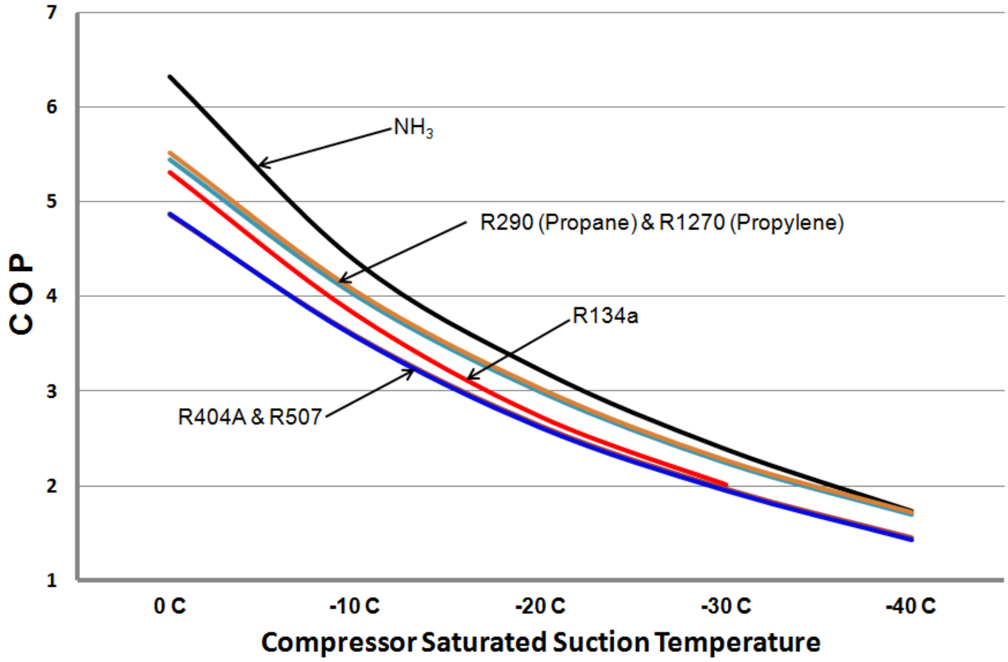

Figure 36. Typical system COPs at 30°C condensing temperature.

IOR[144] also confirms that for larger frozen and chilled stores, the use of ammonia is typical, either delivered directly to evaporators or used to cool a secondary refrigerant such as glycol and more recently carbon dioxide (the latter typically in chilled stores). Ammonia is the refrigerant of choice for maximising system efficiency and reducing operational costs and therefore the total cost of ownership of such large stores. In addition, R717 is environmentally benign.

NH_3 systems were compared with NH_3/CO_2 cascades and trans-critical CO_2 systems by using mathematical modelling.[145] Two-stage NH_3 was more efficient than trans-critical CO_2 at all ambient temperatures but particularly in warmer climates, with trans-critical CO_2 using 5% more energy in Stockholm and up to 30% more in Rome. Cascades used typically 5% more energy than two stage NH_3. R507 was included for comparison and a two-stage system was roughly similar in consumption to the trans-critical CO_2.

Arguably use of NH_3 is the industry standard, but Pearson 2014 provided useful advice on CO_2 as an alternative in the IIR Guide 'CO_2 as a refrigerant'. More typically used in food retail systems, CO_2 is also used in cold storage, particularly where the ammonia charge needs to be minimised. It can be used as a secondary refrigerant, or as the low temperature circuit of a

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[144] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

[145] Lund, T., Skovrup, M.J. and Holst, M., 2019. Comparing energy consumption and life cycle costs of industrial size refrigeration systems. *25th IIR International Congress of Refrigeration*, Montréal, Canada. https://doi.org/10.18462/iir.icr.2019.0947

cascade system. The energy efficiency of these systems was questioned, with the suggestion that a cascade carbon dioxide system efficiency will be slightly less efficient than a two stage NH_3 system, but slightly better than a single stage economised system.

An interesting early application of CO_2 for cold stores in Australia was described by Bellstedt et al.[146] Special design considerations were presented, along with experience in charging and commissioning the plants, and equipment failures which occurred in operation. Although the environmental credentials of the refrigerant itself was emphasized, no data on energy consumption was included.

Scope 1 emissions savings (% or another quantifiable metric)	Use of low GWP natural refrigerants is already commonplace, but if replacing older synthetic refrigerant systems there would be large savings in direct emissions.
Quality of scope 1 emissions information	H
Scope 2 emissions savings (% or another quantifiable metric)	If not already using NH_3, energy consumption savings could be achieved. These vary depending on the local ambient temperatures, ranging from 5% in colder European locations to 30% in warmer locations compared to R744.
Quality of scope 2 emissions information	H but limited number of studies.
Availability barriers	None, but safety and cost are factors to consider.
TRL level	8-9
Maintainability issues	Higher engineering standards are required for NH_3 and CO_2 systems, and it is logical to assume that this may translate into lower maintenance requirements.
Legislative concerns	None.
Payback time (years)	Not clear from the sources found.

