shecco

ENVIRONMENTAL INVESTIGATION AGENCY

Climate

Technical report on energy efficiency in HFC-free supermarket refrigeration

For the project Global Corporate and Policy Measures to Incentivise Highly Efficient HFC-Free Cooling

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ABOUT shecco

shecco is a global market accelerator helping its partners in the heating, air conditioning and refrigeration sectors bring their innovative solutions faster to the market. We specialise in integrated services and products to advance the use of the five natural refrigerants carbon dioxide (CO_2), ammonia (NH_3), hydrocarbons (HC), water and air. Our portfolio comprises activities in three areas: media, events and market development.

ABOUT EIA

We investigate and campaign against environmental crime and abuse.

Our undercover investigations expose transnational wildlife crime, with a focus on elephants and tigers, and forest crimes such as illegal logging and deforestation for cash crops like palm oil. We work to safeguard global marine ecosystems by addressing the threats posed by plastic pollution, bycatch and commercial exploitation of whales, dolphins and porpoises. Finally, we reduce the impact of climate change by campaigning to eliminate powerful refrigerant greenhouse gases, exposing related illicit trade and improving energy efficiency in the cooling sector.

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Introduction

Current cooling technologies, such as air-conditioning and refrigeration, rely on human-made F-gases (primarily hydrofluorocarbons (HFC) and hydrochlorofluorocarbons (HCFC)) that are greenhouse gases often several thousand times more potent than carbon dioxide. Left unchecked, HFCs could account for nearly 20 per cent of greenhouse gas emissions by 2050, which is why the HFC phase down under the Kigali Amendment to the Montreal Protocol is such an historic agreement. Cooling also uses huge amounts of energy, often from fossil fuels, and is therefore a critical carbon emissions reduction challenge.

The Environmental Investigation Agency (EIA) and shecco have partnered to work on an initiative to bring about the consideration of energy efficiency requirements by members of the Consumer Goods Forum (CGF) as they roll out HFC-free commercial refrigeration. The second part of the project will focus on robust energy efficiency funding guidelines within the Montreal Protocol.

The partnership seeks to support implementation of the CGF's second Refrigeration Resolution, bringing about replicable transitions to highly efficient HFC-free commercial refrigeration by influencing and supporting multinational CGF members.

The initiative will identify and work with global corporate leaders to advance energy efficiency alongside ambitious actions to adopt low-GWP technologies and remove the remaining barriers to super efficient HFC-free cooling.

This shecco report contributes to the first phase of the project through a technical analysis of the options available to supermarkets for efficient HFC-free cooling.

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Above: TEKO CO_2 refrigeration system

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KIGALI
COOLING EFFICIENCY PROGRAM

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Methodology

shecco, which specialises in market development, undertook research to present and analyse the best available energy efficient HFC-free technologies for the needs of the commercial refrigeration sector.

To fully assess and understand the market, shecco used various means to ensure a thorough evaluation:

Desk research

shecco conducted desk research regarding the current state of the commercial refrigeration market, policy trends, and the available natural refrigerant-based options.

An extensive literature review was conducted to identify data and information regarding energy consumption, energy efficiency of systems, and information related to costs of emerging technologies and savings they can deliver compared to conventional systems using HFCs. An in-depth presentation of the technical characteristics of current available HFC-free technology is made possible by utilising reports from manufacturers, external publications, and the research and analysis of the EU-funded project SuperSmart, which seeks to speed up the uptake of more energy-efficient refrigeration, heating and cooling solutions for Europe's food retail sector by reducing its energy use, lowering its environmental footprint, and increasing its economic benefits.

Interviews with key industry stakeholders

shecco contacted several leading retailers and system and component manufacturers to gather their experience and expectations of the latest market trends for HFC-free commercial refrigeration systems. Interviews were conducted mainly by telephone and email exchange in the period between December 2017 and March 2018.

The interviews aimed to investigate:

• Complementary data on energy efficiency of HFC-free refrigeration equipment;

• Ways to improve energy efficiency of existing refrigeration systems;

• Cost / return on investment for energy efficient HFC-free refrigeration equipment.

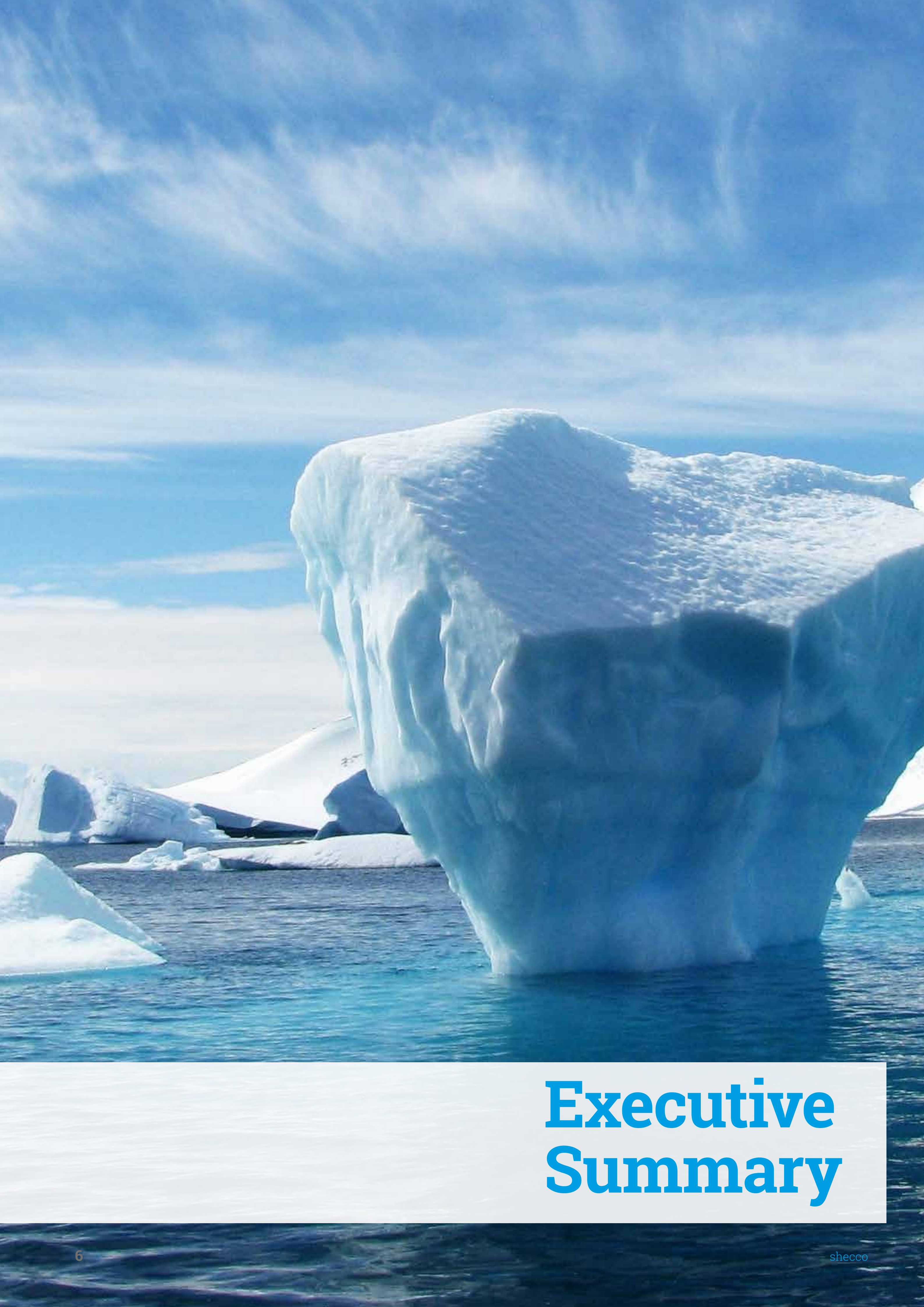
The information received through interviews was incorporated in the main chapters to support the desk research findings however, most interviewees have been anonymized to protect their privacy. Moreover, additional input was received for case studies outlined in this report.

Through the conversations it became clear that the initial cost of systems in absolute terms is information that is rarely publicly communicated. An exception to this is the case study 2.4 that compares installation and operating costs between HFC-based and CO_2 systems.

In general, industry representatives tend to express the cost and energy efficiency differences between systems in percentage ranges as it varies depending on numerous factors (e.g. size of store, climatic conditions, region / country, etc.).

Abbreviations

- COP: Coefficient of performance
- CO_2e: Carbon dioxide equivalent
- GHG: Greenhouse gases
- $GtCO_2e$: Gigatonnes of carbon dioxide equivalent
- GWP: Global warming potential
- HCFC: Hydrochlorofluorocarbon
- HFC: Hydrofluorocarbon
- HVACR: Heating, ventilation, air-conditioning & refrigeration
- kW: Kilowatt hour
- kWh /m^2·a: Kilowatt hour per square meter per annum
- LT: Low temperature
- MBTUH: Thousand British thermal units per hour
- MT: Medium temperature
- ODP: Ozone depletion potential
- TWh: Terawatt hour
- TEWI: Total equivalent warming impact



Executive Summary

The global phase-down of hydrofluorocarbons (HFCs) is underway, with the Kigali Amendment coming into effect in 2019 and the EU F-Gas Regulation already impacting market availability and prices of high-GWP HFCs in Europe.

Industry is on board and HFC-free technology is developing quickly to meet market demand. However, the HFC component of a refrigeration system is only part of the battle for making the HVACR industry climate-friendly. Refrigeration systems are the largest energy consumers in supermarkets, so improving their efficiency is a high priority. Energy consumption is responsible for around 65 per cent of the greenhouse gas (GHG) emissions from the cooling sector, with leakage of HFCs and other F-gases responsible for the remaining 35 per cent. Consequently, tackling the climate impact of refrigerants must be coupled with addressing energy efficiency and energy sources of cooling systems.

Cooling is necessary for the preservation of food, medicine, data and comfort and demand is growing rapidly. Given the relatively long-life span of refrigeration systems, decisions being made now will impact the climate (and the bottom line for end users) for decades to come. Fortunately, future proof energy efficient HFC-free cooling systems exist and are available on the market today. This report provides a thorough, but by no means exhaustive list of these options for commercial refrigeration in supermarkets.

Overall, the evidence from market leaders, case studies, and an extensive literature review indicates that there are a variety of energy efficient HFC-free refrigeration technologies and no valid reasons why the commercial sector should not make a swift transition. Evidence shows that there are energy efficient solutions for any type of application and store format, guaranteeing reliable operation, lower operation costs, and proofing against future regulatory measures. Innovations such as parallel compression, ejectors, waterloop systems, optimised heat exchangers and others have made it possible to use energy efficient HFC-free systems in any climatic condition. The possibility to integrate heating and air-conditioning with the refrigeration system and harness the free rejected energy further increases the overall efficiency of stores.

There are also numerous ways to improve the energy efficiency of existing refrigeration systems, ranging from regular and thorough maintenance and servicing to improved controls and putting doors on display cases. Many supermarkets have already taken steps to improve the environmental impact of their HVACR systems and are reporting positive results including reduced refrigerant leakage and lower energy bills.

Food retailers should use the opportunity of the HFC phase-down to simultaneously improve the energy efficiency and sustainability of their refrigeration systems. They will be key players in ensuring market demand for energy efficient HFC-free technology, encouraging development of new technology and system controls, providing and sharing case studies and success stories and maintaining pressure on the manufacturing industry and policymakers to ensure the success of the HFC phasedown. Decisions concerning refrigeration systems must take into account the total life cycle cost (not just the initial upfront cost) and the full environmental impact. Making the right choice of refrigerant and system now will avoid serious headaches for retailers down the line.

Chapter 1:

Introduction to HFC-free energy efficient commercial refrigeration

The cold food chain is at the nexus of the sustainable development challenge and is fundamental to human health and prosperity in an increasingly urbanised world.[2]

In developing and emerging economies, 23 per cent of food loss is caused by lack of adequate cold chain.[3]

Based on calculations made with data from the International Institute of Refrigeration, developing countries have approximately 10 per cent the refrigerated storage capacity (in m^3/1,000 inhabitants) of developed countries. The International Institute of Refrigeration has estimated that if developing countries had the same level of cold chain infrastructure as developed countries, they could save 200 million tonnes of food each year or 14 per cent of the food supply.[4] However, the resulting HFC consumption and energy use of achieving this would have a severe negative effect on the environment. Energy efficient HFC-free refrigeration needs to be introduced rapidly to avoid locking in damaging technologies in the developing world.

Demand for 'cold chain' services based on networks of refrigerated warehouses and vehicles is booming particularly in developing countries. China's cold chain sector is reported to be growing at 25 per cent per year and was worth an estimated $75 billion by 2017. Cold chain investment is also growing in India, where annual revenues from the sector reached $13 billion in 2017.[5]

To meet the refrigeration demand, different types and formats of stores have been developed. Usually segmented by size, commercial refrigeration typically covers the following store formats: [6]

- Hypermarkets: larger than 4,500 m^2

- Supermarkets: usually 400 – 2,500 m^2, can reach up to 4,500 m^2

- Convenience stores: less than 400 m^2

These types of stores have shown a strong development in recent decades, increasing in numbers across the world. The market size in Europe ranges between 110,000 – 115,000 stores,[7] whereas in the USA the number ranges between 38,000 – 40,000 stores.[8]

In regard to major developing countries, the Brazilian market size is similar to the U.S. (38,000 stores in 2016); [9,10] while China has overtaken the US market, accounting for 65,000 – 70,000 stores, based on statistics consolidated for 2015.[11] Table 1.1 shows data from the U.S. Department of Agriculture (USDA) Foreign Agricultural Service for other developing economies.

Table 1.1: Number of food retail stores in selected developing countries [12]

	Egypt (2016)	Morocco (2016)	Indonesia (2016)	Argentina (2016)
Convenience stores	229	205	29,600	5,500
Hypermarkets	35	67	300	166
Supermarkets	1,056	316	1,400	1,505

1.1 Energy consumption in food retail stores

Considering the type of services supermarkets provide (storage and sales of food products) and their relatively large building sizes, it is clear that this sector is a substantial energy consumer. According to research, supermarkets consume approximately 3-4 per cent of the annual electricity production in industrialised countries. More specifically, the leading literature review on the topic offers the following figures for selected countries:

• 3 per cent in Sweden [13]

• 4 per cent in USA [14]

• 3 per cent in UK [15]

• 4 per cent in France [16]

• 4 per cent in Denmark [17]

These values are in line with more recent studies and calculations on the basis of data from Grocery Universe 2013, Eurostat, and the national statistical institute of Norway.[18]

Compared to other types of commercial buildings, supermarkets usually have one of the highest specific energy consumptions (energy consumption per sales or total area) in developed countries. For hypermarkets, the energy intensity can reach 700 kWh/m^2 per year, and up to 2,000 kWh/m^2 per year for a convenience store.[19]

More specifically, according to research and surveys in various countries on the energy intensity of supermarkets, energy consumption measured in kilowatt hour per square meter per year (kWh /m^2·a) has been reported as detailed in Table 1.3.

Table 1.2: Electricity consumption in supermarkets as a share of a country's total consumption

Country	Electricity consumption in supermarkets (2013) (TWh)	Total electricity consumption (2013) (TWh)	Share of supermarket consumption (%)
Germany	16	523.2	3%
Spain	6.8	230.09	2.9%
Italy	8.2	287.4	2.8%

Table 1.3: Average annual specific energy consumption (in kWh /m²·a) in supermarkets and other buildings

Country	Supermarkets' average annual specific energy consumption (kWh /m²·a)	Other retail buildings (kWh /m²·a)	Source
Sweden	400	<266	Energimydegheten, 2010
Norway	>460	300	NVE, 2014
USA	600	-	Energy Star, 2014
UK	1,000	300	Tassou et al., 2011
Spain	327	118 - 333	CIRCE, 2015
France	570	-	CIRCE, 2015

Supermarkets using electricity from fossil fuel power plants (top) will have higher indirect emissions than those opting for renewable power including solar (bottom)

The major energy consuming systems in supermarkets are refrigeration, lighting, heating, ventilation and air conditioning. Refrigeration systems account for 30-60 per cent of the total energy use in supermarkets (depending on conditions including climate and social habits), making them the highest electricity consuming system in the store.[20] More specifically, studies indicate that of the total energy use in supermarkets, refrigeration systems account for: 35-50 per cent in Sweden,[21] 30-40 per cent in the USA,[22] 29 per cent in the UK,[23] and 45 per cent in South Africa.[24]

Direct versus indirect emissions

The climate impact of commercial refrigeration systems can be split into:

• direct impact due to the emissions of refrigerants used in the refrigeration circuit

• indirect impact due to energy consumption of the refrigeration system (electricity consumed from the grid).

The sum of these two factors is called the 'total equivalent warming impact' (TEWI). The TEWI depends on several factors: direct leakage including leakage during production, annual leakage rates and recovery losses, and indirect factors including the efficiency of the installation and the carbon intensity of electricity production.

