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# COLD CHAIN TECHNOLOGY BRIEF

2025

## COMMERCIAL, PROFESSIONAL, AND DOMESTIC REFRIGERATION

# SUMMARY

This brief provides a comprehensive overview of the role and challenges of commercial, professional, and domestic refrigeration within the global cold chain. These systems are essential for preserving food, medicines, and vaccines, yet they face persistent issues related to temperature control, energy consumption, and refrigerant emissions. The cold chain remains vulnerable to inefficiencies, especially in its final stages, where inconsistent temperatures and poor maintenance practices can compromise product safety and increase environmental impact. Despite technological progress, a significant share of products still exceeds recommended temperature thresholds, and energy use remains high across all sectors.

This document highlights the dual environmental impact of refrigeration systems: indirect emissions from electricity consumption, and direct emissions from refrigerant leakage. While commercial refrigeration systems are particularly prone to leaks, domestic systems are increasingly adopting low global warming potential (GWP) refrigerants such as R-600a. Energy efficiency improvements, such as inverter-driven compressors, better insulation, and smart controls, are key to reducing emissions. However, data gaps persist in many regions, especially in developing countries, limiting the ability to assess and improve performance globally. Emerging technologies, including solid-state refrigeration, offer promising alternatives but require further development to become commercially viable.

To effectively address these challenges, countries may consider the establishment of national governance structures, such as dedicated refrigeration committees. These bodies can play a pivotal role in coordinating policies, integrating refrigeration considerations into national climate and energy strategies, and ensuring alignment with international commitments like the Paris Agreement and the Kigali Amendment.

The brief further recommends the development of harmonised guidelines, enhanced training programs, and robust regulatory frameworks to promote the safe, efficient, and sustainable operation of refrigeration systems across all segments of the cold chain.

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# TABLE OF CONTENTS

# INTRODUCTION

Often overlooked, the food and health cold chain sector is nonetheless significant in the global economy and indispensable for ensuring food security as well as protecting human and animal health.

An estimated 13% of the world's food is lost in the supply chain from post-harvest up to, but not including, retail. Additionally, a further 19% of food available to consumers is then wasted at the retail, food service[i] and household levels (UNEP, 2024). Conservation of food from supply chain to consumption helps to reduce global hunger, greenhouse gas emissions related to food production, and burden on resources spent to produce food. According to the IIR, expanding the global cold chain infrastructure could save 475 million tonnes of food annually, enough to feed 950 million people (Sarr et al., 2021).

Refrigeration technologies are some of the most energy-intensive technologies used in the food supply chain and pose several sustainability-related challenges. For example, in food retail, refrigeration accounts for 40% to 60% of electricity use in supermarkets (Mylona et al., 2018). According to the IIR, the global carbon impact of food cold chain equipment is less than 1% of global greenhouse gas emissions, increasing to 3-3.5% in developed countries (Sarr et al., 2023, p. 2). Indirect emissions from energy consumption of refrigeration equipment represent the majority of this impact.

The OECD-FAO Agricultural Outlook 2025-2034 indicates that with rising incomes and urbanisation, global demand for food products is set to rise, especially in developing and emerging countries (United Nations, 2025). Modernising the global cold chain, based on efficient technologies and sustainable refrigerants, could reduce the $CO_2$ emissions of the current cold chain by nearly 50% (Sarr et al., 2023), therefore contributing to a "win-win" scenario in which nourishment improves for all while agricultural emissions are kept low (United Nations, 2025).

This brief examines the current state of commercial, professional, and domestic refrigeration technologies, which are primarily used in the final stages of the cold chain. It identifies key challenges and explores strategies to improve performance and environmental sustainability.

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[i] The industry is concerned with processing, preparing, preserving, distributing, and serving of foods and beverages.
Source: https://agrovoc.fao.org/browse/agrovoc/en/page/c_3020

# THE COLD CHAIN

The "cold chain" refers to the various stages that a refrigerated product passes through from harvest to human consumption. Lowering the storage and transport temperature of food products slows spoilage by reducing metabolic processes in fruits and vegetables and stopping bacterial growth in animal products stored at frozen temperatures (➔ Figure 1). Maintaining proper temperature control from harvest to consumption is essential to preserve product quality and extend product life throughout storage and transportation.

The economic investment in food refrigeration technologies throughout the cold chain is tremendous in terms of refrigeration equipment worldwide. The IIR estimates that there are approximately 2.2 billion domestic refrigerators and 120 million units of commercial refrigerated equipment (including condensing units, stand-alone equipment and centralised systems) in operation worldwide (Baha et al., 2025). There are also 5.7 million refrigerated road vehicles (vans, trucks, semi-trailers or trailers), 2 million refrigerated containers and 85,000 cold stores (Baha et al., 2025).