146 Bellstedt, M., Elefsen, F. and Jensen, S.S., 2002. Application of CO_2 (R744) refrigerant in industrial cold storage plant. *EcoLibrium*, 1(5), pp.25–30

9.25 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.[147] 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.[148] 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.[149] 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.[139] Adding onsite solar PV system can achieve net-zero energy design for the retail building.[150] Burek and Nutter[139] 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

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[147] Monforti-Ferrario, F., Dallemand, J.-F., Pinedo Pascua, I., Motola, V., Banja, M., Scarlat, N., Medarac, H., Castellazzi, L., Labanca, N., Bertoldi, P., Pennington, D., Goralczyk, M., Schau, E.M., Saouter, E., Sala, S., Notarnicola, B., Tassielli, G. and Renzulli, P., 2015. *Energy use in the EU food sector: State of play and opportunities for improvement*. EUR 27247 EN. Luxembourg: Publications Office of the European Union. Available at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC96121/ldna27247enn.pdf

[148] European Commission., 2022. *EU Solar Energy Strategy*. COM(2022) 221 final. Brussels: European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0221

[149] Burek, J. and Nutter, D.W., 2019. A life cycle assessment-based multi-objective optimization of the purchased, solar, and wind energy for the grocery, perishables, and general merchandise multi-facility distribution center network. *Applied Energy*, 235, pp.1427–1446. https://doi.org/10.1016/j.apenergy.2018.11.042

[150] Syed, A.M. and Hachem, C., 2019. Net-zero energy design and energy sharing potential of retail-greenhouse complex. *Journal of Building Engineering*, 24, p.100736. https://doi.org/10.1016/j.jobe.2019.100736

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.[151]

According to Jiang and Tovey,[152] 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.[153] 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.[154] 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.[155] If the increase in future cold storage capacity were to come

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[151] Monforti-Ferrario, F., Dallemand, J.-F., Pinedo Pascua, I., Motola, V., Banja, M., Scarlat, N., Medarac, H., Castellazzi, L., Labanca, N., Bertoldi, P., Pennington, D., Goralczyk, M., Schau, E.M., Saouter, E., Sala, S., Notarnicola, B., Tassielli, G. and Renzulli, P., 2015. *Energy use in the EU food sector: State of play and opportunities for improvement*. EUR 27247 EN. Luxembourg: Publications Office of the European Union. Available at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC96121/ldna27247enn.pdf

[152] Jiang, P. and Tovey, N.K., 2009. Opportunities for low carbon sustainability in large commercial buildings in China. *Energy Policy*, 37(11), pp.4949–4958. https://doi.org/10.1016/j.enpol.2009.06.059

[153] Ferreira, A., Pinheiro, M.D., de Brito, J. and Mateus, R., 2018. Combined carbon and energy intensity benchmarks for sustainable retail stores. *Energy*, 165, pp.877–889. https://doi.org/10.1016/j.energy.2018.10.020

[154] Sovacool, B.K., Bazilian, M., Griffiths, S., Kim, J., Foley, A. and Rooney, D., 2021. Decarbonizing the food and beverages industry: a critical and systematic review of developments, sociotechnical systems and policy options. *Renewable and Sustainable Energy Reviews*, 143, p.110856

[155] Tubiello, F.N., Rosenzweig, C., Conchedda, G., Karl, K., Gütschow, J., Xueyao, P., Obli-Laryea, G., Wanner, N., Qiu, S.Y., Barros, J.D., Flammini, A., Mencos-Contreras, E., Souza, L., Quadrelli, R., Heiðarsdóttir, H.H., Benoit, P., Hayek, M. and Sandalow, D., 2021. Greenhouse gas emissions from food systems: building the evidence base. *Environmental Research Letters*, 16(6), p.065007. https://doi.org/10.1088/1748-9326/ac018e

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.[156] 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.[157] 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.[158] 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_2e/m^2/y, with "best practice" threshold found below 115 kWh/m^2/y. Non-food retailers' "conventional practice" ranged from 70 to 177 kg CO_2e/m^2/y, with "best practice" threshold found below 70 kWh/m^2/y. Electricity can be responsible for up to 60% of the carbon emissions in food retailers.[148]

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

[156] IRENA and FAO., 2021. *Renewable energy and agri-food systems: Advancing energy and food security towards sustainable development goals*. Abu Dhabi and Rome: International Renewable Energy Agency and Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cb7433en

[157] Yıldız, G., Ağbulut, Ü. and Gürel, A.E., 2021. A review of stability, thermophysical properties and impact of using nanofluids on the performance of refrigeration systems. *International Journal of Refrigeration*, 129, pp.342–364. https://doi.org/10.1016/j.ijrefrig.2021.05.016

[158] Ferreira, A., Pinheiro, M.D., de Brito, J. and Mateus, R., 2018. Combined carbon and energy intensity benchmarks for sustainable retail stores. *Energy*, 165, pp.877–889. https://doi.org/10.1016/j.energy.2018.10.020

surface of about 20,000 m^2 while the second has a total surface of 4830 m^2. In the first case the size of the PV plant can range from a minimum value of less than 500 up to 2100 kW, while in the local store, the PV plant size ranges from 80 to 320 kW. In both the cases, the share of the energy produced with the PV plant moved from about 20 up to 70%, if a storage system of relevant size was used. The energy storage could be interesting both to use the energy in excess produced during the day and it can also help with the fluctuating energy supply and demand. In all the cases considered it was possible to use the roof surface of the store for installation of the PV plant. In general, it appears to be quite easy to define a PV plant that could be able to produce energy for the seasonal peak and covering an amount of the energy required for the whole year in the range between 40 and 60% of the total yearly energy required.[159] Sovacool et al.[160] 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 combined heat and power (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.[161]