According to International Institute of Refrigeration (IIR), 7.8 per cent of global greenhouse gases (GHG) emissions are attributed to the (HVACR) sector, or 4.14 $GtCO_2e$. [25]

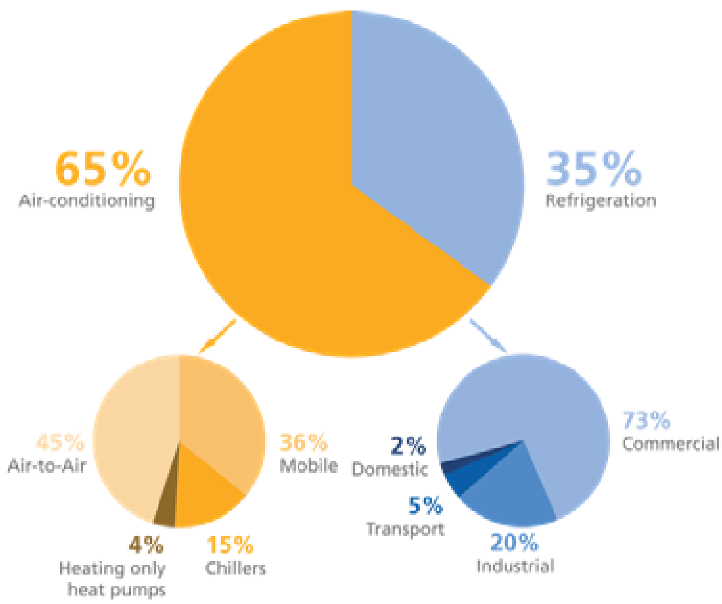
More specifically:

• Direct emissions are equal to 1.53 $GtCO_2e$, or 37 per cent of the total GHG emissions

• Indirect emissions are equal to 2.61 $GtCO_2e$, or 63 per cent of the total GHG emissions

Based on data retrieved from the United Nations Environment Programme (UNEP) and analysis conducted by sheccoBase, the commercial refrigeration sector accounts for approximately 26 per cent of the HVACR sector's total GHG emissions. Furthermore, it is estimated that overall the cold chain is believed to be responsible for approximately 2.4 per cent of GHG emissions (Figure 1.1).[26]

Figure 1.1: HFC use in HVACR sectors (in CO_2e) [27]



From a practical point of view, it is not easy to compute average values of direct and indirect emissions in the commercial refrigeration sector. The literature review on refrigerant leakage in commercial refrigeration shows results vary both between and within individual countries. According to the GreenChill Partnership, run by the US Environmental Protection Agency (US EPA), the average leakage rate of a supermarket's refrigeration system is 25 per cent.[28] The Institute of Refrigeration (IOR) computes a 13 per cent leakage rate in the UK, 8 per cent in the US, 3 per cent in the Netherlands and 5-10 per cent in Germany.[29] In developing countries the situation is more critical. UNEP claims that supermarkets in Brazil can leak up to 100 per cent of the refrigerant charge per year.[30]

Similarly, significant differences can be noted when looking at leakage rates reported by some retailers around the world. Some of the chains considered are operating in the same countries, yet their refrigerant leakage rates vary significantly.

Table 1.4: Leakage rates (in % of refrigerant per year) in selected food retail chains (2015) [31]

Retailer	Leakage rates (% of refrigerant per year)
Dia	20.01%
Kaufland	10%
Marks & Spencer	15%
Metro	9.8%
Delhaize America	12.72%
Ahold USA	11.64%
Delhaize Belgium	17.25%
Albert Heijn Netherlands	5.40%
Alfa Beta (Greece)	9.24%
Delhaize Serbia	58.54%
Lion Super Indo (Indonesia)	46.16%
Mega Image (Romania)	6.66%
Albert (Czech Republic)	8.74%

In such a multifaceted scenario, it is useful to take into consideration the rough average estimate computed from own calculations and validated by the estimations of a leading manufacturer of components for commercial refrigeration equipment, according to which indirect emissions account for approximately 65 per cent of a supermarket's total emissions, whereas direct emissions are approximately 35 per cent of the total emissions.[32] While this figure will vary (depending on leakage rate, GWP of refrigerant, source of electricity etc.) it is a useful starting point to understand the importance of energy efficiency in the food retail sector.

Based on the above numbers and sources, commercial refrigeration is estimated to globally produce annual GHG emissions in the range of 1 to 1.3 $GtCO_2e$, out of which;

• Direct emissions range between 0.35 to 0.46 $GtCO_2e$

• Indirect emissions range between 0.65 to 0.85 $GtCO_2e$ [33]

From the above numbers it is clear that transitioning commercial refrigeration systems to sustainable and more energy efficient HFC-free technology will significantly alleviate the burden on the environment, both in terms of direct and indirect emissions.

Below: A technician searching for a refrigerant leak

1.2 About natural refrigerants

The term 'natural refrigerants' is used to categorise non-synthetic substances that occur in nature's bio-chemical processes.

The most commonly used natural refrigerants today are ammonia (NH_3), carbon dioxide (CO_2) and hydrocarbons, such as propane, isobutane and propylene, also known as propene. In addition, water and air can be used as refrigerants and are already applied in several commercially available applications, and continue to be the focus of further R&D activities.

Natural refrigerants do not deplete the ozone layer and make a negligible – or zero in the case of ammonia, water and air – contribution to GHG emissions. These products were used as refrigerants prior to the 1950s, before fluorocarbon refrigerants became commonplace. They are now being used more extensively due to their low impact on the environment, favourable thermodynamic properties, and low cost.

Natural refrigerants represent a 'basket of solutions' with different characteristics that can cover a wide range of temperature needs for different types of application.

Carbon dioxide (CO_2)

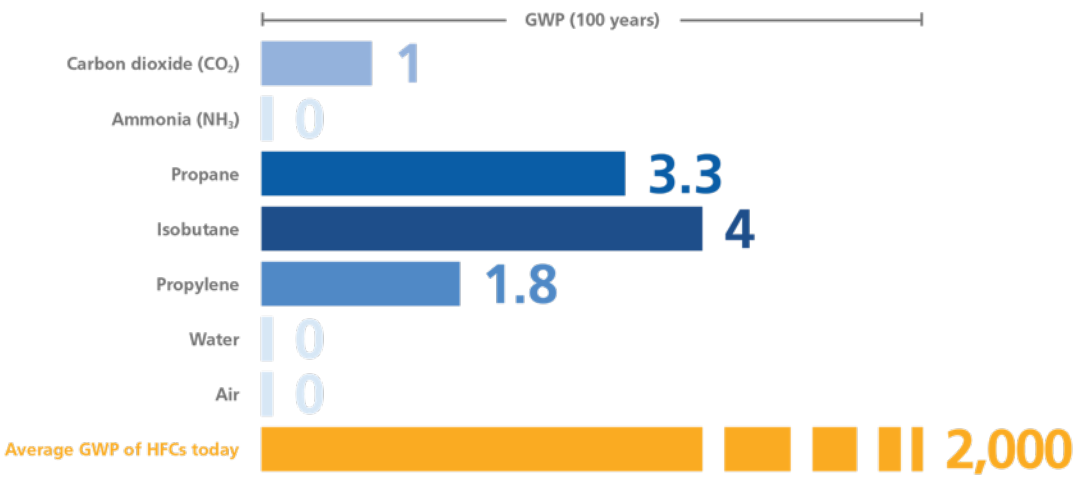
CO_2 is a non-flammable, non-toxic and environmentally benign natural refrigerant. With a global warming potential (GWP) of one, CO_2 is the reference value for comparing a refrigerant's direct impact on global warming. CO_2 as a refrigerant is sourced as a by-product from numerous production methods.

When used as a refrigerant, carbon dioxide typically operates at a higher pressure than fluorocarbons and other refrigerants. Although CO_2 is a higher-pressure refrigerant, only in a few parts of a CO_2 system will the pressure be higher than in a conventional system, and special components are available for that purpose. From a thermodynamic perspective, CO_2 is not as efficient as other refrigerants due to its relatively low critical temperature. However, it has other unique thermo-physical properties, e.g. very good heat transfer coefficient, that allow it to deliver very high performance in practical applications through better heat exchange, low pumping power and heat reclaim.

Key applications

The first CO_2 compression refrigeration system in Europe dates back to 1881. Until the 1950s, CO_2 was used in 60 per cent of ship refrigeration plants and 10 per cent of the land refrigeration plants.[34] Today, CO_2 is established in various new applications, while there is continuous research and development ongoing to deploy the refrigerant on a wider scale. In Europe, the use of CO_2 in centralised systems has become particularly popular, while the refrigerant is also deployed in small to medium-sized industrial refrigeration plants, either as a sole refrigerant or in combination with ammonia of HFCs.

Figure 1.2: Global Warming Potential (GWP) of natural refrigerants compared to average GWP of HFCs used today



Besides these large equipment applications, CO_2 is a common refrigerant in plug-in commercial refrigeration equipment, such as vending machines, bottle coolers and display cabinets. Moreover, CO_2 heat pumps for residential, commercial and industrial use have been increasingly utilised and are poised to gain more popularity in the years to come. In transport applications, CO_2 has been used for refrigeration of goods in transit, while air-conditioning systems using the refrigerant have been developed for cars, buses and trains.

Ammonia (NH_3)

Ammonia is a colourless gas at atmospheric pressure. With zero ozone depleting potential (ODP) and GWP, as well as a short atmospheric lifetime, it does not form any by-products or decomposition products with a negative environmental impact.

Ammonia is known for its higher toxicity, therefore its use is often prohibited in areas with public access, but can normally be used without limits in unoccupied spaces or outside. In occupied spaces, ammonia can be successfully and safely used in indirect systems in conjunction with other refrigerants (often CO_2) where the ammonia refrigerant is safely contained in an unoccupied closed room (or outdoors) and its amount is considerably smaller than in traditional ammonia systems. Moreover, in case of leakage, the strong odour of ammonia makes it easy to detect even in very small quantities.

Key applications

Ammonia was one of the first refrigerants to be used in mechanical systems. It has been deployed in cold storage and food processing industries since the 1900s. Today, more than 90 per cent of large industrial refrigeration facilities in Europe use ammonia as a refrigerant.[35] In China, more than 30,000 end-users use ammonia.[36] Besides food processing, cold storage and distribution, ammonia has found a place in breweries, wineries, ice rinks, chemical plants, cargo ships and fishing vessels as well as district heating and cooling and large-scale air-conditioning for office buildings, universities and airports.

Hydrocarbons

Hydrocarbons are non-toxic refrigerants that have no ODP and minimal GWP. Thanks to their excellent thermodynamic properties, they have equal or better efficiency than HFC or HCFC refrigerants in most applications.

Hydrocarbons are classified as highly flammable (A3) refrigerants, which means that charge sizes are limited in certain applications. The flammable properties of hydrocarbons are well understood and managed in different applications. The safety of hydrocarbons (as well as other refrigerants) is governed by international, regional and national standards. Many of these, however, restrict the safe use of hydrocarbons and need to be updated to account for recent technological progress.

Key applications

Typical applications for hydrocarbons include self-contained residential and light commercial equipment, such as domestic refrigerators and freezers, air conditioners and dehumidifiers as well as stand-alone light commercial refrigerators, bottle coolers, ice cream freezers, beverage dispensers and beer coolers.

In addition, hydrocarbons are used in supermarket refrigeration in combination with secondary cooling or as a high temperature stage in a CO_2 cascade system. Four major consumer brands (The Coca-Cola Company, PepsiCo, Red Bull and Unilever), members of the Refrigerants, Naturally! initiative to take action against global warming and ozone layer depletion, have placed more than 4.7 million hydrocarbon-based light commercial units on the market globally.[37]

Natural refrigerants represent a 'basket of solutions' with different characteristics that can cover a wide range of temperature needs for different types of application.

Above: Ammonia refrigeration piping and tanks

Below: Ammonia tanks

1.3 Policy trends for the reduction of direct & indirect emissions

Regulatory requirements and government incentives are among the key drivers for industry to invest in technology improvements in commercial refrigeration around the world. Reduction of direct emissions has been high on the global political agenda and the issue of energy efficiency is increasingly of interest as it has been identified as the single largest action that can be taken to limit warming to less than 2°C, representing about 40 per cent of the additional GHG reduction potential that can be realised across the globe by 2040.[38]

The Paris Agreement reached by nearly 200 countries at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015 aims to keep the global temperature rise to well below 2°C, while pursuing efforts to limit it to 1.5°C (compared to pre-industrial levels.)

In October 2016, the world's nations adopted the **Kigali Amendment to the Montreal Protocol**, an historic accord committing economies worldwide to significantly reduce consumption and production of HFCs. It is estimated that the Kigali Amendment will prevent 70 billion tonnes of CO_2e by 2050 compared to a business as usual scenario, avoiding as much as 0.35 - 0.5°C warming by the end of the century.[39] The agreement enters into force on 1 January 2019 and will drive reductions in direct HFC emissions in developed and developing countries across all sectors through a consumption and production phase-down.

Governments around the world are taking action to reduce the impact of refrigerants on climate change. The changes in legislative landscape are only expected to intensify as world economies will have to deliver on their international commitments. The EU F-Gas Regulation is currently the most ambitious piece of legislation regulating HFCs, impacting industry in 28 EU countries and beyond. It will limit the consumption of HFCs by 79 per cent by 2030 (in CO_2 equivalent). The HFC phase-down has already triggered a five-fold increase in European HFC prices in 2017, which are expected to spike 20 times in 2018 as supplies are significantly reduced, according to Öko-Recherche. California is another region where legislators are working on introducing strict limits on HFC use, and may outstrip the ambition of the EU F-Gas Regulation especially in terms of bans on high-GWP HFCs in new equipment.

In addition, legislation that addresses indirect emissions is affecting the development of technologies in commercial refrigeration. National energy efficiency standards and labelling programmes have been in existence since the 1970s. The International Energy Agency (IEA) estimates such programmes operate in more than 80 countries around the world, covering more than 50 different types of appliances and equipment in the commercial, industrial and residential sectors.[40] While the design and coverage of the programmes vary according to national circumstances, they are included in many national energy efficiency and climate change mitigation programmes.

Some examples of energy efficiency and labelling programmes that cover refrigeration equipment (residential and/or commercial) are outlined in Table 1.5.

Besides national regulations setting minimum energy performance requirements and labelling programmes, financial and fiscal measures are an effective way to motivate manufacturers and end-users to adopt energy efficient commercial refrigeration equipment. These include:

- Energy efficiency funds
- Economic incentives
- Tax credit or deduction
- Accelerated tax deduction.

Some examples of existing financial and fiscal measures to improve energy efficiency of commercial refrigeration equipment are outlined in Table 1.6.

Table 1.5: Examples of energy efficiency and labelling programmes

Programme	Country	More information
Minimum Energy Performance Standards and Labelling	Australia	http://www.energyrating.gov.au/
Minimum Energy Performance Standards	Canada	http://laws-lois.justice.gc.ca/PDF/SOR-94-651.pdf
Appliance Labelling Scheme	Chile	https://top-ten.cl/
Mandatory Energy Efficiency Labelling Scheme	China	http://www.emsd.gov.hk/en/energy_efficiency/mandatory_energy_efficiency_labelling_scheme/index.html
Ecodesign and Energy Labelling	EU	https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/ecodesign_en
Nationally Appropriate Mitigation Action (NAMA) Project	Indonesia	https://www.giz.de/expertise/downloads/giz2015-en-indonesia-greenchillers-nama.pdf
1. Energy Efficiency Label 2. Top Runner Programme	Japan	1. http://www.shouene-kaden2.net/learn/eco_label.html 2. http://www.enecho.meti.go.jp/category/saving_and_new/saving/data/toprunner2015e.pdf
Minimum Energy Performance Standards	New Zealand	http://www.legislation.govt.nz/regulation/public/2002/0009/latest/DLM108730.html
Energy Efficiency Labelling	Peru	http://etiquetaenergetica.minem.gob.pe/
Minimum Energy Performance Standards and Labelling	Thailand	http://www.eppo.go.th/index.php/th/plan-policy/tieb/eep
Energy STAR Programme	USA	https://www.energystar.gov/
Appliance and Equipment Standards	USA	https://www.energy.gov/eere/buildings/appliance-and-equipment-standards-program
Energy Labelling	Vietnam	http://nhannangluong.com/home

Table 1.6: Examples of financial and fiscal measures

Measure	Type	Country	More information
Business Eco-Credit Programme	Economic incentive	Mexico	https://www.inadem.gob.mx/wp-content/uploads/2016/09/wwcd7nf127624l33784u4ehnv177x1q06iwkhv33.pdf
ÉcoPerformance programme	Economic incentive	Canada (Quebec)	http://www.transitionenergetique.gouv.qc.ca/clienteleaffaires/ecoperformance/description/#.WpQ6jRPwboD
National Climate Protection Initiative	Economic incentive	Germany	http://www.bafa.de/DE/Energie/Energieeffizienz/Klima_Kaeltetechnik/klima_kaeltetechnik_node.html
Energy Investment Allowance	Accelerated tax deduction	The Netherlands	https://english.rvo.nl/subsidies-programmes/energy-investment-allowance-eia

1.4 Chapter conclusions

• The demand for refrigeration is booming especially in developing countries.

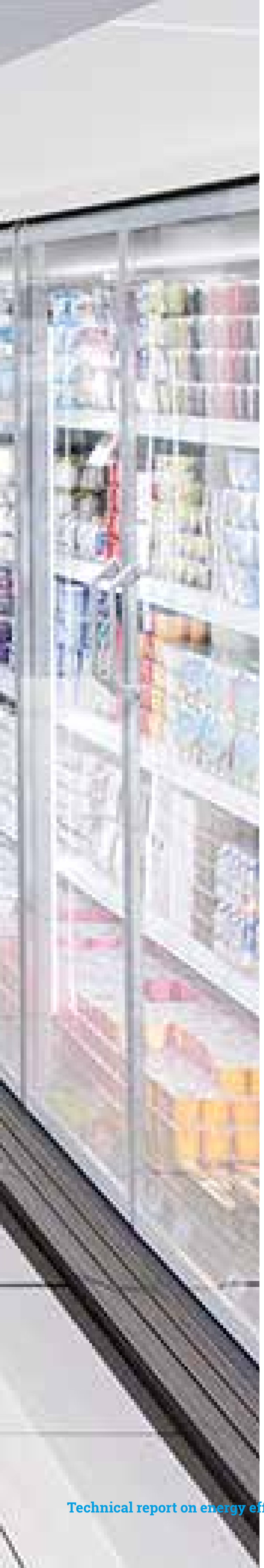
• Supermarkets consume up to 4 per cent of the annual electricity production of industrialised countries.

• Refrigeration systems are by far the most energy consuming systems, accounting for up to 60 per cent of the total energy use in supermarkets.

• Leakage rates among supermarket chains and country vary substantially across and within regions. In some developing countries, refrigerant leakage can reach up to 100 per cent per year.

• Energy efficiency has been identified as the single largest action that can be taken to limit warming to less than 2°C, representing about 40 per cent of the additional GHG reduction potential that can be realised across the globe by 2040.

Chapter 2: Technology options for energy efficient HFC-free refrigeration



2.1 Overview of HFC-free technologies for supermarkets

Refrigeration systems within supermarkets provide storage and display of perishable food and drink prior to sale. Food is stored in walk-in storages/ cold rooms before they are transferred to display cases in the sales area.

There are two main temperature levels in supermarkets:

- Medium temperature (MT) for preservation of chilled food (1°C to 14°C)

- Low temperature (LT) for frozen products (-12°C to -18°C)

To provide the desired food temperatures, the refrigerant evaporation temperature range is typically between -15°C and 5°C for the MT level and between -30°C to -40°C for the LT level. In an integrated solution, the refrigeration system is also connected to the air conditioning (AC) of the store.

The desired temperature levels are summarised in Table 2.1.