Guidelines and decision-making frameworks for selecting cold chain technologies that are environmentally sustainable, energy-efficient, and economically viable are currently fragmented across various institutions and stakeholder groups within the same country.

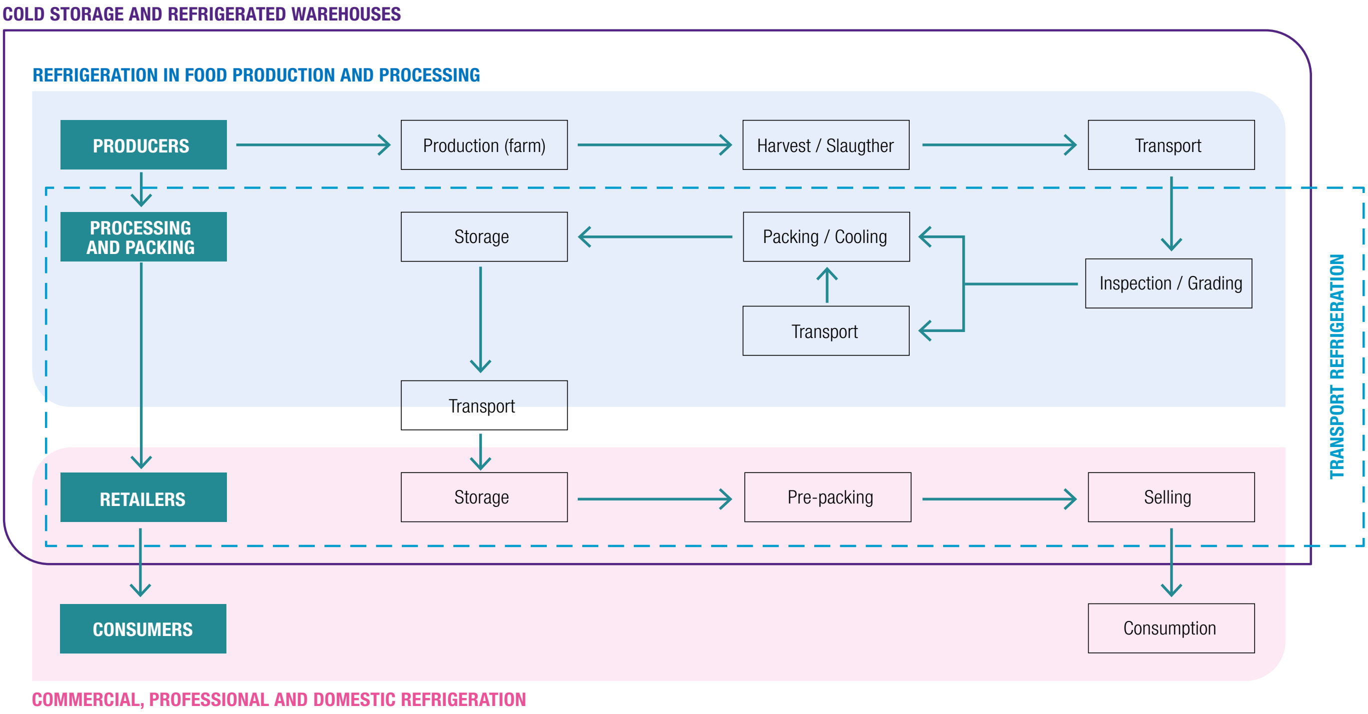


Figure 1 | Overall cold chain with the different components.

# OVERVIEW OF COMMERCIAL, PROFESSIONAL AND DOMESTIC REFRIGERATION

Commercial, professional, and domestic refrigeration all occur at the later stages of the cold chain, where the retailer or food service operator stores the food or the consumer purchases the food product.

Commercial refrigeration encompasses supermarkets, convenience stores, bars, and restaurants where food is on display for purchase by consumers (➔ Figure 2). Smaller systems are integrated units of usually less than 3 kW electrical consumption, but the sector also covers larger systems with multiple cabinets served by central refrigeration systems with capacities on the order of dozens of kilowatts. Vending machines, water coolers, drinking fountains and small displays are considered commercial refrigerators in this context.

Professional refrigeration encompasses restaurants, cafés, and fast-food outlets, as well as some supermarkets where food is stored before being prepared for the consumer (➔ Figure 3). Most professional appliances are solid door cabinets used for both chilled and frozen food storage, but blast coolers and freezers are also part of this sector. Most of the cabinets sold are integral cabinets, which are plug in units with their own individual refrigeration system, but remote units, where the refrigeration system is separate from the cabinet, are also available.