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

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[159] Franco, A. and Cillari, G., 2021. Energy sustainability of food stores and supermarkets through the installation of PV integrated plants. *Energies*, 14(18), p.5678. https://doi.org/10.3390/en14185678

[160] Sovacool, B.K., Bazilian, M., Griffiths, S., Kim, J., Foley, A. and Rooney, D., 2021. Decarbonizing the food and beverages industry: a critical and systematic review of developments, sociotechnical systems and policy options. *Renewable and Sustainable Energy Reviews*, 143, p.110856

[161] Caritte, V., Acha, S. and Shah, N., 2013. Enhancing corporate environmental performance through reporting and roadmaps. *Business Strategy and the Environment*, 24(5), pp.289–308. https://doi.org/10.1002/bse.1818

approach.[162] Main barriers for the adoption of the described practices can be summarized as follows[152]):

– 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.[163]

Presently, the renewable energy systems (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.

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[162] Galvez-Martos, J.-L., Styles, D. and Schoenberger, H., 2013. Identified best environmental management practices to improve the energy performance of the retail trade sector in Europe. *Energy Policy*, 63, pp.982–994. https://doi.org/10.1016/j.enpol.2013.08.061

[163] Naidoo, M. and Gasparatos, A., 2018. Corporate environmental sustainability in the retail sector: drivers, strategies and performance measurement. *Journal of Cleaner Production*, 203, pp.125–142

There is significant progress in roof mounted photovoltaic systems powering conventional vapour compression refrigerating units.[164]

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.[165]

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.[166]

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,

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[164] Fikiin, K., Stankov, B., Tsvetkov, T., Popov, D., and Tsvetkova, E., 2017. Refrigerated warehouses as intelligent hubs to integrate renewable energy in industrial food refrigeration and to enhance power grid sustainability. *Trends in Food Science & Technology*, 60, pp.96–103. https://doi.org/10.1016/j.tifs.2016.11.011

[165] ARENA (Australia Renewable Energy Agency), 2022. Advanced control and forecasting algorithm (ACFA) for thermal energy storage at a winery – case study. *University of South Australia*. Available at: https://arena.gov.au/projects/acfa-winery-case-study

[166] Meneghetti, A., Dal Magro, F. and Simeoni, P., 2018. Fostering renewables into the cold chain: how photovoltaics affect design and performance of refrigerated automated warehouses. *Energies*, 11(5), p.1029. https://doi.org/10.3390/en11051029

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.[167]

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}.

[167] Xia, M., Yuan, Y., Zhao, X., Cao, X. and Tang, Z., 2016. Cold storage condensation heat recovery system with a novel composite phase change material. *Applied Energy*, 175, pp.259–268. https://doi.org/10.1016/j.apenergy.2016.05.001

	Brussels, 18.5.2022. COM 221 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN[168]
Payback time (years)	Dependent on technological solution and electricity prices. Typically (without financial support instruments) 13.7 years.

9.26 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.[157]

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.[169]

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[168] European Commission., 2022. *EU Solar Energy Strategy*. COM(2022) 221 final. Brussels: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 18 May. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN

[169] Ferreira, A., Pinheiro, M.D., de Brito, J. and Mateus, R., 2018. Combined carbon and energy intensity benchmarks for sustainable retail stores. *Energy*, 165, pp.877–889. https://doi.org/10.1016/j.energy.2018.10.020

Mekhilef et al.[170] 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.[171] 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.[172]

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

[170] Mekhilef, S., Saidur, R. and Safari, A., 2011. A review on solar energy use in industries. *Renewable and Sustainable Energy Reviews*, 15(4), pp.1777–1790. https://doi.org/10.1016/j.rser.2010.12.018

[171] Sovacool, B.K., Bazilian, M., Griffiths, S., Kim, J., Foley, A. and Rooney, D., 2021. Decarbonizing the food and beverages industry: a critical and systematic review of developments, sociotechnical systems and policy options. *Renewable and Sustainable Energy Reviews*, 143, p.110856

[172] CNI (Confederación Nacional de Instaladores y Mantenedores)., 2022. *La energía del presente y del futuro: Bomba de calor ambiente con apoyo de energía solar fotovoltaica*. Madrid: CNI. Available at: https://www.cni-instaladores.com/cni-publica-un-nuevo-documento-tecnico-la-energia-del-presente-y-del-futuro-bomba-de-calor-ambiente-con-apoyo-de-energia-solar-fotovoltaica

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 221 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN[173]
Payback time (years)	Dependent on solution, heat prices and geographical location. 2-4 up to 46 years.