As discussed in the previous chapter, the choice of the refrigeration system is crucial because the energy efficiency and emissions depend on the type of system and refrigerant used. There are three types of refrigeration systems typically used in food stores, depending on the size of the building and the quantity and type of products:

- Centralised systems

- Condensing units

- Plug-in units

Aspects of the three types of supermarket refrigeration systems are summarized in Table 2.2. The numbers in the table are estimates and depend on many factors including country, system design evolution, regulations, etc.

Table 2.1: Temperature levels for refrigeration and AC in supermarkets [41]

	Desired temperature level (°C)	Typical evaporation temperature (°C)
Chilled food	1 to 14	-15 to -5
Frozen food	-12 to -18 or lower	-40 to -30
AC	~20	~3

Table 2.2: Supermarket refrigeration systems [42]

Type	Application	Capacity (kW)	Refrigerants typically used	Refrigerant charge (kg)
Centralised systems	Grocery retailers (discounters, supermarkets, hypermarkets, etc.)	20 to >1,000	HCFC-22 HFC-134a HFC-404A HFC-507A CO_2 HC-290 (propane) Ammonia	10 to >3,000
Condensing units	Stores, petrol stations, offices, hotels, etc	5 to >25	HCFC-22 HFC-134a HFC-404A HFC-507A CO_2	1 to >5
Plug-in units	Stores, petrol stations, offices, hotels, etc.	0.1 to 2	HCFC-22 HFC-134a HFC-404A HFC-507A HC-290 (propane) HC-600a (isobutane) CO_2	0.05 to 1

These systems are presented in more detail in the following sub-sections.

Centralised systems

Centralised systems consist of a central refrigeration unit located in a machine room. There are two types of centralised systems:

• Direct system (DX): Racks of compressors in the machine room are connected to the evaporators in the display cases and to the condensers on the roof by long pipes containing the refrigerant.

• Indirect systems: The central refrigeration unit cools a fluid that circulates between the evaporator in the machine room and the display cases in the sales area. This fluid is known by different names, such as secondary refrigerant, secondary fluid, secondary coolant, heat transfer fluid, or brine. Secondary fluid is typically a solution of water with salts or alcohols, which decreases the freezing point of water well below zero.

Because centralised systems need to meet the demand of large stores and are made up of lots of pipes, they are a substantial consumer and emitter of HFC refrigerants. In addition, it is common that large supermarkets operate using centralised systems, thus increasing the importance of having energy-efficient HFC-free options for this segment of the market.

CO_2 is currently gaining market share for centralised commercial refrigeration systems. The reasons for the increasing uptake of CO_2 in this segment of the market are the very good environmental performance (GWP=1), low toxicity and non-flammability (A1 refrigerant), and good energy performance compared to traditional systems with HFCs. In addition, CO_2 is a future-proof refrigerant thus providing a long-term solution for the commercial sector.

Table 2.3 gives an overview of the available types of CO_2-based refrigeration systems (including combinations).

Direct systems with CO_2 are currently popular solutions for centralised refrigeration systems, used in commercial refrigeration. According to sheccoBase 2018 statistics, the number of stores using CO_2 transcritical refrigeration technology has been increasing substantially all over the world, especially in Europe, where there are currently 14,000+ stores equipped with this type of system. The next highest concentration is in Japan with 3,100+ stores. A number of developing economies have started introducing CO_2 transcritical technology in supermarkets; South Africa has 102 stores and many other countries like China, Indonesia, Colombia, Chile, Argentina, Brazil, Jordan, Malaysia are also starting to work with CO_2. [43] There are signals in the market that the number of CO_2 stores in China will increase, now that the first store has

Figure 2.1: Number of stores using CO_2 transcritical systems globally (February 2018) [43]

Table 2.3: Types of CO_2 based central refrigeration systems

Type of system		Description
CO_2 transcritical booster systems		Systems are called transcritical when heat rejection takes place above the critical point of the refrigerant. Systems with two temperature levels and with low-stage and medium-stage compressors, are referred to as booster systems. The low-temperature (LT) cabinets/evaporators are served by a separate smaller booster compressor, which lifts the pressure to the medium temperature level. The discharge gas from the booster is then merged with the gas coming from medium-temperature (MT) evaporators.
CO_2 cascade systems	General	A cascade system comprises two separate one-stage refrigeration cycles, each working with a different refrigerant, best suited for the working conditions. It is necessary to use a cascade system when the difference between the temperature at which heat is rejected and the temperature at which refrigeration is required is so large that a combination of refrigerants is a more optimal solution. CO_2 is the low-stage refrigerant in a cascade system in which the CO_2 is always subcritical. The heat rejected by the condensing CO_2 is absorbed by the evaporating high stage refrigerant. The high-stage system is usually a conventional system using HFC, ammonia or hydrocarbons, in which case this is termed hybrid cascade. In some systems CO_2 is used in the high-stage as well as the low-stage. The CO_2 in the low stage is always subcritical, but in the high-stage will be transcritical at high ambient conditions.
	HFC-CO_2 cascade	Cascade systems, where an HFC refrigerant is used with CO_2, so that the charge of the HFC can be reduced significantly.
	Ammonia-CO_2 cascade	Cascade systems, where the amount of ammonia (NH_3) refrigerant is reduced and kept outside the store for safety reasons, and CO_2 circulates in the cabinets.
	Hydrocarbons - CO_2 cascade	Cascade systems, where the amount of hydrocarbon refrigerant is reduced and kept outside the store for safety reasons, and CO_2 circulates in the cabinets.
CO_2 secondary systems		CO_2 is used as a secondary volatile fluid and is pumped through the heat exchangers (cooling load). The CO_2 is not completely evaporated, the gas is condensated by a chiller. The difference between secondary and cascade systems is that secondary systems have compressors only on the primary system, which typically would use HFC, ammonia or hydrocarbon refrigerants. Similar to cascade systems, the benefit of secondary systems is that the primary system refrigerant is kept at lower quantities and not inside the store where the customers are.

Table 2.4: CO_2 transcritical major markets: growth trends

Country	2015	2018*	Growth
USA	52	340	554%
Australia	4	20	400%
New Zealand	9	41	356%
Europe	5,500	14,000	155%
Japan	1,500	3,100	107%
South Africa	63	102	62%
Canada	139	210	51%

** until February 2018*

Ever since the first CO_2 system was installed for commercial refrigeration, the technology has evolved to overcome technical challenges and increase the efficiency of the systems for different climatic conditions and store requirements.

Depending on the region, the technology used and a store's cooling needs, the total installation price for the entire CO_2 refrigeration system in the EU is currently 0 per cent or 5-10 per cent higher compared to conventional HFC systems.[44]

The main types of CO_2 transcritical systems, as depicted in the figure 2.2 are:

• 1st generation: The booster system

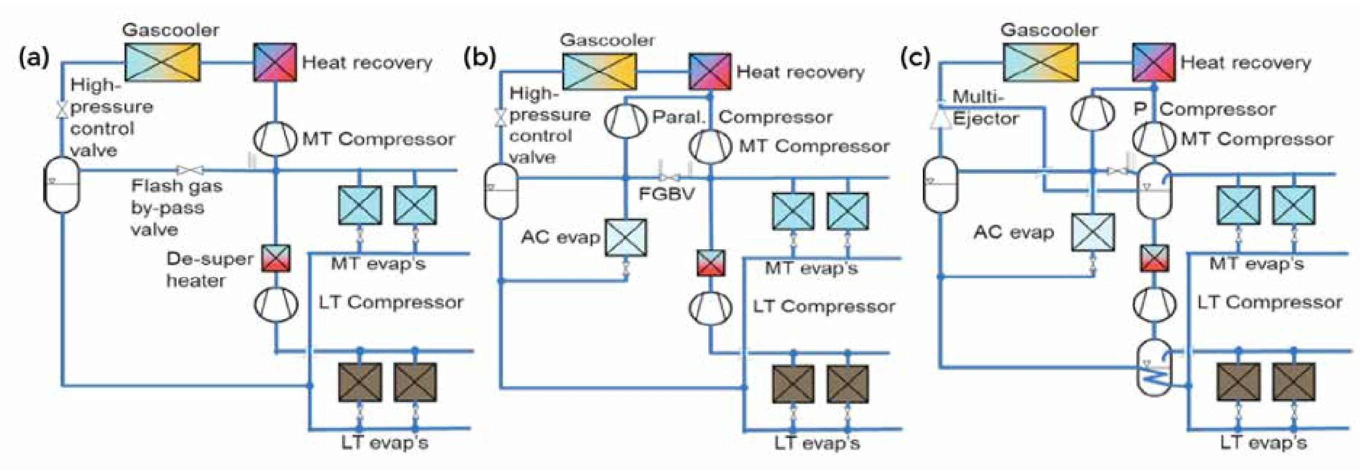
• 2nd generation: Booster system with parallel compression

• 3rd generation: The ejector system

An increase in outside temperatures leads to more work required by the compressor, resulting in increased energy consumption for the refrigeration system. A solution to this issue is to include an auxiliary parallel compressor to alleviate some of the burden as a result of higher ambient temperatures. Such systems are called booster systems with parallel compression. The auxiliary compressor comes into work only when required by the system, whereas during wintertime it operates as a standard booster system.

A supermarket's centralised refrigeration unit is a capital-intensive part of a building. Nevertheless, there are opportunities to integrate the heating and air-conditioning into the refrigeration system, reducing or completely eliminating the need for additional heating and air-conditioning devices. Integration of heating and air conditioning into the refrigeration system converts

Figure 2.2: a) 1st, (b) 2nd and (c) 3rd generation central CO_2 refrigeration systems for supermarkets.

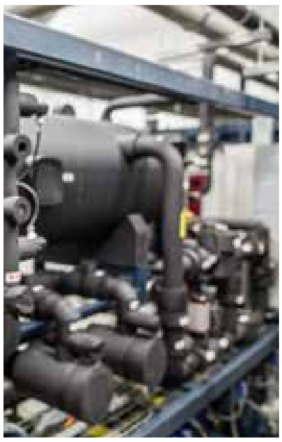


For the needs of cold climates, where AC is not a priority requirement, the booster system is currently the most widely used solution. The low-temperature (LT) cabinets/evaporators are served by a separate smaller booster compressor, which lifts the pressure to the medium temperature level. The discharge gas from the booster is then merged with the gas coming from medium-temperature (MT) evaporators.[45] Two-stage compression is used for transcritical low temperature applications because the discharge temperature of CO_2 is high and will potentially result in lubricant break down.

the refrigeration system into a multi-functional all-in-one integrated solution.

CO_2 transcritical booster systems provide excellent opportunities for heat recovery that can be utilised to cover the store's needs for hot water and space heating. By increasing the discharge pressure of CO_2 and switching from subcritical to transcritical, the amount of available heat increases considerably in CO_2 systems. To achieve an efficient heat recovery process and increase the heating capacity from the CO_2 booster system, a step-wise control of the refrigeration system is recommended.[46] The heat

Equipment shot of a CO_2 transcritical rack



Above: A CO_2 transcritical rack for supermarkets used in South Africa

Below: CO_2 transcritical rack options for North America, Europe, and Australia

recovered from a CO_2 refrigeration system is free and reduces retailer's capital and operating cost otherwise accrued from using additional energy systems. Further information on heat recovery is provided in section 2.3 of this report.

In addition, parallel compression in a CO_2 system allows integration of energy efficient air-conditioning with the refrigeration system. An auxiliary compressor provides the AC cooling capacity. Such a solution can be characterised as an all-in-one integrated CO_2 solution, which can provide the entire or a significant share of cooling and heating demand in supermarkets. The only refrigerant used in this system is CO_2. The base function of this system is refrigeration.[47]

Studies analysing the benefits of heat recovery in CO_2 transcritical systems indicate very positive results. A German supermarket using heat recovery with a gas cooler by-pass managed to increase the total coefficient of performance (COP) of the CO_2 system by 20 per cent.[48] Another German supermarket using a CO_2 system with a parallel compressor connected to ground thermal storage as the auxiliary heater in parallel with heat recovery from the refrigeration system, reported that up to 50 per cent of the heat rejected by the de-superheater was recovered in the cold months.[49] A case study from a Danish supermarket has shown that by replacing the gas heating system with heat recovery from a CO_2 transcritical booster system, they were able to provide the entire heating demand of the supermarket (160kW cooling capacity). The payback period for the heat recovery was less than 5 months.[50]

The latest and one of the most significant developments for CO_2 refrigeration technology is ejector systems. Ejectors typically replace the high-pressure control valve, enabling expansion work recovery. This is particularly important for CO_2 systems operating in warm climates, where the expansion losses are high, however, this ejector configuration can also be applied in cold climate locations. An ejector partly entrains the low-pressure fluid downstream of the MT evaporators by means of high-pressure fluid coming from the gas cooler, accelerated in the motive nozzle of the ejector.[51]

Case study 2.1: 10 per cent energy savings from fully integrated CO_2 installation in Italy [52]

Top: Fresco & Vario supermarket in Italy, using a CO_2 transcritical system, featuring parallel compression, a CO_2 heat pump and air conditioning.

Supermarket: Fresco & Vario

Country: Italy

Key parameters:

• An SCM Frigo-designed CO_2 system in an Italian supermarket featuring parallel compression, a CO_2 heat pump and air conditioning is delivering strong energy savings. Store size: 600 m^2.

• 23 cabinets and a cold room.

System information:

• Parallel compression, providing a better performance during the summer

• Bitzer compressors (three for MT/ parallel/AC and two for LT).

• Harmonised operation with controls, valves and a front-end system from Danfoss

• Cooling capacity of 45 kW at -35°C evaporation.

Current results:

The fully integrated system installed at the frozen food supermarket chain 'Fresco & Vario' in Conegliano (close to Treviso, Italy) was reported to have reached an energy saving of 10 per cent, compared to HFC systems.

Since its installation in March 2016, the CO_2 system has provided 71 kW of air conditioning for the supermarket. During colder months, the system operates as a heat pump. The gas cooler is equipped with a built-in evaporator that produces the false load for the heat pump. One parallel compressor is connected to the external load to operate as a heat pump.

When the cooling demand is low and heating is required, the system activates the heat pump mode to provide sufficient heating on the system (51 kW of water at 50/60°C).

Case study 2.2: CO_2 transcritical system in Chile[53]

Supermarket: Jumbo

Country: Chile

Key parameters:

• Chile's first transcritical CO_2 system was installed at a Jumbo supermarket in the southern city of Valdivia. The project was implemented by the Ministry of Environment's Ozone Unit and was funded by the Climate and Clean Air Coalition (CCAC).

• Store size: 5,300m^2

System information:

• 100 per cent LED lighting

• Integrated building energy management system

• CO_2 only refrigeration system

Current results:

The project leaders indicate that the refrigeration system at Valdivia store delivers energy savings of about 20 per cent, compared to a system that would use HFCs. This effort to showcase alternatives to HFCs marks a national commitment to promote more climate-friendly refrigeration technologies.

Case study 2.3: US retailer Piggly Wiggly's NH_3/CO_2 experiment[54]

Supermarket: Piggly Wiggly

Country: USA

Key parameters:

U.S. retailer Piggly Wiggly has recorded energy savings averaging 28.5 per cent over a seven-month period in a supermarket, thanks mainly to its NH_3/CO_2 refrigeration system.

• Store size: 3,345 m^2

System information:

The ammonia condenses the CO_2 which circulates throughout the store; cooling low-temperature cases via direct expansion and medium-temperature through pumped liquid overfeed. For energy comparison purposes, an HFC (R407A) rack alternates every few weeks with the ammonia rack in condensing the CO_2.

• NH_3/CO_2 cascade system

• Ultra-low charge (24 kg) of ammonia, confined to the roof in the ammonia rack

• Store equipped with several other energy-saving elements, including LED lights, skylights, occupancy and daylight controls, doors on display cases, and heat reclaim for hot water

• NH_3/CO_2 system accounts for 60 per cent of the store's electricity consumption.

Current results:

The reported data comes from a comparison between the Columbus store's power consumption and an HFC-407A Piggly Wiggly store in La Grange, Georgia. For the period ranging from October 2015 to April 2016, the new Piggly Wiggly consumed 23 per cent to 33 per cent less energy than the conventional outlet, for an average energy saving of 28.5 per cent ($33,170 in total).

The superior energy efficiency, even in a warm climate like central Georgia, makes NH_3/CO_2 one of the more promising natural refrigerant technologies in the world.

Case study 2.4: Understanding return on investment (ROI) for CO_2 refrigeration systems[55]

Supermarket: Three supermarkets were used for the case study, only the name of one was disclosed - Sprouts Farmers Market (referred to as Supermarket C.)

Country: USA

Key Parameters:

Hillphoenix conducted a cost/benefit analysis of CO_2 commercial refrigeration systems currently operating in three US supermarkets which showed a positive return on investment across different project sizes. ROI can vary from immediate, upfront savings to a break-even point that occurs 10 years after installation. Note that these results do not reflect intangible benefits, such as future cost avoidance and reduced regulatory paperwork.

A grocer who's considering retrofitting or replacing commercial refrigeration systems will gain a truer view of the costs and benefits of different systems by considering more than just initial price.

Comparing the short- and long-term return on investment of traditional HFC systems vs. CO_2 systems offers a more thorough analysis.

Determining ROI on commercial refrigeration systems requires considering variables such as the cost of refrigerant, energy, equipment, installation, maintenance and regulation. Understanding ROI allows a grocer to make strategic, forward-thinking decisions that not only meet today's challenges, but also help future-proof the business.

System information:

• CO_2 transcritical booster system

• Supermarket A: Based on a low-temperature refrigeration load of 330 MBTUH and a medium-temperature load of 1,050 MBTUH

• Supermarket B: Based on a low-temperature refrigeration load of 250 MBTUH and a medium-temperature load of 750 MBTUH

• Supermarket C: Based on a low-temperature refrigeration load of 200 MBTUH and a medium-temperature load of 650 MBTUH

Current results:

According to Hillphoenix, supermarkets can save from 5 per cent to 18 per cent on energy bills, depending on their location and source of power.

Refrigeration installation costs are consistently lower with CO_2. The CO_2 design requires smaller copper pipe sizes, which lowers material costs. And the smaller line sizes in a CO_2 system are easier to install, which lowers labour costs. Overall, grocers can expect savings of 12 per cent to 18 per cent on CO_2 refrigeration installation costs.

The ROI of the three case studies can be from 0 to 5.6 years. The results can be seen in detail opposite.

Compressors on a CO_2 transcritical rack

Supermarket A: Based on a low-temperature refrigeration load of 330 MBTUH and a medium-temperature load of 1,050 MBTUH.

ROI Summary	MT Glycol LT HFC DX	Advansor CO_2 Booster	Difference	
Equipment Costs	$1,125,353	$1,246,939	$121,586	10.8%
Initial refrigerant cost	$31,724	$1,980	$(29,744)	-93.8%
Refrigeration install cost	$557,375	$414,933	$(142,442)	-25.6%
Electrical install cost	$75,030	$98,850	$23,820	31.7%
Installation costs	$664,129	$515,763	$(148,366)	-22.3%
Annual refrigerant cost	$4,160	$396	$(3,764)	-90.5%
Annual operating cost	$121,447	$108,622	$(12,825)	-10.6%
Annual Totals	$125,607	$109,018	$(16,589)	-13.2%
Equipment Cost Difference			$121,586	
Installation Cost Savings			$(148,366)	
Balance			$(26,780)	
Annual Maintenance and Operating Cost Savings			$(16,589)	
ROI in years			Saving starts at install	

Supermarket B: Based on a low-temperature refrigeration load of 250 MBTUH and a medium-temperature load of 750 MBTUH

ROI Summary	MT HFC DX LT HFC DX	Advansor CO_2 Booster	Difference	
Equipment Costs	$826,570	$1,024,630	$198, 060	24.0%
Initial refrigerant cost	$20,800	$2,250	$(18,550)	-89.2%
Refrigeration install cost	$398,486	$298,000	$(100,486)	-25.2%
Electrical install cost	$277,388	$248,000	$(29,388)	-10.6%
Installation costs	$696,674	$548,250	$(148,424)	-21.3%
Annual refrigerant cost	$3,188	$275	$(2,913)	-91.4%
Annual operating cost	$110,332	$93,477	$(16,855)	-15.3%
Annual Totals	$113,520	$93,752	$(19,768)	-17.4%
Equipment Cost Difference			$198,060	
Installation Cost Savings			$(148,424)	
Balance			$49,636	
Annual Maintenance and Operating Cost Savings			$(19,768)	
ROI in years			2.5 years	

Supermarket C: Based on a low-temperature refrigeration load of 200 MBTUH and a medium-temperature load of 650 MBTUH

ROI Summary	MT HFC DX LT HFC DX	Advansor CO_2 Booster	Difference	
Equipment Costs	$870,600	$1,015,235	$144,635	16.6%
Initial refrigerant cost	$10,500	$3,600	$(6,900)	-65.7%
Refrigeration install cost	$300,988	$246,000	$(54,988)	-18.3%
Electrical install cost	$126,700	$101,450	$(25,250)	-19.9%
Installation costs	$438,188	$351,050	$(87,138)	-19.9%
Annual refrigerant cost	$2,100	$720	$(1,380)	-65.7%
Annual operating cost	$122,459	$113,500	$(8,959)	-7.3%
Annual Totals	$124,559	$114,220	$(10,339)	-8.3%
Equipment Cost Difference			$144,635	
Installation Cost Savings			$(87,138)	
Balance			$57,497	
Annual Maintenance and Operating Cost Savings			$(10,339)	
ROI in years			5.6 years	

Condensing units

Condensing units are typically found in medium-sized and small stores, reaching a cooling capacity up to approximately 30 kW. According to the needs of a store, several display cabinets can be connected to the system.

The market is mainly dominated by high-GWP refrigerant systems, with manufacturers primarily based in Asia. The most environmentally friendly alternative in this range is CO_2, which in principle does not face any technical obstacles to be applied in condensing units. Due to the slightly higher system complexity of using CO_2 in condensing units, costs are higher compared to their HFC counterparts. According to companies producing such systems, it is mainly the initial cost that is higher, with the life cycle cost proving to often be lower for CO_2 condensing units, due to increased efficiency during operation.

In Japan more than 3,100 small supermarkets have transitioned from HFCs to CO_2 by 2017, using in total around 8,500 CO_2 condensing units.[56] According to an end-user in Japan, CO_2 condensing units are 27 per cent more energy efficient than traditionally used HFC units.[57]

In addition, a technology transfer has occurred from Japan to Indonesia, with Japanese CO_2 condensing units being installed in 12 Indonesian pilot stores by 2016. The proximity to the equator and challenging climate of the area has not proved to be a barrier for CO_2, reaching 20 per cent energy savings compared to R22 and an additional 15 per cent higher turnover. [58-59]

The above systems in Asian countries are reported to be operating without ejector technology, leaving room for further improvement in energy efficiency. However, the higher investment cost, compared to HFC systems, is still a significant barrier for large-scale commissioning of the technology.

In Europe, several manufacturers are currently active and making efforts to promote their CO_2 condensing units in the market. However, according to end-users contacted for interviews, the progress is slower than desired, and they are trying to push manufacturers to bring solutions to the market faster. The main requests come from large end-users who want to transition to CO_2 because of the environmental and regulatory stability it can provide to their business. Nevertheless, they currently cannot cover the higher initial cost of converting hundreds of medium-sized stores to CO_2 condensing units.

Hydrocarbons are also making headway in the condensing unit sector. A major compressor manufacturer showcased its first line of propane condensing units, including reciprocating hermetic compressors, in January 2018 at the AHR Expo in Chicago. According to the director, the move was based on customer demand from foodservice companies like convenience stores and restaurants. The HC-290 units are designed to deliver energy improvements of up to 30 per cent compared to HFC counterparts. The new solution offers increased performance in low- and medium-temperature refrigeration applications and is designed with manufacturer and end-user concerns in mind that go beyond meeting the minimum energy efficiency requirements set by regulations such as capacity equivalence and same or reduced footprint. The line could also accommodate small-format grocery stores. [60]

Left: A CO_2 condensing unit

Case study 2.5: Malaysia's first CO_2 condensing unit [61-62]

Supermarket: Jaya Grocers

Country: Malaysia

Key Parameters:

The first CO_2 condensing unit in Malaysia was installed and commissioned in May 2017 at one of Malaysian retailer Jaya Grocer's supermarkets.

The project was carried out under the framework of Stage 1 of Malaysia's HCFC Phase-out Management Plan, which included assistance from the Multilateral Fund for the Implementation of the Montreal Protocol.

System information:

Two Panasonic 15 kW CO_2 outdoor condensing units were installed at the supermarket, providing cooling for a total of 23 medium temperature CO_2 display cases.

Current results:

Though cost challenges remain, feedback from the end-user has so far been positive, according to installation contractor Coolcare.

The representative from Coolcare announced that energy savings have been about 12.8 per cent (in energy consumption costs compared to HFC-based systems).

Above: Advansor condensing unit

Case study 2.6: Advansor – efficient CO_2 condensing units[63-64]

Supermarket: Biedronka - Jeronimo Martins

Country: Poland

Key parameters:

In recent years, the positive development and popularity of transcritical CO_2 refrigeration systems has led to increased demand for small refrigeration systems (condensing units) using CO_2 as the refrigerant.

Polish supermarket chain Biedronka, owned by the Portuguese company Jeronimo Martins is currently in the process of converting 3,000 small stores in Poland from HFCs to CO_2.

• Number of stores to be equipped: 3,000

• Type of compressor: Toshiba BLDC rotary compressor (25-100 RPS)

• Cooling capacity: 32.8/3.3 kW @ -8/-30/34°C

The stores are around 920 m² each. The applications that need to be covered include:

• MT multidecks (+2- +4) °C: 38.75m, 27.1 kW

• MT Coldroom: 5.4 kW

• LT Coldroom: 2.33 kW

System information:

Technical specifications of the system:

• CompSuperXXS minibooster 4x2/ 4x1

• Capacity 32.8/3.3 kW @ -8/-30/34°C

• WxDxH = 1000/ 800/ 2000 mm

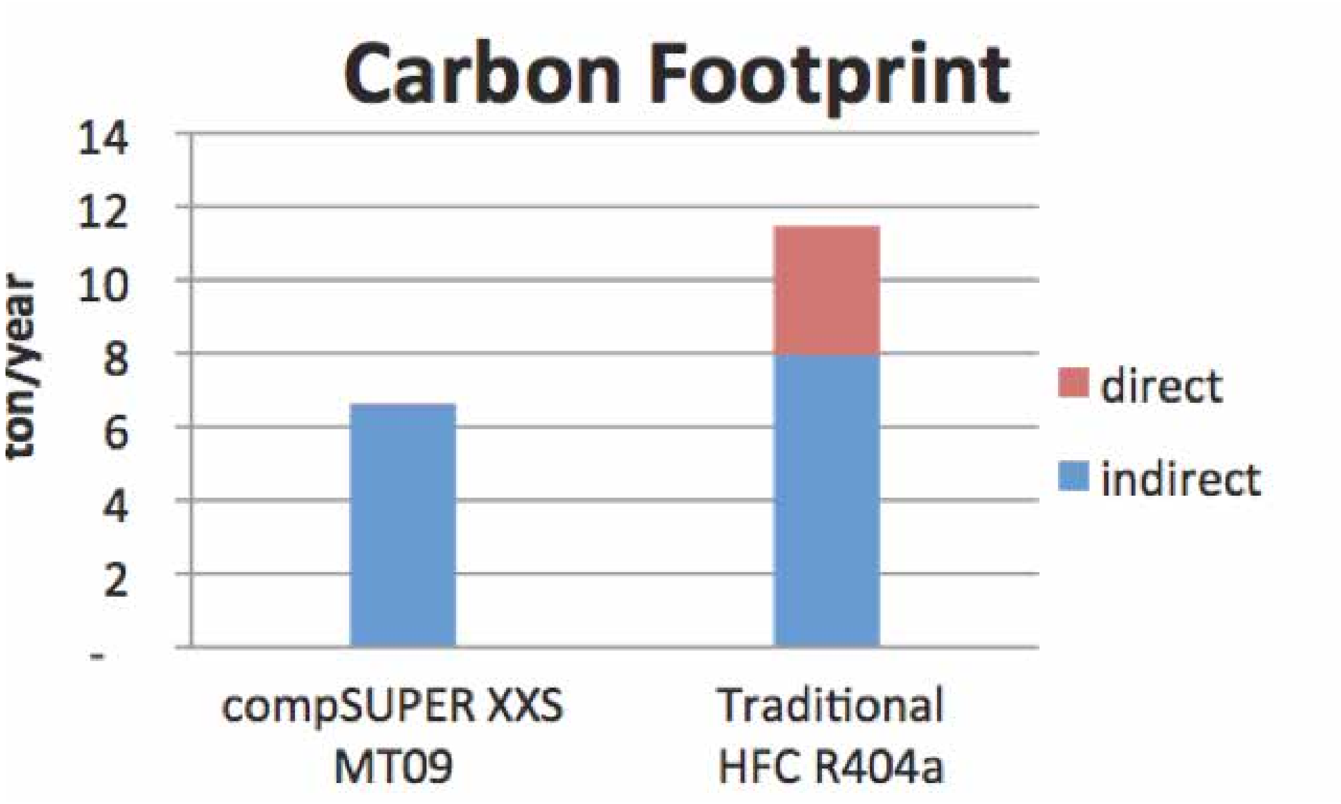
• Weight: App. 400 kg

• 120/ 80/ 60 bar + PRV's + PS (all safety)

• Toshiba BLDC compressor (25-100 RPS)

• 4xRY100 + 1xDY45

Case study image: Carbon footprint comparison for two systems in tons of CO_2e per



• All piping in K65 copper

• Service valves, compressors and rack

• Oil management (separator + return valve)

• IHX MT suction/ flashgas SH

• Filter dryer

• CO_2 liquid receiver – 53 l/ 80 bar

• Carel Prack 300T

Current results:

The company is at the early stages of installing the technology in Polish supermarkets, therefore no official data regarding energy performance of units in the field are currently available.

However, according to tests by Advansor, an energy saving of 20 per cent can be achieved when comparing a compSUPER XXS unit to a traditional HFC condensing unit. These savings are achieved through better evaporator regulation and frequency controlled compressor. Also, improved control of the evaporator expansion valve is gained, due to this being electronically operated. Instead of a fluctuating evaporator temperature, which is often found in a traditional HFC unit, the XXS unit will give a stable and even evaporator temperature, which also contributes to improving the unit's COP.

The energy savings achieved with a compSUPER XXS unit naturally result in reduced CO_2 emissions. CO_2 has a GWP of only 1, HFC-134a and HFC-404A have GWPs of 1,300 and 3,300, respectively. This means that emissions of 1 kg HFC-404A will have the same effect as 3,300 kg of CO_2. If an average annual leakage rate of 10 per cent is expected, the annual CO_2 emissions (carbon footprint) will equal those shown in the model (dimensioning ambient temperature of 30°C and an evaporator capacity of 9 kW at -8°C).

Case study 2.7: CO_2 condensing units in Indonesian stores[65-66]

Supermarket: Alfamidi grocery stores

Country: Indonesia

Key parameters:

Alfamidi, is a convenience store chain operated by PT MIDI UTAMA INDONESIA Tbk (Hereinafter referred to as MIDI). MIDI is an Indonesian company allied with Lawson. To date, Lawson has assisted with project management for the installation of a total of 26 Panasonic CO_2 condensing units at 12 Alfamidi grocery store locations in Jakarta, Indonesia.

The installations are part of a programme that began in 2013, called the 'Joint Crediting Mechanism Model Project'.

The programme is a joint collaboration between the Japanese and Indonesian governments, aiming to introduce energy-efficient technology to retailers while contributing to the emissions reduction targets of both countries.

These projects are all part of a larger push to raise awareness of natural refrigerants, especially among end-users, in Southeast Asia.

An Alfamidi grocery store in Indonesia.

System information:

General configuration at Alfamidi stores is:

- 3 reach-in showcases
- 1 open showcase

The system installed in Indonesia employs "split cycle" refrigeration circuit. It enhances the cooling capacity and the efficiency of CO_2 refrigeration systems. The efficiency is better with commercial refrigeration evaporating temperature range compared to HFC-404A refrigeration systems (16 per cent better in refrigeration and 25 per cent better in freezing, estimated at Japanese climate conditions). According to tests and comparisons conducted in Japan, results indicate that these CO_2 units can reduce annual CO_2 emissions up to 67 per cent.

Current results:

Combined with the installation of LED lighting and inverter type air conditioning, the installation of Panasonic's CO_2 systems has allowed all 12 stores to achieve an average 40.3 per cent reduction in total yearly power consumption.

The initial cost of CO_2 refrigeration systems, including installation, are approximately 1.5 times as much as conventional systems. Remote monitoring costs such as system charge and communication fee are an additional operational cost.

Besides Japan and South East Asia, Panasonic aims to cater to demand for CO_2 condensing units in other markets. The roll out of the systems in Europe started in August 2017 and 10 installations have been completed so far. Panasonic is positive that installations will increase rapidly in Europe and beyond.

The products are designed so that the upper capacity condensing units can cover open showcase, dessert showcase and walk-in refrigerators with 6 or 7 doors, whereas the 1.6kW unit can cover reach-in freezers with 2 or 3 doors.

An HC-290 plug in system for supermarkets.

Plug-in units

A plug-in unit is a display case where the entire refrigeration system and components are integrated into the cabinet. The system is sealed and compact, and it does not require any installation efforts apart from plugging the cabinet into electricity, hence the name "plug-in units".

The main strength of these systems is that the initial costs are much lower compared to centralised systems, and their maintenance is cheap and easy, with the option to replace a stand-alone cabinet upon failure. On the other hand, the main disadvantage is that the condenser heat is released directly to the sales area, creating an additional heat load to the supermarket and increasing the energy costs (AC requirement).

To tackle the heat disadvantage, innovative waterloop solutions have been developed and rolled onto the market using hydrocarbons, mainly propane and propylene. The waterloop systems are designed so that every cabinet has its own self-contained refrigeration unit. The heat generated is not released to the surrounding environment of the store, as it is carried outside by a waterloop to a simple dry cooler. Based on a recent data collected from system manufacturers, there are more than 1,500 hydrocarbon waterloop systems in Europe, with growing interest in Asia. The manufacturer reports around 16 per cent better energy performance with hydrocarbon waterloop technology compared to similar HFC models.[67]

According to one end-user interviewed, the most efficient HC-290 waterloop systems, for which they had at least 1 year of measurements, used around 2,500 kWh annually per meter of cooling unit. Measurements indicate that the annual energy consumption of the new waterloop systems currently being installed will be around 2,000 kWh.[68]

A study comparing energy efficiency and cost of hydrocarbon self-contained display cases and CO_2 centralised refrigeration in a typical European discount store (10 display cases and a vending area of approximately 1,000 m^2) found that retailers could achieve savings on maintenance, energy consumption and refurbishment of €50,000 per store over a 10-year period.[69]

It is, however, clear that comparisons between CO_2 and hydrocarbon systems are difficult to make given the many variables in play, and their impact on the efficiencies and costs of the systems. According to an interview with a manufacturing company it was mentioned that both types of systems have their advantages. There are multiple variables such as store location and size, geographical and climate conditions, the presence of other HVACR technologies, and the in-store share of chilled and frozen food categories as influencing the

Table 2.5: 10-year life cycle cost savings from using HC-290 integral display case system architecture instead of a CO_2 remote rack [69]

Cost benefit	Saving per store
Reduced capital investment	€29,204
Lower energy consumption	€9,093
Lower service, maintenance and insurance cost	€6,429
Simpler decommissioning	€2,014
Reduced store closure time during installation	€1,800
Reduced cost of store shutdown during refurbishment	€1,800
Loss of performance due to leaks	€715

Case study 2.8: Hydrocarbon waterloop system in Belgian Carrefour store[70]

Supermarket: Carrefour

Country: Belgium

Key parameters:

In September 2016, the first Carrefour Belgium propylene (R1270), store was opened in Belgium.

• Store size: 200 m² (Carrefour Express)

System information:

Each of the store's eight cabinets was fitted with one or two self-contained, factory-sealed, and pre-charged refrigeration systems featuring a compressor, an evaporator and a water-plate condenser.

A hydraulic circuit connecting the cabinets, fitted with pumps and an external dry cooler, circulates a mixture of water and propylene glycol through the store. Circulating the water mixture removes heat from the cabinets. The heat is rejected via a heat exchanger into the ambient air. The water itself is cooled down by air from outside, eliminating the need for external chillers.

Mixing the water with propylene glycol stops the fluid from corroding the pipes and freezing when the temperature outside is cold.