9.27 Stacking patterns

Numerous investigations have been carried out to examine the airflow and heat transfer properties within and between pallets of stacked foods in various stages of cold chain operations, including cold storage. Firstly, these investigations have facilitated a deeper understanding of the diverse phenomena occurring within refrigerated storage units. Secondly, they have enabled the evaluation of cooling rates and uniformity within cooling rooms, as well as the assessment of the impact of various factors on cooling and product quality. Extensive research has been dedicated to exploring factors such as package design (vent area, shape, number, position, etc.), stacking patterns of food items within packages, and package stacking patterns on pallets. Given that packages serve vital functions in containing, protecting, preserving, storing, and distributing food, this subject has garnered significant attention over the past decade. Experimental and numerical studies have been conducted on various scales, ranging from entire cooling facilities to individual pallets or even the scale of a corrugated tray. The primary emphasis of most studies has been on analysing airflow characteristics, as well as cooling and storage performance.[174]

Stacking patterns of vented boxes on a pallet are determinant for the airflow rate through the pallet. This in turn will determine the cooling rate and uniformity of cooling and storage.

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[173] European Commission., 2022. *EU Solar Energy Strategy*. COM(2022) 221 final. Brussels: European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0221

[174] Nasser Eddine, A., Duret, S. and Moureh, J., 2022. Interactions between package design, airflow, heat and mass transfer, and logistics in cold chain facilities for horticultural products. *Energies*, 15(22), p.8659. https://doi.org/10.3390/en15228659

Quantifying the cooling time and rate is particularly relevant for precooling, as this determines how fast the field heat can be removed.[175] These quantities do not only affect product quality and shelf life, but also the actual time the precooling equipment needs to run, and thus the related operational costs and total product throughput. Product cooling is usually evaluated by the fractional unaccomplished temperature change, a dimensionless quantity which is determined from the temperature-time profile of the internal product temperature, taking into account the initial and cooling air temperature. The cooling time is evaluated based on this dimensionless cooling curve by determining the half cooling time (HCT) or seven-eighths cooling time (SECT). The spread on the cooling time (e.g., the standard deviation on the SECT) between individual products in a box, pallet or container can be used to reflect the heterogeneity at the packaging scale of interest.

In this context, it is also important to consider the size, dimensions and alignment of vent holes in the stack, to create pathways for the airflow that will remove the heat from the food. The total open area percentage (TOA [%]) is frequently used in guidelines on packaging design as a measure for the ventilation potential.[164] It is the amount of vent area relative to the total area of that specific side of the box. More detailed vent opening characteristics, such as size, shape, number and location, are inherently related to the TOA. The TOA is often correlated to the flow resistance of the box (pressure drop) and the related energy efficiency. Preferential airflow pathways, where air bypasses the produce, can occur due to improper stacking, the package design itself or inadequate sealing of gaps such as head space below ventilator units creating shortcuts for airflow not reaching the product. Also, packages of some foods are not entirely filled to the top, by which a distinct headspace is present. Such airflow bypass is not necessarily negative as this can imply that colder air reaches the boxes more downstream, which can improve cooling uniformity between boxes.

The energy required for fan operation and for removing the heat they produce is substantial: [164] (1) during forced-air cooling, it can nearly equal the amount of energy needed for cooling the fruit; (2) during long-term storage, alternative on-off cycles and fan frequency control strategies are considered to reduce energy costs. Fan energy consumption can be minimised by reducing the required fan power, by reducing the time needed to maintain this airflow and by increasing fan efficiency and stacking have been put forward as key factors to improve fan energy consumption. The aerodynamic (airflow) resistance of the produce-packaging system is expressed as the relation between the total pressure drop over the packaging and the volumetric airflow rate through it. It typically follows a quadratic relationship. The required power to move air through the package is equal to the product of pressure drop and airflow rate, thereby creating a 3rd power relationship. Combining the resulting operational conditions with fan and motor efficiencies, allows to determine the power consumption. Multiplied with

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[175] Defraeye, T., Lambrecht, R., Tsige, A.A., Derens, E., Nicometo, M. and Opara, U.L., 2015. Towards integrated performance evaluation of future packaging for fresh produce in the cold chain. *Trends in Food Science & Technology*, 44(2), pp.201–225. https://doi.org/10.1016/j.tifs.2015.04.008

cooling time, the total energy consumption related to airflow through a package/stacking can be obtained. This energy consumption can be related to the net energy needed to remove heat from the product as to obtain a coefficient of performance of the system.

A comparison of energy consumption of two alternative box designs for citrus fruit during precooling was made.[176] The energy required to force airflow through the boxes until the SECT is reached as a function of airflow rate was assessed. For the same airflow rate of 1 L/(s kg), the net energy use for ventilation was almost 1 order of magnitude lower (90%) for a more optimal design with a more connected vent hole distribution compared to a standard package design with suboptimal vent hole design due to significant cooling time savings. Cooling uniformity was also found more uniform. The same flow rate level could be achieved in the new package with a reduced fan power at the same efficiency by a lowered rotation speed adding additional savings. On the other hand, if the rotation speed is not adapted which often the case in practice, the fan power of the more ventilated package is likely to be higher due the operation at a higher flow rate (due to the lower airflow resistance, and the 3rd power relationship) and a potentially lower fan efficiency. If the gain in cooling time is then only small, there will be no net energy savings possible, on the contrary. A careful trade-off between the different factors needs to be considered when designing packaging/stacking and fan systems. Thereto, simulation approaches based on Computational Fluid Dynamics have been advocated.[165]