Only the glycol piping needed installing on site. This feeds each cabinet with the necessary condensing glycol. The glycol is cooled down by a dry cooler outside. This eliminates the need for hydrocarbon-based chillers located outside the store.

Fitting such a system also saves space by eliminating the need for a refrigeration rack. The compressors are integrated into the top of each cabinet. The cabinets themselves are fitted with double doors and LED lighting to save energy.

System key characteristics:

• 8 propylene-based cabinets

• Total refrigerant charge in the whole system is less than 5.5kg, divided between different circuits in each cabinet

Current results:

This pilot project in the commercial refrigeration field is part of the Carrefour Group's commitment to reducing greenhouse gas emissions and energy consumption.

Although exact numbers have not been reported, Carrefour Belgium representatives have mentioned that according to preliminary calculations and modeling these types of systems have increased energy efficiency and are a solid solution for medium-sized stores.

Top: Supermarket from above

Left: Arneg HC-290 waterloop system

Case study 2.9: Water-cooled hydrocarbon plug-ins by Waitrose[71]

Supermarket: Waitrose

Country: United Kingdom

Key parameters:

Waitrose has chosen to use plug-in units with propane (HC-290) or propene (HC-1270), and has currently installed them in 133 of its 292 stores. Store sizes range from 280 m^2 to 3,700 m^2.

System information:

The third-generation system that Waitrose has installed comprises hydrocarbon integrals for store cabinets with a water-cooling loop connected to an external dry air cooler – reducing the power needed to cool the water.

Current results:

Compared to the previous remote system running on HFC-404A, each converted store saves 7 per cent of its electricity and 60 per cent of its gas, since the waste heat from the cooling loop is used to provide space heating. This reduces operating costs by £65,000 per store per year, and the capital cost of each new system saves the company around £85,000. The hydrocarbon leakage rate is 2.9 per cent and each store reduces total carbon emissions by around 700tCO_2e per year from energy efficiency and reduced leakage. The system is also considered 99.6 per cent reliable.

The most common natural refrigerant chosen to replace high-GWP HFCs in plug-in systems is HC-290. According to system manufacturers surveyed by sheccoBase, strong growth in the range of 10-20 per cent is expected in the next 1-2 years for HC-290 plug-in systems in Europe, mainly driven by high customer demand and future proofing against legislation on high-GWP refrigerants. According to most manufacturers higher energy efficiency is guaranteed from HC-290 plug-ins compared to HFC counterparts. Most stated energy efficiency gains are between 20-30 per cent, whereas a few indicated their HC-290 systems can be up to 40 per cent more energy efficient than HFC plug-ins.

Testing of propane-based units compared to HFC-404A conducted by a leading international compressor manufacturer in three applications yielded the following results:

• ice cream freezers using HC-290 generated a 16 per cent reduction in energy expenditure compared to units using HFC-404A, equivalent to a real gain of US$ 26 per year for the consumer and 1,954 kg less CO_2 in the atmosphere over 10 years;

• point-of-sale glass door freezers using HC-290 provided a 32 per cent energy reduction compared to a unit using HFC-404A, a real gain of US$ 38 per year for the retailer, and 2,277 kg of CO_2 emission was avoided over 10 years;

• vertical freezers had the highest savings with 43 per cent reduction in electricity consumption, representing savings of US$ 226 per year, and 12,764 kg less CO_2 in the atmosphere over 10 years.[72]

Further evidence of the energy efficiency of HC-290 plug-in units comes from an American refrigeration manufacturer that has completely redesigned their propane cabinets as a “ground-up new product”. The refrigerated and “dual-zone” cabinets (split between refrigerated and room temperature) each come in glass and mirror ends, between 36-inch and 77-inch in width, for a total of 14 models. The four glass-end refrigerated cabinets are each at least 50 per cent lower in energy consumption (kWh/day) than the maximum allowable value set by the US Department of Energy (DOE) as of

Above and below: Examples of supermarket display cabinets using HC-290.

March 27, 2017. The DOE maximum for the TDM-R-48-GE model is 13.64 kWh/day, while the company has designed the unit to consume 5.53 kWh/day, or 59.5 per cent less. The energy savings come from the use of propane refrigerant, as well as LED lighting, ECM motors, and the proper "balancing of the refrigeration system".[73]

According to a large number of manufacturers, the main barrier preventing a wider market uptake of these systems is hydrocarbon charge limits anchored in industry safety standards. Currently the charge limits for refrigeration appliances in confined spaces is 150g per circuit. This charge corresponds to a cooling capacity of approximately up to 500W for LT and 700W for MT, meaning that if manufacturers want to reach a higher cooling capacity per system, they need to combine more circuits, thus increasing the initial cost of the system. According to them, the current charge limits are prohibitive and obstructive for hydrocarbons. The ongoing review of the international standard IEC 60335-2-89 for commercial refrigeration foresees an increase of the maximum allowable charge limit up to 13 x LFL (lower flammability level). This would increase the charge limit for HC-290 to 500g from the current limit of 150g. The increase in charge limits has the potential to clear the path for hydrocarbons so that they can reach higher cooling capacities more efficiently and at lower costs, thus serving a larger part of the market.

Besides hydrocarbons, plug-ins utilising CO_2 are also available from a few manufacturers. In tests by a European manufacturer comparing plug-in units utilising HFC-404A, propane and CO_2, 14 per cent lower energy consumption was obtained with the propane unit and 16% reduced energy usage was measured with the CO_2 unit compared to the HFC-404A unit.[75] The initial system cost however was 8 per cent higher for both the propane and CO_2 unit compared to the HFC-404A unit, owing to the double compressor for the propane unit and heat exchanger costs for the CO_2 unit. Another company with such units reports 21 per cent reduced energy use and 15 per cent higher initial costs when comparing a CO_2 plug-in unit with an HFC unit.[76]

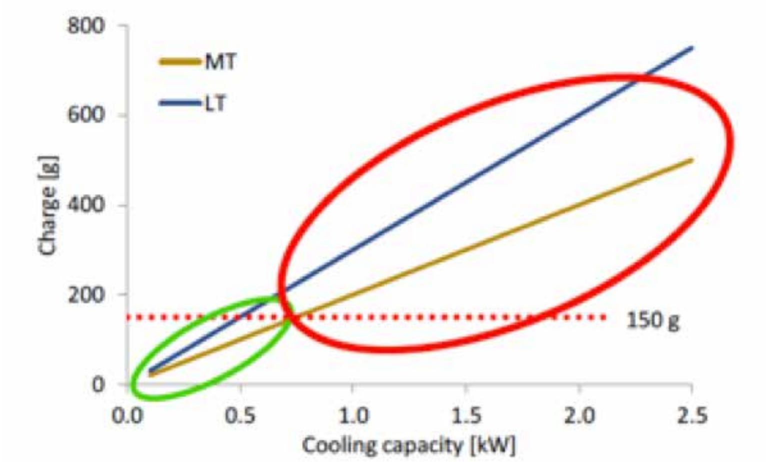


Figure 2.3: Current limit for commercial refrigeration appliances in confined spaces (IEC standard 60335-2-89): Max charge 150g of flammable refrigerant [74]

2.2 Technology solutions for CO_2 in warmer climates

For a long time, the greatest challenge for CO_2 refrigeration systems has been efficiency in warmer climates. In order to overcome such challenges, experts in the field developed and introduced certain types of processes and components, which managed to overcome the so-called CO_2 equator (a geographical line below which CO_2 systems were believed to be less energy efficient than their HFC counterparts). These include parallel compression, ejectors, adiabatic cooling and mechanical sub-cooling.

While cooler climates allow for higher efficiency, transcritical systems in warmer climates can leverage energy-enhancing technologies to reduce energy costs. Adding an adiabatic gas cooler to the transcritical system, for example, offers additional annual savings of 8-12 per cent.[77] Adding parallel compression delivers 6-8 per cent savings for the operation of the transcritical system, and in combination with gas ejectors, savings can reach 8-10 per cent compared to a transcritical system not using these enhancements.[78]

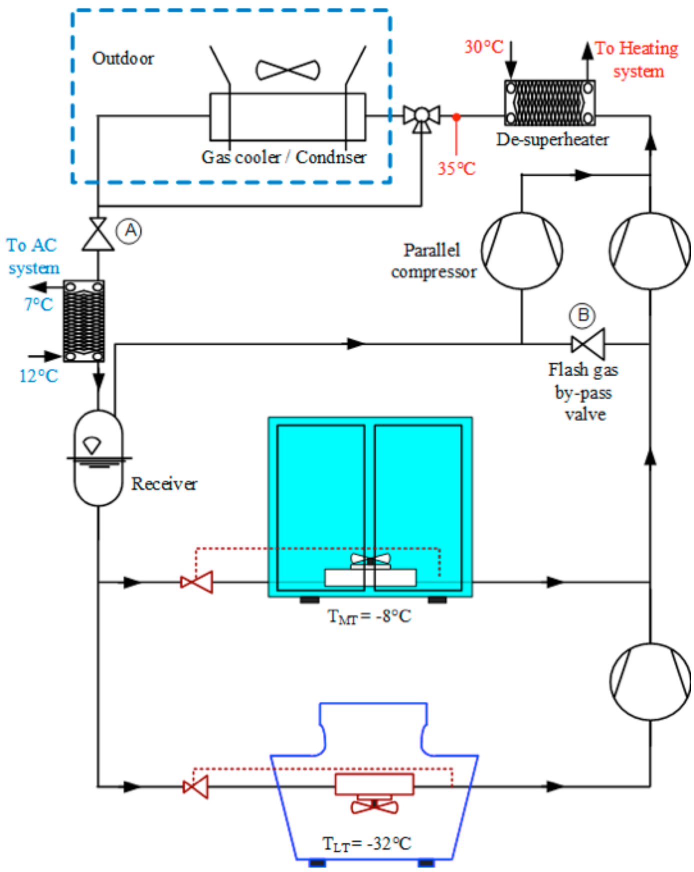
With parallel compression and ejectors the CO_2 transcritical technology is suitable for warmer climates up to 45°C. Although the technology is now more expensive than HFC-based systems in terms of initial cost, this is expected to go down as technology becomes more widespread (as has been proven for the standard CO_2 booster system). Industry experts estimate that with ejector technology and parallel compression, the price of a system is a maximum 10 per cent higher (compared to a standard CO_2 booster system.)[79]

It is important to note that improved CO_2 technology is one of the options that end-users can opt for when they want to introduce energy efficient HFC-free commercial refrigeration system in warmer climates. Technology based on hydrocarbons is suitable in all climatic conditions and is often considered, especially for medium and small installations.

Parallel compression

Parallel compression is used to compress the flash gas vapour directly from the receiver to the high pressure side, instead of the less efficient expansion to MT pressure level. A parallel compressor is shown in Figure 2.4. Different research based on computer modelling has concluded that parallel compression can improve the energy efficiency of CO_2 booster systems significantly (by 10-15 per cent.)[80] Integration of AC with CO_2 systems is generally recommended to be accompanied by parallel compression. In a field measurement analysis, it has been shown that AC delivery is 25 per cent more efficient when using parallel compression instead of standard flash gas by-pass.

Figure 2.4: Schematic of an integrated CO_2 refrigeration system with heat recovery, AC and parallel compression [81]



Above: CO_2 transcritical rack in Al-Salam supermarket in Jordan

Case study 2.10: Al-Salam supermarket in Jordan[82]

Supermarket: Al-Salam

Country: Jordan

Key Parameters:

The first transcritical CO_2 supermarket in Jordan was inaugurated in February 2018 at the Al-Salam supermarket in the Middle Eastern country's capital of Amman. The CO_2 transcritical system installed is a pioneer in the Middle East.

With a total surface area of 2,000 m^2, the supermarket, which previously used a chemical refrigerant that is known to deplete the ozone layer and have a high global warming potential, was retrofitted to CO_2 with help from the Jordan Ministry of Environment. The demonstration project was funded by the Climate and Clean Air Coalition (CCAC) and implemented by the United Nations Industrial Development Organisation (UNIDO).

System information:

The system is designed to cope with temperatures reaching up to 32°C between June and September, thanks to the use of parallel compression and multi-ejector technology.

The CO_2 booster system is from Italian manufacturer Enex S.r.l., using Dorin compressors and Danfoss multi-ejectors. Local firm Abdin Industrial designed, manufactured and installed the display cabinets. This Jordanian company will also be responsible for the future servicing of this technology.

The system also features non-superheated evaporator technology for both chilled and frozen food cabinets and storage rooms. The waste heat from the system is recovered for hot sanitary water supply, which further increases the energy efficiency of this system.

The new refrigeration system in the supermarket in Amman, Jordan, is able to maintain chilled food at the set-point temperatures with an evaporation temperature of -2°C, while the frozen foodstuff is cooled by evaporating carbon dioxide at -25°C.

Current results:

This supermarket represents a test for CO_2 in challenging weather conditions. If successful, it could open the door to the expansion of CO_2 across the region.

Results regarding the performance and cost of the system have not yet been shared with the public.

Case study 2.11: A CO_2 transcritical booster system with parallel compression in South Africa[83]

Supermarket: Makro

Country: South Africa

Key parameters:

Makro worked alongside Commercial Refrigeration Services (CRS) to develop a more environmentally friendly refrigeration system for the Makro Strubens Valley store that combines the lower GWP and improved energy efficiency of a new CO_2 transcritical booster system with parallel compression.

System information:

New system:

2 x CO_2 transcritical booster systems with parallel compression

- Medium temperature:
  - Evaporation temperature: -5°C
  - Refrigeration load: 300.46 kW
- Low temperature:
  - Evaporation temperature: -30°C
  - Refrigeration load: 88.45 kW
- Refrigerant: CO_2

Old system:

- Medium temperature:
  - Evaporation temperature: -8°C
  - Refrigeration load: 201.02 kW
- Low temperature:
  - Evaporation temperature: -30°C
  - Refrigeration load: 88 kW
- Refrigerant: HFC-507

Current results:

The new CO_2 system was implemented in April 2016 with an extra 100 kW of additional refrigeration cooling capacity on the medium temperature. Even with the added cooling capacity, the system led to a 53 per cent reduction in energy usage, compared to the old system using HFC-507. More specifically, with the old system the monthly electricity consumption could reach a minimum of 120,000 kWh a month, whereas with the new CO_2 system, the maximum monthly consumption is less than 90,000 kWh.

Due to the energy savings, the average return on investment (ROI) for this system is approximately 3-4 years.

Case study 2.12: Selgros Cash and Carry in Romania[84]

Supermarket: Selgros Cash and Carry

Country: Romania

Key parameters:

A Selgros Cash and Carry store in Târgu Mureș, Romania is fitted with a CO_2 transcritical rack that relies on a booster system, parallel compression, and ejector technology. The system also includes the first-ever CO_2 transcritical chiller for air-conditioning with overfeed flooded evaporators.

System information:

A heat recovery system delivers hot tap water and heating for the sales and office areas. This reduces the supermarket's carbon footprint, recycling waste heat that would otherwise be emitted to the atmosphere.

The CO_2 booster rack – serving 127 metres of low- and medium-temperature cabinets, as well as 268 m^2 of cold rooms and freezers – delivers up to 145 kW of medium temperature and 44kW of low temperature cooling capacity at the Târgu Mureș store.

The system harnesses gas and liquid ejectors together with parallel compressors to recover the energy released during high-pressure expansion and to reduce internal throttling losses. Driven by the pressure difference in the refrigeration system between high and receiver pressure, the ejectors convey either liquid or gaseous refrigerant.

Current results:

The first CO_2 transcritical chiller for air-conditioning with overfeed flooded evaporators provides air-conditioning for the entire sales and office area. The system harnesses ejectors to increase system efficiency, raising the medium suction pressure of the medium temperature range from -8°C up to -2°C. Energy savings reach up to 25 per cent compared to traditional CO_2 systems.

Ejectors

A drawback of using CO_2 systems in warm climates (transcritical operation) is high throttling losses in high pressure expansion valves. Ejectors are used to recover part of the expansion losses and convert it to work for pre-compressing CO_2 before the compressors suction line (vapour ejectors) or to allow higher evaporation pressures in flooded evaporators (liquid ejectors). Various computer simulation and field measurement analyses show that a multi-ejector device can improve the system efficiency up to 20 per cent.[85,86] Some experts in the field believe that ejector technology is the solution to remove the CO_2 equator.

Major manufacturing companies during interviews claim that their ejector rack systems can offer very high energy savings. One manufacturer indicated that their new ejector rack offers up to 40 per cent energy savings compared to HFCs and 30 per cent compared with classical CO_2 transcritical booster systems. This system is a CO_2 booster rack with modulating ejector technology, and provides environmentally sustainable and energy efficient refrigeration through a patented modulating vapour ejector, but also a patented cycle with a liquid pump assisting the ejector. The smart ejector technology adjusts to capacity variation and is key to providing these substantial energy savings. Depending on application these ejectors come in six different sizes. The company can also put up to four ejectors in parallel to achieve more than 500 kW of cooling power.[87]

According to a case study for a supermarket in Torino, Italy, energy savings can be achieved by using a standard CO_2 booster technology (compared to traditional direct expansion HFC-404A system) in most of Italy's geographical regions. The systems can deliver energy savings of up to €19,000 a year in most northern areas. In warmer climates, however, they can cost up to €11,000 more to run than an HFC-404A if no ejector is installed. Installing an ejector eliminates this running cost and can even save end-users €1,000 a year compared to HFC-404A even when temperatures reach up to 45ºC.[88]

By mid-2017, it is estimated that there were around 200 CO_2 transcritical booster systems running with either gas or liquid ejectors in Europe.[89] The application of ejectors in other regions is limited, but has the potential to record a strong growth in the coming years.

Three years ago, a Migros supermarket in Ibach, central Switzerland opted to install a new CO_2 refrigeration system with an ejector, reducing electricity consumption by 23 per cent. Migros, the largest retailer in Switzerland, now boasts 60 stores fitted with CO_2 refrigeration technology using ejectors and plans to add 30 more every year.[90]

The estimated pay-back time for an ejector is between one and six years depending on the size of the supermarket, according to a study titled 'Ejector cooling system conquers the market', conducted by the Swiss Federal Office of Energy (SFOE). In the report, Frigo Consulting Project Manager Jonas Schönenberger states; "While we achieve savings of 20 to 30 per cent in Switzerland thanks to an ejector, 30 to 40 per cent are possible at sites with less mature predecessor systems, depending on the building, the load profile, the waste heat recovery and the site climate."[91]

Ejectors in different sizes.

©EIAimage

MIGROS

Top: CO_2 transcritical rack used in a Migros supermarket

Case study 2.13: Migros in Switzerland[92]

Supermarket: Migros

Country: Switzerland

Key parameters:

In 2014, a large Migros branch in Ibach, Switzerland was due for renovation. The managers of the Migros cooperative took advantage of the renovation of the Mythen Center to technically upgrade the refrigeration system.

System information:

• CO_2 system with parallel compression and ejectors

• 170 metres of medium and low-temperature cabinets

• 280m^2 of cold rooms and freezers

• Two identical CO_2 booster units provide a total of 250 kW of refrigeration capacity

Current Results:

The facility achieved an increased efficiency of at least 25 per cent compared to traditional CO_2 systems, and 45 per cent compared to the previous HFC-based system.

For the innovation, the Migros branch received the German EHI (scientific institute of the retail industry) Energy Management Award in 2015.

Case study 2.14: CO_2 transcritical vs CO_2-HFC cascades in warm ambient temperatures[93]

Supermarket: IPER

Country: Italy

Key parameters:

An analysis provided by Arneg of two systems installed in similar supermarkets, one with CO_2 transcritical ejector system and the other with a CO_2-HFC cascade system.

• 10,000 m^2 supermarket - CO_2 TC ejector

• 9,500 m^2 supermarket - CO_2-HFC cascade

• Ambient conditions reaching 40°C during the summer months

System information:

Plant description of CO_2 with ejector and parallel compressor system.

Two racks:

• Compressors: Dorin

- 3 x CD4000H
- 2 x CD4000H
- 2 x CD750M

• Gas cooler: LU-VE EHVD 1 x 6226 4 fans EC

• Controller: Danfoss AKPC 781

Energy saving devices:

• Parallel compressors

• Multistep vapour ejector

• Inverter on:

- 1° MT compressor
- 1° LT compressor
- 1° parallel compressor

• Heat recovery (300 kW)

Design conditions:

• Evaporating temperature LT: -30 °C

• Evaporating temperature MT: -8°C

• Maximum ambient temperature: 40°C

• Maximum pressures:

- HP 120 bar
- MP 60 bar
- LP 60 bar

Current results:

The CO_2 transcritical ejector system was found to save 9 per cent over the twelve-month period with 60,300 kWh/year saved, which translates to a €10,800 annual saving for the end-user compared to an HFC-CO_2 cascade system.

According to calculations for the carbon footprint over a 10-year system lifetime, the CO_2 ejector system has 44 per cent lower total CO_2 eq. emissions than the HFC cascade system, which is equivalent to saving 7,100 trees.

Case study table: Carbon footprint comparison over a 10-year lifetime

Plant	Direct emissions (tCO_2e)	Indirect emissions (tCO_2e)	Total emissions (tCO_2e)
CO_2 TC ejector	2	2,020	2,022
CO_2-HFC cascade	1,416	2,217	3,633

Mechanical sub-cooling

Sub-cooling has a significant positive impact on refrigeration COP in CO_2 systems. But it is a challenge to provide enough sub-cooling from the gas cooler on warm summer days. One technique applied in some southern European supermarkets is to install a separate refrigeration system for sub-cooling the CO_2 cycle. This technique is known as mechanical sub-cooling and HCs or NH_3 can be used in the sub-cooler for a climate friendly solution. Mechanical sub-cooling can be set to be activated only in warm climate conditions. Computer modelling works,[94,95] laboratory tests and field measurements report significant COP improvements for CO_2 systems applying mechanical sub-cooling in warm conditions. However, the energy efficiency gains versus the expenses of using an extra unit for sub-cooling should be investigated in the design stage.

Mechanical sub-cooler with HC-290 for a CO_2 transcritical system in Romania

Case study 2.15: Carrefour Alzira in Spain[96]

Supermarket: Carrefour Alzira

Country: Spain

Key parameters:

The Carrefour Alzira hypermarket in Valencia was equipped with a transcritical CO_2 booster system following its refurbishment in November 2013.

System information:

The refrigeration system pairs parallel compression with an air-cooled flash-gas sub-cooler, also working with the natural refrigerant propene (HC-1270). The integration of a CO_2 sub-cooler makes it possible to maintain the output temperature of the gas-cooler at 26°C all year long, while the flash-gas is evacuated from the manifold through the parallel compression at an evaporating temperature 9°C above a positive circuit.

By incorporating mechanical hydrocarbon sub-coolers and economisers in the transcritical CO_2 booster system, Carrier's solution will allow food retail stores situated in higher-temperature regions to install natural refrigerant solutions that can reduce greenhouse gas emissions and consume less energy than traditional systems using HFC refrigerants.

Current results:

The energy efficient system is responsible for a cut in electrical consumption of more than 100,000 kWh per year (10 per cent savings compared to a conventional cooling system using HFCs). When compared to the previous system installed, with a 270kW of cooling capacity for MT refrigeration and 65kW for the LT refrigeration, the savings reach 35 per cent.

While previously the refrigeration system's excess heat was mostly lost and sent directly into the atmosphere, it is now recovered and used to warm around 5,000L of sanitary water per day. This significantly reduces the store's fossil fuel consumption, therefore generating less indirect CO_2 emissions.

A reduction of 10 million kg of CO_2 emissions over 15 years will be achieved by the system, which is equal to the exhaust emissions of 4,600 medium-size cars.

Right: Adiabatic gas cooler (Güntner)

Adiabatic / evaporative cooling

Another method for warm climates, to avoid operating the refrigeration system at elevated transcritical discharge pressures, is to spray water in the inlet air stream to the gas cooler. This way the system gets less affected by the peak outdoor temperatures. The evaporative cooling is activated when the outdoor temperature is higher than 30-35°C.[97] This technique might have limited application in some regions due to water availability, water treatment, scaling and corrosion issues.

Outside of Europe, adiabatic coolers are increasingly popular in the United States. Over 1,000 have been installed in the USA, of which around 250 are for CO_2, according to German manufacturer Güntner.

DeCicco & Sons QUALITY FIRST

Case study 2.16: DeCicco & Sons in New York, USA[98]

Supermarket: DeCicco & Sons

Country: USA

Key parameters:

DeCicco & Sons, a seven-store food retailer based in Pelham, N.Y., compared its store in Larchmont, N.Y., which has operated a transcritical system from Hillphoenix for 12 months, with another of its stores in Ardsley, N.Y., which has a conventional HFC-404A system. The utility rate is 18.8 cents/kWh. Both stores were similar in size and refrigeration needs.

System information:

Both stores were similar in size and refrigeration load (1 million BTUs medium temperature, 200,000 BTUs low temperature); and except for the refrigeration system, they also employed the same equipment, including LED lights, motion sensors, night curtains, anti-sweat heaters and variable-frequency drives. (The Larchmont store also has 100 kW solar panels, which were not included in the comparison.)

• Transcritical CO_2 booster refrigeration from Hillphoenix

•12-month operation

Current results:

The reduction in energy consumption alone was about 292,000 kWh over the 12 months, a saving of $55,000. The power demand reduction over that period was 720 kW, or 60 kW/month. The energy saving allows for a two-to-three-year payback on the premium paid for the transcritical system over a traditional system. An adiabatic condenser, which keeps the temperature of CO_2 gas from exceeding 88°F, CO_2's critical point ensured that even in the summer months (June - September) the CO_2 system delivered good energy performance.

In addition to the savings in energy consumption and demand, the transcritical system offers 1.1 million BTUs in recovered heat, used for hot water, in the entrance vestibule and in the kitchen.

2.3 Role of components and design in improving energy efficiency in new and existing systems

Compressors

A compressor removes heat through the evaporator and is the most energy-consuming element within a refrigeration unit. To ensure optimum efficiency a compressor should be set to the lowest condensing temperature possible and suction pressure should be kept as low as possible.

CO_2 compressors are now available in all capacity ranges (from small stores to hypermarket scale) from a number of manufacturers. Reciprocating compressors are the dominant technology, due to the strongly varying heat rejection conditions (condensing pressure). A reciprocating compressor can adapt to the varying conditions better, with less variation in efficiency, than other compressor designs.

In the EU, where the CO_2 transcritical technology is the most widespread, the cost of CO_2 compressors is now on par or even lower than the cost of equivalent HFC compressors. A representative of a major compressor manufacturer confirmed in an interview that currently the price of a 35 kW CO_2 compressor is on par with a comparable HFC compressor in the EU.[99] This contrasts with the situation 5-6 years ago when the price of a CO_2 compressor was double that of an HFC compressor, with the most rapid decrease taking place in the last 2-3 years. The reason for the decrease in prices was said to be due to increased production capacity, being led by an increased market demand for CO_2 commercial refrigeration systems.

Variable speed compressor technology brings to the HVACR industry whole new levels of efficiency, comfort, reliability and versatility.

While hydrocarbons boost the efficiency of refrigeration systems, an even larger boost can come from variable-speed technology, which utilises an inverter to control the cooling provided by the system. The trend to adopt this technology is currently taking off in Latin American, Asian and European markets and is expected to accelerate in the future.

According to a leading compressor manufacturer, there is a minimum 10 per cent efficiency gain just by switching to hydrocarbons. Adding variable speed compressors can guarantee another 20-40 per cent improvement in efficiency.[100]

According to another leading manufacturer of hydrocarbon-based compressors with the conversion to HC-290 from HFCs you gain 20-25 per cent in energy savings. Adding variable-speed technology, the industry can realise more than a 40 per cent system efficiency improvement compared to fixed-speed compressors with HFCs or HFOs as the refrigerant.[101]

Currently, cost is still an issue for variable speed technology, especially for larger equipment. Nevertheless, the energy savings offered by variable-speed compressors is greater than that of expansion valves, at lower cost. Another key benefit for OEMs is that one variable speed compressor can cover a wide range of applications. Normally, if there are 10 models there might be 10 different compressors, one for each model. But with variable speed, it can reduce this to one or

Below: GEA's CO_2 compressor

two compressors.

According to interviews with manufacturers, another important way to improve compressor performance is by reducing their size without compromising the capacity and efficiency. Smaller and more compact compressors require lower refrigerant charge. Additionally, noise reduction is an end user demand, especially for plug in units or systems that are kept inside or near customer areas. This improvement is connected more to better customer experience, rather than increased efficiency.

Expansion valve

An expansion valve is the component that controls the amount of refrigerant flow into the evaporator thereby controlling the heat expelled at the outlet of the evaporator.

Use of electronic expansion valves instead of thermostatic expansion valves allows an adaptive adjustment of the control characteristics during operation. Electronic expansion valves are also able to operate with a lower pressure difference, allowing a more radical decrease in condensation temperature. In a large Italian supermarket, energy savings of between 20 per cent (summer) and 35 per cent (winter) were achieved by using electronic expansion valves for the MT and LT evaporators, compared with a similar supermarket using thermostatic expansion valves.[102] For future CO_2 refrigeration systems, the individual local expansion valves of the cooling and freezing equipment attached to the centralised unit should also be able to handle flooded operation.

Heat exchangers (evaporators / condensers)

Heat exchangers are an important component of the refrigeration system and hold the potential of improving efficiency of the system though modifications in the design and operation of the evaporators and the condensers. One of the trends to improve the performance is the reduction of the tube diameter used for the heat exchanger. Thinner tubes lead to a reduction in refrigerant charge, increase in system energy efficiency, and lower material costs.[103]

Another trend is heat exchangers with all-steel construction (traditional materials are copper and aluminum). The benefits of using steel include corrosion resistance, long life, more compact design, low maintenance due to the clog-free steel, and steel is more cost effective than other heat exchangers. In addition, through design changes in heat exchangers it is possible to reduce risk of failure and leaks by allowing expansion and contraction of tubes during large changes in temperature and pressure, with very low resulting strain and stress.[104]

Energy efficiencies can also be harnessed by optimising evaporation and condensing temperatures. An evaporation temperature increase by 3 Kelvin (K) reduces the energy use by approximately three per cent.[105] Increased evaporation temperature can be achieved by increased evaporator area, and by using an IHX installed after the evaporator. An IHX allows transferring superheat, only required to safeguard the compressors, into the refrigerant leaving the evaporator from the refrigerant leaving the gas cooler, which is then simultaneously sub-cooled. This increases the overall energy efficiency.

Increased evaporation temperature is also facilitated by using flooded direct expansion evaporators, enabled through the use of ejectors. For flooded evaporators, the evaporation temperature should ideally be -2°C for MT chillers and -25°C for LT freezers. These temperature levels are the highest that can be achieved today in pilot supermarkets.

As the energy use of the compressor is dependent on the lowest evaporation temperature, it is of utmost importance that all cabinets connected to the same compressor are designed for the same evaporation temperature.

Evaporators are often defrosted by means of a time shift, even if defrosting is not necessary at the time pre-set by the timer. In new CO_2 refrigeration systems using flooded evaporators with elevated evaporation temperatures, defrosting once a week is sufficient. Alternatively, defrost on demand can be performed by observing the evaporation temperature (the evaporator temperature drops upon defrosting).[106] Furthermore, adequate defrosting flaps or socks, controlled by motors, can be used to interrupt the air

Above: Carel controls for CO_2 racks

exchange with the refrigeration room during defrosting.

For condensers, condensation temperature/high-side pressure should be lowered as far as possible. In CO_2 systems, gas cooler outlet temperatures can be lowered by using evaporative condenser/ gas cooler cooling. Serial arrangement of gas coolers should be applied with respect to heat recovery and rejection to different heat sinks.

Air-cooled heat exchangers, in particular, condensers in the plug-in units, are prone to contamination. Periodical cleaning of any heat exchanger surface improves the heat exchange and hence reduces the energy consumption.

Controls

The efficiency of a refrigeration system depends only partly on the efficiency of the individual components. This means that correct sizing and design of high-performance heat exchangers or efficient compressors are not enough on their own to achieve high overall system efficiency.

A significant increase in efficiency can come from the combined operating mode of the components, which often does not simply refer to an individual refrigeration unit but rather the installation as a whole. Consequently, one fundamental aspect is the control system. Electronic controllers use technology that acquire a complete set of information from the units or the system as a whole (temperature, pressure, power consumption, occupancy, etc.), then processes this information based on system rather than single-unit logic so as to ensure optimum control, managing activation or operation of the various components. They thus save considerable amounts of energy.

Recent advances in refrigeration control systems have allowed a shift from deriving energy savings solely from control efficiencies gained at the individual equipment level to taking a store-wide design perspective. It is now feasible and cost-effective to consider all sources of energy usage and flow throughout a store when designing a refrigeration control system with the objective to maximise total store energy savings.

Computerised refrigeration control technology delivers even higher energy efficiencies by employing a comprehensive, whole-system approach to refrigeration equipment operation.

These greater efficiencies are made possible with sophisticated control algorithms that continuously monitor and analyze operating conditions and energy consumption on a plant-wide basis using a refrigeration "Supply / Demand" perspective.

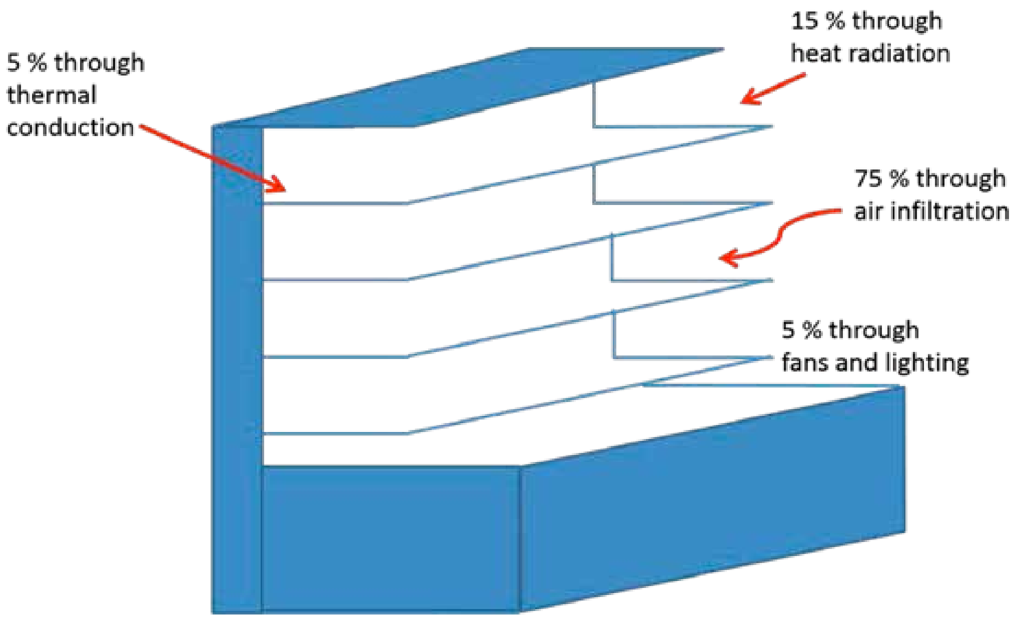
Refrigeration loads, typically evaporators, create refrigeration demand which is met by compressor and condenser operation rejecting heat into the atmosphere. By managing load or demand "at the source," it is possible to effectively manage the entire refrigeration system. As the refrigeration load (demand) declines, compressor and condenser (supply) power requirements are decreased. Consequently, as the refrigeration system stabilises, compressors and condensers benefit from opportunities for tighter control and improved efficiency.[107] Compressor load shedding in supermarkets can reduce energy demands by as much as 80 per cent for short periods of time, by strategically reducing power consumption during peak rate periods.[108]

The next generation of controls by leading manufacturers, allow the use of only one solution for the entire system, rather than multiple controls for different purposes and components. These are called integrated controls. By consolidating all the control functions in one, it offers precise regulation, improves efficiency and helps to make the technology more user friendly. An integrated pack control for transcritical CO_2 booster systems by a leading controls provider claims to have introduced floating receiver pressure control, a feature that can deliver energy savings of up to 4 per cent in warmer climates. In addition, this solution offers control floor heating, space heating and pumps. The graphic interface supports the trouble-shooting and service during daily operation.[109]

Cabinet design

Figure 2.6 illustrates the cooling load for an open multi-deck refrigeration cabinet. There are several ways to reduce the cooling load through improved cabinet design, the single most important of them being the use of glass doors or lids. As shown in Figure 2.6, approximately 75 per cent of the cooling load is due to air infiltration. With cabinets covered by a glass door or lid, the refrigeration capacity of a supermarket can be reduced by up to 40 per cent.[110] In a laboratory study, 60 per cent reduction in daytime energy use was obtained, while the interior storage temperature of the goods was reduced by up to 4K in the daytime and 5K in the night-time.[111] Measurements at a cash-

Figure 2.6: Approximate cooling load for an open refrigerated multi-deck cabinet



Above: Supermarket display cabinets with doors.

and-carry market in Austria, comparing the cooling load of open refrigerated multi-decks with those retrofitted with sliding glass doors, resulted in energy savings of 86 per cent.[112]

In addition, based on interviews with retailers, while the use of doors is widely agreed to lower energy consumption, the use of conventional doors on fridges gives disparate results due to the different contributing factors distinct to every individual supermarket. The fact that there is no standard way of measuring the efficiency of doors has been raised extensively in the past. Besides the reduced cooling load, the energy consumption for defrosting will be reduced as less ambient air and hence less humidity will enter the cabinet. Single, double or triple glazing of low emissivity may be used. If possible, the glass doors/lids should be coated with a thin metal layer to reflect heat (infra-red) radiation, further reducing the energy consumption.[113]

Many retailers are concerned that introduction of glass doors will result in reduction in sales. A market study in the UK, which conducted in-store filming of shoppers, identified that doors can decrease the numbers of sales, mainly attributing this to grab & go shoppers, the ones that read labels in detail, and the ones using baskets, because it makes their shopping experience more time consuming.[114] On the other hand, based on observations from retailers, no losses in sales were documented after retrofitting of individual supermarkets.[115] Furthermore, with glass doors, the air temperature in the aisle in front of the cabinets will be higher, thus reducing "cold aisle syndrome" where the lack of doors makes the aisle unnecessarily cold and uncomfortable to the extent that the customer leaves the aisle, reducing time spent in that aisle and therefore potential sales.