Scope 1/3 emissions savings (% or another quantifiable metric)	More uniform cooling leading to lower quality and eventually food losses. Highly product and case dependent.
Quality of scope 1/3 emissions information	Experimental studies in laboratory.
Scope 2 emissions savings (% or another quantifiable metric)	Up to 90% energy savings on fan operation by a more optimal stacking to remove heat from product more efficiently and uniformly, if • Lowering rotation speed to achieve the same flow rate is possible • Fan operation times reduce significantly to achieve the same cooling time
Quality of scope 2 emissions information	Computational studies in peer reviewed journal articles.

[176] Defraeye, T., Lambrecht, R., Tsige, A.A., Derens, E., Nicometo, M. and Opara, U.L., 2015. Towards integrated performance evaluation of future packaging for fresh produce in the cold chain. *Trends in Food Science & Technology*, 44(2), pp.201–225. https://doi.org/10.1016/j.tifs.2015.04.008

Availability barriers	Case by case evaluation needed. Tools (such as CFD) for optimization available.
TRL level	5-9, depending at what stage the optimization study is executed
Maintainability issues	-
Legislative concerns	-
Payback time (years)	-

9.28 Temperature control set points

In setting the temperatures which cold store refrigeration systems are trying to maintain, it is important to consider at what temperature the desired retention of food quality and safety will be achieved, but care should be taken not to set temperatures colder than necessary. The efficiency of refrigeration systems reduces at lower temperatures, as reflected by reducing Coefficients of Performance (COPs).

While the exact reduction will vary depending on the design and use of the store, various sources have provided 'rules of thumb' for typical impact on energy consumption. For example, advice from a major refrigeration system installer:

https://www.star-ref.co.uk/smart-thinking/minimising-cold-chill-storage-energy-consumption-and-carbon-emissions/

includes a general rule of thumb that every 1K increase in room temperature will result in a 2% to 3% improvement in the energy efficiency of the plant. Similarly, Evans et al.[177] presented the same advice in reverse, i.e., a cold store operating 1°C too low will use 2–3% extra power. A higher typical figure was reported by Cold Chain Federation[178], who suggested that a 1°C raise in cold store temperature set point will typically reduce the power consumption by 5%. It is possible that the higher figure reflects experience with lower temperature frozen stores, or possibly with a range of older as well as new cold stores.

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177 Evans, J.A., Foster, A.M., Huet, J.-M., Reinholdt, L., Fikiin, K., Zilio, C., Houska, M., Landfeld, A., Bond, C., Scheurs, M. and Van Sambeeck, T.W.M., 2014. Specific energy consumption values for various refrigerated food cold stores. *Energy and Buildings*, 74, pp.141–151. https://doi.org/10.1016/j.enbuild.2014.01.019

178 Cold Chain Federation., 2020. *Energy efficiency in cold stores: a practical guide*. Cold Chain Federation. Available at: https://www.coldchainfederation.org.uk/download/energy-efficiency-in-cold-stores-a-practical-guide/

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)	Various rules of thumb suggest between 2 and 5% energy reduction for each 1K rise in set point.
Quality of scope 2 emissions information	Medium, the figures suggested lack measured data to back them up.
Availability barriers	None
TRL level	8-9
Maintainability issues	None
Legislative concerns	None (bearing in mind food safety and quality requirements)
Payback time (years)	If a simple controller adjustment is made, payback is immediate.

9.29 Underfloor heating

Underfloor heating needs to be taken into account when undertaking a heat load calculation. The minimum requirement for cold room floors under 0°C is a dual-circuit low-voltage thermostatically controlled electric heater mat installed above the base slab. The heater mat shall have sufficient capacity (e.g., $15W/m_2$) to offset the thermal losses through the floor insulation and be capable of removing condensation under all conditions.[179]

The most common heater mat designs allow for either electrical or warm glycol systems incorporated immediately above the base slab and laid in a cement screed. However, some stores are built with air heater mats which can either be constructed with air pipes laid in the sub-base below the base slab or alternatively the floor of the store can be suspended with a structural base

[179] AIRAH., 2020. *DA12: Energy efficiency in cold rooms*. Design Application Manual, 73pp. Australian Institute of Refrigeration, Air Conditioning and Heating. Access may require AIRAH membership or login. Available at: https://www.airah.org.au/site/resources/da-manuals

provided by concrete beams suspended between sleeper walls allowing a free flow of ambient air under the whole store floor area.[180]

Under-floor heating can be a use for reclaimed heat, for example from compressors and condensers, particularly as duties are low and temperatures required to prevent floor damage are typically only 10 to 15°C.[181]

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	No data
Quality of scope 2 emissions information	L
Availability barriers	None
TRL level	8-9
Maintainability issues	None
Legislative concerns	None
Payback time (years)	No data

9.30 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

[180] Institute of Refrigeration., 2020. *Cold store code of practice*. London: Institute of Refrigeration. ISBN 1 872719 36 8. Available at: https://www.ior.org.uk

[181] Stoecker, W.F., 1998. *Industrial refrigeration handbook*. New York: McGraw-Hill. ISBN 9780070616233

Organization of the United Nations[182] report, about 33% of human food, totalling about 1.3 billion tonnes annually, is wasted worldwide, which has a production value of $750 billion.[183] [184] [182] 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.[173] Food waste (FW) occurs at all stages of the food supply chain, including agricultural processing, sorting, storage, transport, distribution, sale, preparation and serving.[185] 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.[186] Analysing 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.[187] [182]

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.[173] [172] Slorach et al.[188] reported that globally, food waste accounts for 6.7% of all anthropogenic GHG emissions annually.