Heat recovery

Supermarkets also require heat, either to heat space, for processes or for hot water. Yet all the heat removed by the refrigeration system (plus the energy used by the compressors) is usually wasted. Some, or all, of this heat can be recovered and used to provide useful heating, reducing gas or oil heating bills.

According to data by the Carbon Trust, for a typical mid-size supermarket with a cooling load of around 230kW, the heat rejected to the atmosphere would be around 310kW. Around 10 per cent of this is relatively high-grade heat (known as superheat) and will be available at 50-60°C.

The rest can also be recovered, but it is relatively low-grade heat, at a temperature of 20-30°C.[116]

For high-grade heat recovery, a heat exchanger (the de-superheater) is installed, with the refrigerant on one side and the fluid to be heated on the other. Not only does this de-superheat the refrigerant, it reduces the cooling water or air needed by the condenser.

If the boilers are heating water from 7°C to 80°C in winter, and the heat recovery system pre-heats this water to 20°C, that's an 18 per cent reduction of the load on the boilers (and the corresponding oil consumption). In addition, low-grade heat can also be used for underfloor heating.[117]

Overall, the payback on an efficient heat recovery system can vary greatly depending on the region, and the size of the supermarket. The period length is also driven primarily by the costs of heat exchangers and the additional pipework and controls. However, since any heat recovered is essentially free, the potential savings for the supermarket are significant.

The benefits of using heat recovery in CO_2-based systems are explained in section 2.1 of this report.

Below: CO_2 transcritical rack with heat reclaim used at a Delhaize supermarket in Belgium

2.4 Chapter conclusions

• Technologies such as parallel compression, ejectors, mechanical sub-cooling, and adiabatic/evaporative cooling increase the efficiency of CO_2 systems, making it possible to reach better energy performance compared to HFCs in climates with temperatures up to 45°C.

• There is a growing trend towards full integration of heating and air-conditioning with refrigeration systems and utilising the free heat and free cooling to cover the needs otherwise fulfilled by additional energy systems. CO_2 transcritical booster systems in particular, provide excellent opportunities for heat recovery that can be utilised to cover the store's needs for hot water and space heating demand. The payback period for the heat recovery can be less than five months.

• CO_2 condensing units have been reported to reach up to 27 per cent higher energy efficiency compared to their HFC counterparts, whereas propane units have been reported to deliver up to 30 per cent higher energy efficiency.

• Most manufacturers stated energy efficiency gains for their HC-290 plug-in systems are between 20-30 per cent, whereas a few indicated their systems can be up to 40 per cent more energy efficient than HFC plug-ins.

• Hydrocarbon-based waterloop technology is a promising solution especially for small and medium-sized stores as well as warmer climates. According to a leading technology manufacturer, around 16 per cent better energy performance can be achieved with this technology compared to similar HFC models.

• The restrictive refrigerant charge limits for flammable refrigerants anchored in current safety standards, pose a significant barrier for a wider uptake of energy efficient hydrocarbon-based refrigeration systems.

• With cabinets covered by a glass door or lid, the refrigeration capacity of a supermarket can be reduced by up to 40 per cent.

• Recent advances in refrigeration control systems have allowed a shift from deriving energy savings solely from control efficiencies gained at the individual equipment level to taking a store-wide design perspective. It is now feasible and cost-effective to consider all sources of energy usage and flow throughout a store when designing a refrigeration control system with the objective to maximise total store energy savings.

Top and above: Freezer cabinets in a supermarket

Below: CO_2 transcritical rack used at an ALDI US store in New York

Chapter 3: Improving efficiency in existing systems

Refrigeration systems have an average working life of 20 years, therefore many systems in operation now, whether running on HFCs or natural refrigerants will continue to be used for some time. A number of options exist to make these systems more energy efficient.

3.1 Ways to improve energy efficiency

Apart from improvement in the operation of specific components (as described in the previous chapter), proper maintenance and leakage management should be a priority, to avoid the leakage of high-GWP HFC refrigerants and ensure optimised energy performance of the refrigeration system.

To ensure that correct and efficient maintenance and service is performed, technicians must be sufficiently trained and certified. More specifically, they need to have knowledge of the latest tools available for leak detection and maintenance, as well as have training on different refrigerants and their thermodynamic properties.

Refrigerant leaks are caused by material failure. Below is a list of possible causes for refrigerant leaks.[118]

• Vibration: Vibration can lead to material failure, misalignment of seals, loosening of bolts to flange connections, etc.

• Damage due to frictional wear: There are many cases of frictional wear causing material failure, and they vary from poorly-fixed pipework to malfunctioning shaft seals.

• Improper material used: There are certain cases where unsuitable material is used that will eventually lead to leaks. Examples include using flexible connection hoses, which are known to have a potential risk for leaking, or using materials that cannot withstand the high pressure of the system or pressure/temperature difference changes that are occurring in the system.

• Poor quality control: An important factor during the production process itself is the quality control of both material components and assembly process bearing in mind the excessive temperature/pressure difference that the material needs to comply with.

• Poor connections: There are different types of joints, brazed, flared or even valves with no caps, and these points are potential places where refrigerant can leak out of the system.

• Corrosion: Corrosion can be caused by different chemicals in different weather conditions that will eventually decay the used material.

• Accidental damage: Accidents should be prevented during transport, installation, operation, and service. Packaging should prevent mechanical damage during transport and the system should be designed, installed, and located to prevent external mechanical damages as much as possible.

According to a few end-users, replacing HFC-404A refrigerant with a low-GWP drop-in refrigerant could help to increase the energy efficiency and reduce the direct emissions of the refrigeration system.

A well-scheduled and structured implementation of both service and maintenance is the most cost-effective approach to ensure reliability and energy efficient operation of a refrigeration system. This will lead to significantly enhanced performance with small initial investments. During a service visit, a refrigeration service engineer should perform the following tasks to optimise the performance of the system: [119]

• Optimise compressor set points: Ensure optimum efficiency by properly setting the condensing temperature and suction pressure;

• Expansion valve optimisation: Calibrate Thermal Expansion Valves (TEV) or Electronic Expansion Valves (EEV) for optimal efficiency;

• Ensure efficient operation of condensers and evaporators: Maintain and clean condensers and evaporators and repair leakages to minimise energy used for refrigeration;

• Optimise evaporator set points: Maintain the temperature at optimal levels to save energy and keep costs low;

• Reduce refrigerant leakage: Always check and repair leakages.

Further measures to improve energy efficiency for a refrigeration system (both new and existing) include: [120]

High-efficiency fan motors and fan power adjustment

By using energy-saving (PM) motors and aerodynamic optimization of the fan blades, the energy consumption of the fans can be reduced by up to 70 per cent - when compared to conventional fans.[121-122]

Evaporator fan outside the cabinet

By placing the fan motor outside the part of the refrigeration unit to be cooled, only a small part of the propeller fan mechanical power is fed to the air to be cooled.

Anti-condensate heaters on the display door

The design of the anti-condensate heaters depends on the door characteristics, cabinet configuration, ambient conditions (dehumidification by the AC unit) and frequency of the door opening.

Use of LEDs for lighting inside the cabinet

LED lights consume approximately half of the lighting energy used by fluorescent tubes while maintaining adequate product lighting. Lighting power reduction serves the additional benefit of reducing the heat load in the cabinet. LED lights also consume less energy the cooler they are kept, the opposite is true for fluorescent tubes. Use of LED lights may therefore reduce the energy use by 60-70 per cent compared with the use of fluorescent lamps.[123] Additionally, it may also be possible to place the lighting outside the refrigerated zone, or install reflectors or light conductors.

Improvement of insulation materials

Thermal conduction through walls is responsible for approximately 5 per cent of the cooling load. This load can be significantly reduced by improved thermal insulation, such as PU-foam.

Infrared reflecting shades and baldachins

Approximately 15 per cent of the cooling load of an open multideck cabinet results from heat radiation exchange with the surrounding air, and the share is even larger for open chest freezers. This impact can be efficiently reduced by using infrared reflecting shades or baldachins/ canopies mounted at the top of the cabinet.

Use of night covers

Night covers for cabinets can potentially reduce the energy required to maintain low temperatures. Energy savings of 25-40 per cent have been reported through the use of night covers.

Above: A supermarket at night with lights in display cabinets left on

Below: Servicing and maintenance tools

Improved anti-sweat heaters, edge/rim heating, dew point control

Rim heating for chest freezers prevents condensation from ambient air, and improves customer safety/comfort through increased edge temperature. A portion of this heat is conducted to the refrigeration unit and thus creates an additional cooling load. By demand-controlled edge heating, i.e. adjusting the surface temperature slightly above the dew point temperature of surrounding ambient air, a reduction in this cooling load by 5 per cent is possible.[124]

Correct cabinet loading

Proper cabinet loading (no products on return grid) and proper cabinet location (especially for open cabinets), i.e. no interaction of the air curtain with the unit air discharge, is important. Overfilled open refrigerated multi-decks consume up to 6 per cent more energy, while the temperature of the warmest products increases by 6K.

Visual inspection and testing

Visual inspection and testing with appropriate test equipment should be carried out according to refrigeration principles, procedures, and safety requirements. Maintenance staff should be aware of the environmental impact of refrigeration systems and should understand their legal responsibilities under the F-gas Regulation and Ozone Depleting Substances Regulation.

Refrigerant charge inspection and loading correction of compressors

Refrigerant charge should be checked regularly, as over- and undercharged systems have a significantly reduced efficiency. The load on the compressor will increase, causing it to run for longer periods of time; suction and head pressures decrease, and ultimately there is an inability to maintain required temperatures within refrigerated cabinets. Regular inspections should identify possible leaks and should be repaired immediately. Under the F-gas Regulation it is obligatory to have log books for any refrigerant additions and removals, dates for leak tests, and actions that have been taken with time interval according to system refrigerant charge. For systems that have over 300kg of charge, automatic leak detection equipment should be mounted.[125]

Proper door operation and sealing

Proper door operation and sealing of display cabinets is also very important for energy savings, since these items are

exposed to very frequent use. Special care should be focused on function and cleanliness of door gaskets, and they should be replaced if damaged. Damaged or dirty door gaskets result in air leakage leading to energy loss and increased refrigeration load.

Inspection of cabinet fans and lubrication

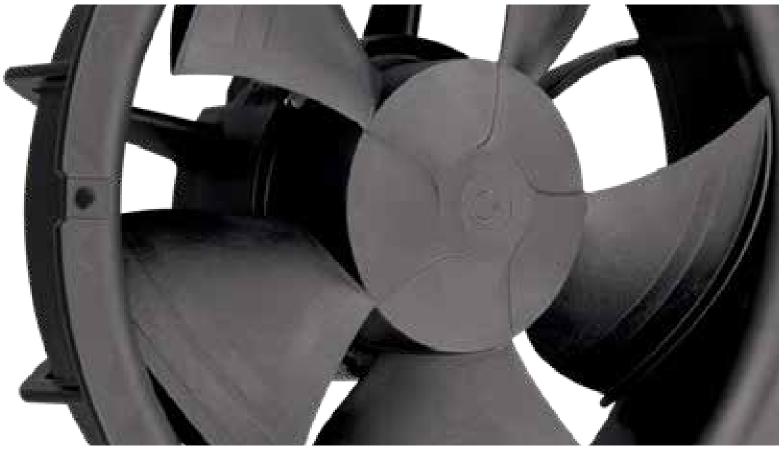
Inspection of cabinet fans is important to ensure the meeting of expected fan lifetime and proper operation of the cabinet. Bearings should be inspected and lubricated according to manufacturer recommendations.

Optimised defrosting schedule

According to a representative from a large European supermarket chain, a substantial share of the energy consumed by their refrigeration systems is due to defrosting. Monitoring, scheduling and reducing the number of defrosts required can potentially decrease the energy consumed by the system.

Inspection and cleaning of condensers and evaporator coils

Dirty condenser and evaporator coils reduce air flow and hence cooling capabilities. Layers of dirt on evaporators and condensers prevent heat convection, leading to lower heat transfer efficiency and higher energy consumption. Dirty refrigerated display cases are not only unhygienic and inefficient, but also cause operating faults. They should be both inspected regularly and cleaned if necessary. One way of cleaning the coils is a power washer, specially approved for copper/aluminium coils, that supplies chemical cleaning solution into a high-pressure water flow. Another method is spray-on cleaning solutions that are intended to be used with a brush and a hose. This may not be an ideal solution especially in heavy clogged coils since the outer surface of the heat exchanger can be seen brightened and shiny but the heat exchange surface itself still can be heavily blocked.



Above: Cabinet fan

Below: Cleaning of dirty equipment

Above: Alfa Laval fans in a biostore

3.2 Chapter conclusions

• Given the relatively long life of refrigeration systems, improving the energy efficiency of existing systems is paramount with proper maintenance and leakage management a priority

• Well-scheduled and correct implementation of service and maintenance increases the reliability and efficiency of refrigeration systems.

• Continuous monitoring and optimisation of the refrigeration system needs to be conducted regularly by trained engineers.

• Some important points for improving energy efficiency in existing and new refrigeration systems include:

- Regular visual inspection, monitoring and testing of the equipment

- Optimising compressor set points and expansion valve calibration

- Monitoring refrigerant charge and repairing leakages

- Correct loading of cabinets

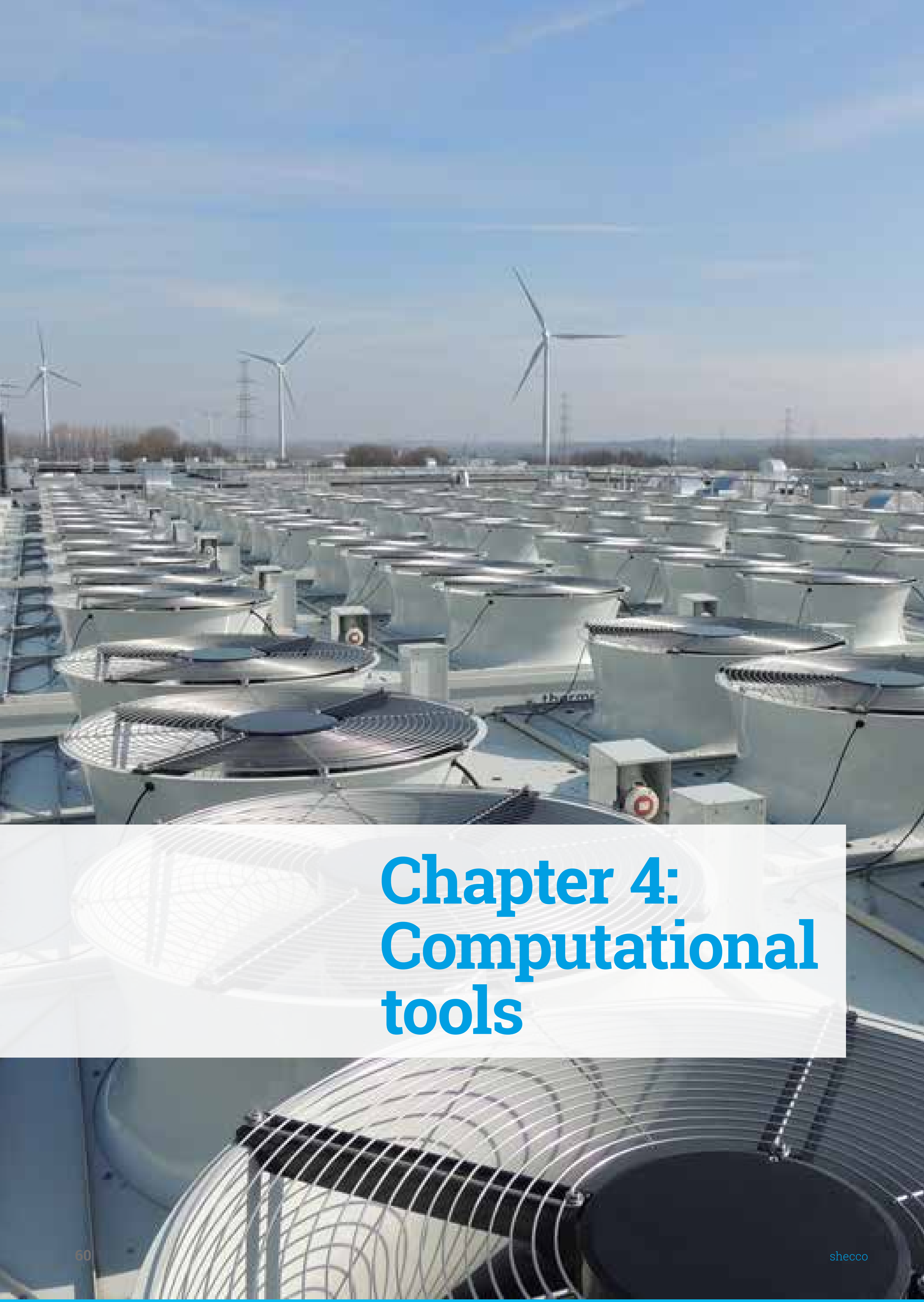
- Use of LED lighting

- Servicing and improving insulation material, and door sealing

- Adding doors and night covers on display cabinets

- Optimising defrosting schedule

- Inspecting and cleaning heat exchangers.