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[182] FAO (Food and Agriculture Organization of the United Nations)., 2019. *The State of Food and Agriculture 2019: Moving forward on food loss and waste reduction*. Rome: FAO. Available at: https://www.fao.org/3/ca6030en/ca6030en.pdf

[183] Pramanik, S.K., Suja, F.B., Zain, S.M. and Pramanik, B.K., 2019. The anaerobic digestion process of biogas production from food waste: prospects and constraints. *Bioresource Technology Reports*, 8, p.100310. https://doi.org/10.1016/j.biteb.2019.100310

[184] Mirmohamadsadeghi, S., Karimi, K., Tabatabaei, M. and Aghbashlo, M., 2019. Biogas production from food wastes: a review on recent developments and future perspectives. *Bioresource Technology Reports*, 7, p.100202

[185] Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., & Meybeck, A. (2011). *Global food losses and food waste: Extent, causes and prevention*. Food and Agriculture Organization of the United Nations (FAO).

[186] Stenmarck, A., Jensen, C., Quested, T., Moates, G., Buksti, M., Cseh, B., Juul, S., Parry, A., Politano, A. and Redlingshofer, B., 2016. Estimates of European food waste levels. *IVL Swedish Environmental Research Institute*, p.80

[187] Monforti-Ferrario, F., Dallemand, J.-F., Pinedo Pascua, I., Motola, V., Banja, M., Scarlat, N., Medarac, H., Castellazzi, L., Labanca, N., Bertoldi, P., Pennington, D., Goralczyk, M., Schau, E.M., Saouter, E., Sala, S., Notarnicola, B., Tassielli, G. and Renzulli, P., 2015. *Energy use in the EU food sector: State of play and opportunities for improvement*. EUR 27247 EN. Luxembourg: Publications Office of the European Union. Available at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC96121/ldna27247enn.pdf

[188] Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R. and Azapagic, A., 2019. Environmental sustainability of anaerobic digestion of household food waste. *Journal of Environmental Management*, 236, pp.798–814. https://doi.org/10.1016/j.jenvman.2019.02.001

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.[189] [190] [191] [192] [193] [194]

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.[181] 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.[179] 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.[181]

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

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[189] Chew, K.R. et al., 2021. Effects of anaerobic digestion of food waste on biogas production and environmental impacts: a review. *Environmental Chemistry Letters*, 19(4), pp.2921–2939. https://doi.org/10.1007/s10311-021-01220-z

[190] Eriksson, M., Strid, I. and Hansson, P.-A., 2015. Carbon footprint of food waste management options in the waste hierarchy – a Swedish case study. *Journal of Cleaner Production*, 93, pp.115–125. https://doi.org/10.1016/j.jclepro.2015.01.026

[191] Mirmohamadsadeghi, S., Karimi, K., Tabatabaei, M. and Aghbashlo, M., 2019. Biogas production from food wastes: a review on recent developments and future perspectives. *Bioresource Technology Reports*, 7, p.100202

[192] Mondello, G., Salomone, R., Ioppolo, G., Saija, G., Sparacia, S. and Lucchetti, M., 2017. Comparative LCA of alternative scenarios for waste treatment: the case of food waste production by the mass-retail sector. *Sustainability*, 9(5), p.827. https://doi.org/10.3390/su9050827

[193] Moult, J.A., Allan, S.R., Hewitt, C.N. and Berners-Lee, M., 2018. Greenhouse gas emissions of food waste disposal options for UK retailers. *Food Policy*, 77, pp.50–58. https://doi.org/10.1016/j.foodpol.2018.04.003

[194] Pramanik, S.K., Suja, F.B., Zain, S.M. and Pramanik, B.K., 2019. The anaerobic digestion process of biogas production from food waste: prospects and constraints. *Bioresource Technology Reports*, 8, p.100310. https://doi.org/10.1016/j.biteb.2019.100310

impacts, including volatile GHG emissions, eutrophication, acidification, and the generation of photochemical oxidants.[195] [196] [197] [198] [199] [200].

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)	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

[195] Albizzati, P.F., Tonini, D. and Astrup, T.F., 2021. A quantitative sustainability assessment of food waste management in the European Union. *Environmental Science & Technology*, 55(23), pp.16099–16109. https://doi.org/10.1021/acs.est.1c03940

[196] Chew, K.R. et al., 2021. Effects of anaerobic digestion of food waste on biogas production and environmental impacts: a review. *Environmental Chemistry Letters*, 19(4), pp.2921–2939. https://doi.org/10.1007/s10311-021-01220-z

[197] Eriksson, M., Strid, I. and Hansson, P.-A., 2015. Carbon footprint of food waste management options in the waste hierarchy – a Swedish case study. *Journal of Cleaner Production*, 93, pp.115–125. https://doi.org/10.1016/j.jclepro.2015.01.026

[198] Mondello, G., Salomone, R., Ioppolo, G., Saija, G., Sparacia, S. and Lucchetti, M., 2017. Comparative LCA of alternative scenarios for waste treatment: the case of food waste production by the mass-retail sector. *Sustainability*, 9(5), p.827. https://doi.org/10.3390/su9050827

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[200] Vandermeersch, T., Alvarenga, R.A.F., Ragaert, P. and Dewulf, J., 2014. Environmental sustainability assessment of food waste valorization options. *Resources, Conservation and Recycling*, 87, pp.57–64. https://doi.org/10.1016/j.resconrec.2014.03.008

Payback time (years)	Dependent on solution. e.g., 1 MW plant pawer payback time is 3.2–4.8 years.

([201] [202] [203] [204] [205] [206] [207] [208])

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.[209] [210] This organic-rich product is used as a natural fertilizer in the

[201] Albizzati, P.F., Tonini, D. and Astrup, T.F., 2021. A quantitative sustainability assessment of food waste management in the European Union. *Environmental Science & Technology*, 55(23), pp.16099–16109. https://doi.org/10.1021/acs.est.1c03940

[202] Benato, A. and Macor, A., 2019. Italian biogas plants: trend, subsidies, cost, biogas composition and engine emissions. *Energies*, 12(6), p.979. https://doi.org/10.3390/en12060979

[203] De Clercq, D. et al., 2017. A review of global strategies promoting the conversion of food waste to bioenergy via anaerobic digestion. *Renewable and Sustainable Energy Reviews*, 79, pp.204–221. https://doi.org/10.1016/j.rser.2017.05.047

[204] Goodman-Smith, F., Mirosa, M. and Skeaff, S., 2020. A mixed-methods study of retail food waste in New Zealand. *Food Policy*, 92, p.101845. https://doi.org/10.1016/j.foodpol.2020.101845

[205] Mirmohamadsadeghi, S., Karimi, K., Tabatabaei, M. and Aghbashlo, M., 2019. Biogas production from food wastes: a review on recent developments and future perspectives. *Bioresource Technology Reports*, 7, p.100202

[206] Mondello, G., Salomone, R., Ioppolo, G., Saija, G., Sparacia, S. and Lucchetti, M., 2017. Comparative LCA of alternative scenarios for waste treatment: the case of food waste production by the mass-retail sector. *Sustainability*, 9(5), p.827. https://doi.org/10.3390/su9050827

[207] Moult, J.A., Allan, S.R., Hewitt, C.N. and Berners-Lee, M., 2018. Greenhouse gas emissions of food waste disposal options for UK retailers. *Food Policy*, 77, pp.50–58. https://doi.org/10.1016/j.foodpol.2018.04.003

[208] Pramanik, S.K., Suja, F.B., Zain, S.M. and Pramanik, B.K., 2019. The anaerobic digestion process of biogas production from food waste: prospects and constraints. *Bioresource Technology Reports*, 8, p.100310. https://doi.org/10.1016/j.biteb.2019.100310

[209] Palaniveloo, K. et al., 2020. Food waste composting and microbial community structure profiling. *Processes*, 8(6), p.723. https://doi.org/10.3390/pr8060723

[210] Rastogi, M., Nandal, M. and Khosla, B., 2020. Microbes as vital additives for solid waste composting. *Heliyon*, 6(2)

agricultural sector because it has a positive effect on the soil and the environment, thanks to its high fibre content and inorganic nutrients.[211] [212]

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.[202] 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.[213] [202] 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.[214] [202]

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

[211] Mondal, S. & Palit, D., 2019. Effective Role of Microorganism in Waste Management and Environmental Sustainability. In: *Sustainable Agriculture, Forest and Environmental Management*. Springer, Singapore, pp. 485–515. https://doi.org/10.1007/978-981-13-6830-1_14

[212] Palaniveloo, K. et al., 2020. Food waste composting and microbial community structure profiling. *Processes*, 8(6), p.723. https://doi.org/10.3390/pr8060723

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[214] Favoino, E. and Hogg, D., 2008. Effects of composted organic waste on ecosystems – a specific angle: the potential contribution of biowaste to tackle climate change and references to the soil policy. *Compost and Digestate: Sustainability, Benefits, Impacts for the Environment and for Plant Production*, 27, pp.29

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.

([215] [216] [217]).