Chapter 4: Computational tools

When choosing or maintaining refrigeration systems in supermarkets, several metrics regarding the energy performance, leak rates, life cycle cost, and return on investment need to be calculated and monitored.

These metrics are important to assess whether the systems are performing according to expectations, and to compare with other types of systems for new stores.

Companies tend to develop their own calculation tools, however there are a variety of calculation tools available for companies who cannot afford to develop their own tools. This chapter provides an overview of available computational tools, which among other tasks, are also used to calculate metrics regarding the refrigeration systems. The tools have been chosen and analysed by an expert in the field, PhD candidate Nicolas Fidorra (TU Braunschweig), and were presented as part of the EU-funded SuperSmart project.[126]

4.1 List of computational tools for supermarket planning

Table 4.1: Overview of computational tools (Fidorra 2016)

Tool	Scope/Category	Difficulty to use	License
CoolPack	Refrigeration systems	Medium	Freeware
CoolTool	Refrigeration systems	Easy / Medium	Commercial tool
CyberMart	Entire supermarket planning	Easy / Medium	Freeware
Excel	Modelling and simulation platform	Easy / Medium	Commercial tool
PackCalculationPro	Refrigeration systems	Medium	Free / Commercial (depending on usage)
SuperSmart-Tool	Entire supermarket planning	Easy / Medium	Not yet defined

CoolPack [127]

CoolPack is a “collection of simulation programs that can be used for designing, dimensioning, analysing and optimizing refrigeration systems” and thus belongs to the category of “Calculation tools for subsystems”. The tool deals with vapour compression refrigeration systems. Thus, it is not specifically designed for supermarkets, but can be used for the calculation of some subsystems. The scope of the program has six categories:

1) Refrigeration utilities

2) CoolTool: Cycles analysis

3) Design

4) Evaluation

5) Auxiliary

6) Dynamic

In the “CoolTool” module it is possible to analyse different refrigeration cycles, including one- and two-stage cycles or transcritical CO_2 ones. The design-module supports the user with the design of a one-stage cycle. Additionally, the “auxiliary” category offers help with different tasks, for instance, calculation of the cooling demand of a display cabinet, the comparison of refrigerants or the calculation of life cycle costs (LCC).

CoolTool [128]

CoolTool is commercial software for the planning and calculation of refrigeration and air conditioning systems developed by CoolTool Technology GmbH. It consists of 14 modules for different purposes including calculation of one- and two-stage compression refrigeration systems, one-stage plants with compounded direct evaporation, flooded evaporators or secondary fluid systems. Furthermore, it can be used to estimate the cooling load for cold rooms or air conditioning systems or to compare different plant options.

One feature is a component database with more than 8,000 parts from a broad range of manufacturers. The database can be used for the selection of compressors based on real thermodynamic conditions or the selection of evaporators based on the EUROVENT standard. The tool can also be used to select suitable tubes based on pressure drop calculation. There are more than 30 refrigerants available and aspects including energy consumption and CO_2 emissions can be calculated.

CyberMart [129-130]

CyberMart is a tool for estimating the annual energy consumption of an entire supermarket. It has a user-friendly interface and enables the user to compare the energy consumption, environmental impact (total equivalent warming potential - TEWI) and LCC. The tool considers the building, HVACR system, display cabinets and refrigeration system. The tool has been developed by Jaime Arias in his PhD thesis. The purpose of the tool is to enable the user to compare the energy consumption of two refrigeration/energy system layouts for a supermarket. So far, it is the only tool that focuses on planning an entire supermarket and has a specific graphical user interface (GUI).

There are eight different refrigeration systems available including direct systems, indirect systems, cascade systems or CO_2 booster system. The user can also choose the number and types of display cabinets and additionally add details on pressure drop in the pipes of an indirect system.

Excel

Excel by Microsoft is a widely used spreadsheet-program. Although it is not primarily developed to be used for supermarket planning, it can be a quite useful tool for this purpose. A typical task within supermarket planning that can be carried out with Excel is the calculation of refrigeration cycles. For this purpose, AddIns are needed that allow the calculation of thermophysical fluid property data. By calculating the fluid properties of refrigerants, it is possible to perform a thermodynamic analysis of refrigeration cycles. Each state point of the refrigeration cycle has several thermodynamic state variables – for instance pressure and specific enthalpy. These can be calculated via the corresponding functions from the AddIn as a function of other states. Another use of Excel relevant to supermarkets is the analysis of measurement data collected by measurement/monitoring systems in supermarkets.

Depending on the knowledge and data available to the person responsible for the analysis, Excel can be used to calculate the TEWI and LCC of the refrigeration system.

PackCalculationPro [131]

PackCalculationPro is a simulation tool that belongs to the category of "calculation of subsystems". It has been developed by IPU, and there are different license options available (free and commercial), depending on the usage. The tool can be used to estimate and compare the annual energy consumption of refrigeration systems and heat pumps. The user can choose between 11 commonly used refrigeration cycles and define their parameters and, to a certain extent, the operation strategy. The simulation models are predefined, but the user can adapt and change several parameters. This includes choosing profiles for the refrigeration load and the evaporation temperatures as well as different climate profiles. On the discharge side, there are several options for the condenser type and the control parameters. In some cases, heat recovery can be chosen with additional parameters.

One main feature of PackCalculationPro is the compressor database with more than 7,000 commercially available compressors. Besides the estimation of the annual energy consumption of one or several refrigeration systems, the comparison of these systems can be amended by a comparison of the LCC and the TEWI. An additional, valuable feature of this tool is the possibility to automatically generate a report with the system specifications and the simulation results. Amongst the tools described in this report, it is one of the most useful tools for planning the refrigeration system, since it includes many desired features (component database, user-friendly interface, automatic report generation and recent refrigeration system layouts.)

SuperSmart-Tool [132,133,134]

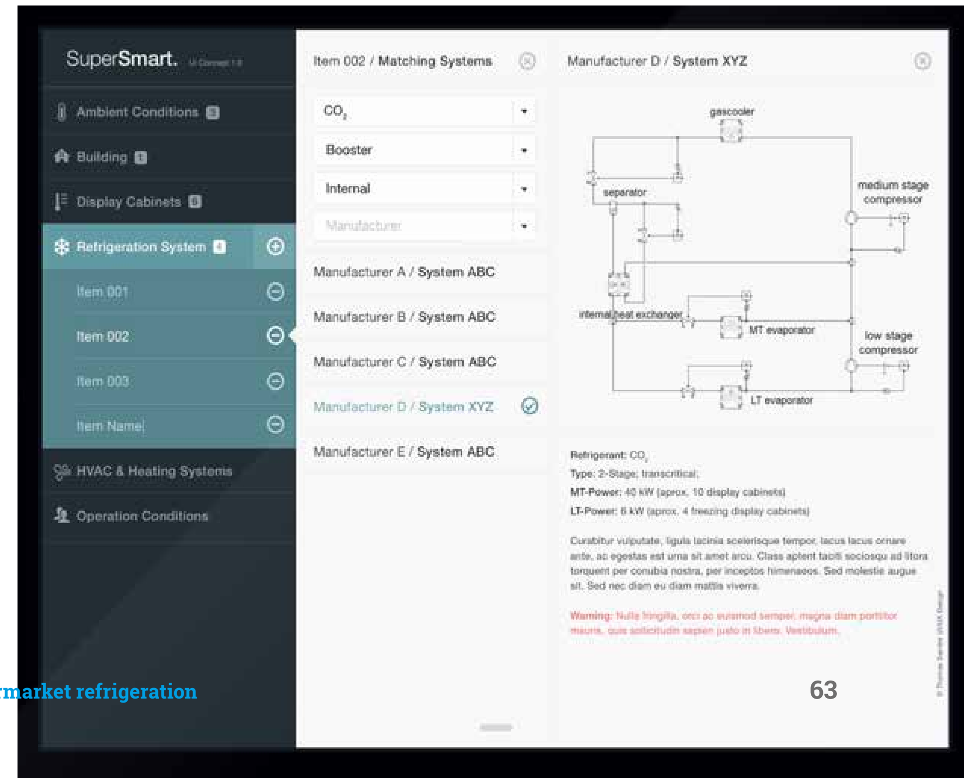
The "SuperSmart Energy Benchmark tool for supermarkets" (short "SuperSmart-Tool") is a software tool that has been under development since 2012. The main idea behind this tool is to provide the user with an energy benchmarking tool, which will consider the entire supermarket and all relevant subsystems and interactions between them. The development of the "SuperSmart-Tool" was initiated in the CREATIV project (CREATIV 2016) of SINTEF and described in several publications.

The tool development is still ongoing as part of a PhD thesis at TU Braunschweig. During the development of the basic ideas for this tool, the name "SuperSmart" was created and consequently used for projects related to supermarkets for instance the current European Horizon 2020 project "SuperSmart or the "SuperSmart-Rack" project, which aims "to increase knowledge related to design and control issues of ejector supported commercial refrigeration units".[135] Although these projects and the tool share the name "SuperSmart" and have the goal of improving energy efficiency in supermarkets, they are strictly separate in terms of funding.

The objective of the SuperSmart Tool is to provide the user with a tool to evaluate the energy consumption of an entire supermarket and all its subsystems. This shall enable the user to evaluate the interactions between the different subsystems in the supermarket and choose the best equipment. As it aims to help the supermarket designer in the daily work, it shall have a component database with predefined models, commercially available components and still allow the opportunity to load one´s own models.

SuperSmart logo (below) and computational tool in action (bottom)

SUPERSMART



4.2 Methodology of supermarket planning focused on refrigeration systems

Estimation of cooling load of display cabinets

Display cabinets are central elements in a supermarket, since they thermally connect the sales area with the refrigeration system. The cooling loads of refrigeration systems are heavily dependent on the number and types of display cabinets and on the indoor thermal conditions (such as temperature and humidity). Naturally, the refrigeration load increases with the number of display cabinets, as well as with higher indoor temperature and humidity. The higher the sales floor indoor temperature, the higher the heat infiltration into the cabinet and consequently the heat flow that has to be withdrawn from the cabinet. Additionally, humidity in the air condenses and forms frost on the surface of the heat exchangers, reducing the heat transfer abilities and hence increasing the refrigeration load.

There are several investigations showing that display cabinets with doors can reduce the cooling demand and thus the electrical energy consumption.[136] In order to plan a remote refrigeration system, it is important to know the maximum cooling load it must provide. Thus, the cooling load for a certain display cabinet must be estimated.

Various useful parameters for the calculation are:

• Length of the display cabinet

• Length of the display area

• Data from the manufacturer

• Data for thermal conditions of the surroundings

The results from the various computational tools are:

• Values of heat conduction

• Infiltration of air

• Thermal radiation

Estimation and comparison of energy consumption of refrigeration systems

One of the main tasks in planning the technical equipment in supermarkets is the selection of an adequate refrigeration system. There are many types of refrigeration systems available. Predominantly used in supermarkets are vapour compression systems. Currently, there is a trend towards natural refrigerants, especially CO_2.[137] There exists a broad range of different modified/improved CO_2 refrigeration systems, which also perform well at high ambient conditions, – for example those using ejectors or parallel compression. The performance of these systems depends very much on the boundary conditions, especially the ambient temperature, as well as on the specific components used in the refrigeration system.

Various useful parameters for the calculation are:

• Temperature levels of cycles

• Cycle capacity

• Compressor performance and heat loss

• Heat infiltration to the suction line

• Pressure losses

Calculation of recoverable heat flow

Heat recovery from the refrigeration systems for space heating is an important option to increase overall efficiency in supermarkets. Depending on the boundary conditions and operation strategy, between 40-100 per cent of the supermarket heating demand can be covered by heat recovery.[138] The space heating demand depends on the building envelope, the climatic conditions, the number and type of display cabinets (with/without doors) and the number of customers, amongst other considerations.

Above: Recheio Cash & Carry in Portugal using a CO_2 transcritical with heat reclaim system

Far bottom right: CO_2 transcritical rack with parallel compression and heat reclaim, used at Recheio Cash & Carry in Portugal

The recoverable heat flow depends specifically on the type of refrigeration system, the cooling load and the temperature level needed for space heating. CO_2 systems operating in transcritical mode are especially suitable for heat recovery. When comparing refrigeration systems, the cooling demands for the display cabinets and cold store must be considered alongside the possibility to recover waste heat.

Estimation of life cycle costs

The LCC of a supermarket refrigeration system considers not only the investment costs, but also costs for operation including energy consumption, maintenance etc. The relevant point regarding supermarket planning in this report is the comparison between investment costs and operational costs. In supermarkets, more efficient equipment is normally more expensive initially, but consumes less energy. Thus, the LCC perspective can help to take this into account.

Various useful parameters for the calculation of the LCC are:

- Interest rate
- Inflation rate
- Energy cost
- Expected lifetime
- Initial costs
- Annual operation costs

The results from the various computational tools are:

- Life cycle costs
- Effective interest rate
- Internal rate of return
- Present value of maintenance cost
- Payback time

Calculation of total equivalent warming impact (TEWI)

The TEWI measures the environmental impact of a refrigeration system, specifically how much it contributes to global warming. It consists of the direct and indirect emissions. For refrigeration systems, the direct emissions are from refrigerants with global warming potential. The indirect emissions are caused by the consumption of the electrical energy that is required for the operation of the refrigeration system. When using natural refrigerants, the direct emissions are already quite low (or zero), thus the indirect emissions are more important. To estimate the indirect emissions, it is crucial to know the electrical energy consumption of the refrigeration systems. The basic

Above: Refrigerated display units with doors and LEDs

formula for the TEWI is quite simple. The challenge is to estimate the electrical energy consumption of the refrigeration system. Additionally, information on the emission factors for electrical energy is required, which depends very much on the electricity production.

Various useful parameters for the calculation are:

- Refrigerant charge (kg)
- Recycle rate (%)
- Leakage rate (% / year)
- CO_2 released due to electricity generation (kg / kWh)
- System lifetime (years)

The results from the various computational tools are:

- Indirect and direct emissions
- Total emissions as CO_2 equivalents

4.3 Chapter conclusions

- To facilitate better monitoring and optimisation of refrigeration systems, a number of computational tools exist that can calculate important metrics.
- The choice of the tool should be made based on the monitoring requirements and the budget of the end-user.
- According to conversations with leading end-users, important metrics to be monitored are:

- Energy costs
- Leakage rates
- Energy consumption
- Payback time
- Life cycle costs
- GHG emissions

Conclusions

Eliminating high-GWP HFCs addresses only part of the battle for climate-friendly HVACR systems; energy usage must be considered simultaneously. As the largest energy consumer in a supermarket, the refrigeration and air-conditioning systems must be a primary target for energy efficiency measures. Fortunately, the evidence from market leaders, case studies and an extensive literature review indicates that there are a variety of energy efficient HFC-free refrigeration technologies and no valid excuses why the commercial sector should not transition swiftly to such technologies. There are energy efficient solutions available today for any type of application and store format, guaranteeing reliable operation, lower operation costs and proofing against future regulatory measures. Innovations such as parallel compression, ejectors, waterloop systems, optimised heat exchangers and others have made it possible to use energy efficient HFC-free systems in any climatic condition. The possibility to integrate heating and air-conditioning with the refrigeration system and harness the free rejected energy further increases the overall efficiency of stores.

Various energy efficient HFC-free commercial refrigeration options currently exist for different sizes of supermarkets and types of systems:

• Centralised systems utilising any form of CO_2 technology can achieve significant energy savings compared to traditional HFC technologies. The level of energy savings depends on the climatic conditions and the design of the system.

• HFC-free options for condensing units exist with CO_2 and to a lesser extent with hydrocarbons. According to case studies presented in this report, CO_2 condensing units have been reported to reach up to 27 per cent higher energy efficiency compared to their HFC counterparts, whereas HC-290 units have been reported to deliver up to 30 per cent higher energy efficiency. However, outdated refrigerant charge restrictions for hydrocarbons currently pose a barrier for a wider uptake of this type of condensing units in the market.

• According to most manufacturers higher energy efficiency is guaranteed from HC-290 plug-ins compared to their HFC counterparts. Most stated energy efficiency gains between 20-30 per cent, while a few indicated their HC-290 systems can be up to 40 per cent more energy efficient than HFC plug-ins. In addition, innovative waterloop solutions, designed to remove the heat generated from the plug-in units outside the store, have been developed and are being installed in the market, with companies reporting energy savings of up to 35 per cent.

Switching refrigeration systems away from HFCs offers an ideal opportunity for supermarkets to simultaneously improve their energy efficiency. Through careful planning and assessment of future proof decisions, supermarkets can now be designed and installed with both the climate and the bottom line in mind. An obvious example of this is full integration of heating and air-conditioning with refrigeration systems and utilising the free heat and free cooling to cover the needs otherwise requiring additional energy systems. Components, system and cabinet design, and control systems all play a vital role in the energy efficiency of a refrigeration system, including simple measures such as adding cabinet doors to reduce the refrigeration load of a supermarket by up to 40 per cent.

Furthermore, the addition of technologies such as parallel compression, ejectors, mechanical sub-cooling, and adiabatic/evaporative cooling allow CO_2 systems to reach better energy performance than HFCs in high ambient climates. Given the relatively long life of refrigeration systems, well-scheduled and structured implementation of both service and maintenance is the most cost-effective approach to ensure reliability and energy efficient operation of a refrigeration system (both new and existing). This will lead to significantly enhanced performance with small initial investments. To achieve the most efficient performance, continuous monitoring and optimisation of the refrigeration system need to be conducted by trained engineers. To facilitate this work, a number of computational tools exist that can calculate important metrics such as energy costs, leakage rates, energy consumption and other useful indicators for the monitoring of refrigeration systems.

1. MBTU : The unit MBTU is a measure unit of energy, defined as one thousand the British thermal unit (symbol: BTU). The "M" stands for one thousand, distinguishing with the SI mega (M) prefix, which stands for one million. In order to avoid confusion, many companies and engineers use MMBTU which stands for one million BTU.

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