[215] Albizzati, P.F., Tonini, D. and Astrup, T.F., 2021. A quantitative sustainability assessment of food waste management in the European Union. *Environmental Science & Technology*, 55(23), pp.16099–16109. https://doi.org/10.1021/acs.est.1c03940

[216] Chen, Y.T., 2016. A cost analysis of food waste composting in Taiwan. *Sustainability*, 8(11), p.1210

[217] Moult, J.A., Allan, S.R., Hewitt, C.N. and Berners-Lee, M., 2018. Greenhouse gas emissions of food waste disposal options for UK retailers. *Food Policy*, 77, pp.50–58. https://doi.org/10.1016/j.foodpol.2018.04.003

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11 mathematical modelling of cold stores

11.1 Cold store model

The model described in Foster et al., 2016 [218] was applied. The model is a user-friendly tool that allows cold store operators to predict the energy consumption as heat loads vary due to changes in ambient conditions and store usage patterns. Weather data and construction and usage details are used to predict heat load and refrigeration COP on an hourly basis over a whole year. The model was validated against the industry standard CoolPack model and the features of the two models were compared. The model identified which cold store features and operating parameters have the greatest impact on energy consumption and assess the scope for measures aimed at reducing it.

11.2 Model inputs

The model inputs for the cold store modelled is shown in Table 13.

11.2.1 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. To simulate the baseline stores based on real data, the weather files associated with London and Aberdeen, where the stores were located were applied.

Table 13. Attributes of case cold stores.

Parameter	Chilled store	Frozen store
Geometry		
Wall surface area (N, E, W, S) (m^2)	643.5, 748.0, 748.0, 643.5	1240, 490, 490, 1240
Foor and ceiling surface area (m^2)	3978	6076
Shaded from sun	Yes	No
Is floor temperature controlled (control temperature)	No	Yes (-17°C)
Entrance		
Width of door m	2.34	2.4
Height of door m	4	4
Internal or external door	External	External

[218] Foster, A.M., Reinholdt, L.O., Brown, T., Hammond, E.C. And Evans, J.A. (2016) Reducing energy consumption in cold stores using a freely available mathematical model. Sustainable Cities and Society. Volume 21, February 2016, Pages 26–34

Parameter	Chilled store	Frozen store
Door openings per day	144	20
Duration of each opening (s)	60	15
Volume of traffic passing through the door	Low	Medium
Door protection	No protection	Strip curtain
Door seal condition	Good	Medium
Refrigeration		
Store temperature (°C)	3	-18.2
Refrigerant	R134a	R717
Internal or external condenser	External temperature from weather data	External temperature from weather data
Number of expansion stages	1	1
Isentropic efficiency of compressor	Medium (0.6)	Low (0.5)
Insulation		
Type of insulation (wall, floor and ceiling)	Polyurethane foam	Polyurethane foam
Thickness of insulation (wall, floor and roof) (mm)	100,100,100	150, 0, 150
Forklifts		
Number	3	2
Size	Medium	Medium
Power source	Electric	Electric
Operation time (h/day)	13	10
Lights		
Operation time (h/day)	24	24
Lux (lm/m^2)	947	100
Efficacy (m/W)	80	100
Personnel		
Number	8	2
Time (h/day)	16	1

Parameter	Chilled store	Frozen store
Time in store	Long	Short
Product		
Mass loaded (tonnes/day)	250	50
Temperature when loaded (°C)	6	-16
Total mass in store (tonnes)	500	40,000
Product type	Yogurt (flavoured)	Carrot
Weight loss (tonnes/day)	2.5	3288
Defrost		
Type	Electric	Electric
Evaporator fans		
Number	27	7
Shaft power (W)	667	4000
Motors inside refrigerated space	Yes	Yes
Motor efficiency	32.5%	85
Condenser fans		
Energy ratio (maximum rejected heated /condenser power)	30 (D/E efficiency rating)	30 (D/E efficiency rating)
Minimum condensing temperature (°C)	21	21
Temperature difference between condensing temperature and air onto condenser (ambient temperature) (K)	15	15
Fan control type	On/off	On/off
Other heat loads		
Other heat loads average power (kW)	19.9	19.9
Weather files		
Weather files for period 2007-2021.	London-Gatwick, Aberdeen	London-Gatwick, Aberdeen

11.3 Total equivalent warming impact (TEWI)

TEWI characterizes CO_2 emissions and is a useful tool to study the impact of cold store systems on global warming. The TEWI combines the direct and indirect emissions of CO_2. For any system, TEWI is based on the following relation:

$$TEWI = (GWP \times m \times L \times n) + [GWP \times m \times (1 - \alpha)] + (E \times \beta \times n) \qquad \text{(eq. 1)}$$

Where TEWI is quantity of CO_2 produced during the life time of the equipment (kg); (GWP×m×L×n) are direct emissions of CO_2 due to refrigerant leakage; [GWP×m×(1-α)] are direct emissions of CO_2 related to refrigerant losses at the end of the system's life; (E×β×n) are indirect emissions of CO_2 associated with electrical energy consumption; GWP is the Global Warming Potential of refrigerant; m is the Refrigerant charge (kg); L is the proportion of total charge, m, leaked per year; n is the System operating life (years); α is the Recovery/recycling factor (0 to 1); E is the electrical energy consumption per year (kWh/year); β is the electrical emission factor (kg CO_2/kWh).

11.4 Bibliography for modelling

Foster, A.M., Reinholdt, L.O., Brown, T., Hammond, E.C. And Evans, J.A. (2016) Reducing energy consumption in cold stores using a freely available mathematical model. Sustainable Cities and Society. Volume 21, February 2016, Pages 26–34 was applied.