At the consumer level, domestic refrigerators are almost universally integral systems with an electrical consumption of 20 W to 150 W.

Figure 2 | Typical commercial refrigerators.

Figure 3 | Typical professional refrigerators.

# CURRENT CHALLENGES AND MARKET TRENDS

## 4.1. Temperature performance

Temperature is the prime factor controlling food quality and bacterial growth on foods. Generally, lower temperatures will achieve longer storage life. For chilled products, there are minimum storage temperatures which are dependent on either the initial freezing point or a point where chilling damage occurs.

### 4.1.1 Temperature control in food service establishments

Globally, temperature control in food service establishments is a critical factor for food safety, yet detailed regulatory guidance and enforcement mechanisms vary significantly across regions. While many countries adopt general food hygiene standards that recommend refrigeration below 5 °C and freezing below -18 °C, the specificity and enforcement of these requirements differ depending on national legislation, infrastructure, and inspection systems.

In Europe, temperature control is more rigorously regulated. Under existing food hygiene regulations, such as Regulation (EC) No 852/2004 and Regulation (EC) No 853/2004, food business operators are required to store perishable goods at safe temperatures, typically below 5 °C for refrigerated items and at or below -18 °C for frozen goods.

Additionally, regulation (EU) 2024/1781 introduces a new framework for ecodesign requirements for sustainable products, including professional refrigerated and frozen storage cabinets (Official Journal of the European Union, 2024a). While it does not directly set temperature limits, it enables future delegated acts that will define performance standards. These are expected to align with existing benchmarks, such as maintaining 5 °C for professional refrigerated cabinets and -18 °C for professional frozen cabinets under ambient conditions of 30 °C and 55% relative humidity.

These performance standards are consistent with both food safety needs and energy efficiency goals (Official Journal of the European Union, 2024a).

### 4.1.2 Temperature control in commercial refrigeration

In commercial refrigeration temperature requirements for equipment, such as remote display cabinets and stand-alone units, are typically defined by food safety regulations, international standards, and specifications set by supermarket chains.

However, a consistent challenge lies in the difference between the recommended temperatures and the actual operating conditions observed in practice. These discrepancies can result from several factors:

- Improper setup or calibration of the refrigeration unit.
- Frequent door openings or overloading by users.
- Variations in the placement of temperature control probes, which may not accurately reflect the warmest or most critical areas inside the cabinet.

Such inconsistencies can compromise food safety, reduce energy efficiency, and make regulatory compliance more difficult. For policymakers, this highlights the need to strengthen monitoring practices, promote standardised testing protocols, and encourage the adoption of smart technologies that ensure accurate and consistent temperature control across all types of commercial refrigeration equipment.

| ASPECT | REGULATION | TEMPERATURE |
|---|---|---|
| Food safety | Reg. (EC) 852/2004, 853/2004, 543/2008 | 0-5 °C (refrigerated), ≤ -18 °C (frozen) |
| Equipment performance | Reg. (EU) 2015/1095, MEPS | 5 °C (refrigerated), –18 °C (frozen)<br>at 30 °C/55% RH |

Table 1 | EU regulations for temperature control in food service establishments.

### 4.1.3 Retail display in the cold chain

Apart from home refrigerators, retail display is the weakest link in the food cold chain. Indeed, compliance to regulations is not homogeneous and there is considerable variability in actual food preservation at the point of sale. Studies in real supermarkets show that between 7% and 35% of the establishments do not maintain the right temperature in refrigerated and frozen foods (Organización de Consumidores y Usuarios, 2015). Studies in UK supermarkets show that even the setpoint temperatures were below the recommended frozen display cabinet temperature, actual product temperatures in most of the studied devices frequently exceeded the maximum recommended temperature limit for frozen products of -12 °C (Talbot et al., 2020). Larger variations on product temperature were found in opened cabinets compared to the doored cabinets, which maintained more consistent temperatures. Frequent and prolonged door openings lead to temperature increases near the front of the case and decreases at the back. Despite these fluctuations, enclosed cases generally provided lower and more uniform product temperatures compared to open cases (de Frias et al., 2020). Temperature fluctuations in frozen foods may cause gradual dehydration resulting in freezer burn and in-pack frost formation (Laguerre, 2008).

Proper management of temperature and time throughout the entire cold chain is crucial to preserve the safety and quality of perishable foods and reduce food waste. However, there are significant weaknesses in current practices and management systems based on time and temperature measurement are required (Mercier et al., 2017).

Temperature irregularities in commercial refrigeration do not end at the point of sale. After products are stored in supermarkets, often under varying and sometimes suboptimal conditions, their transport to consumers' homes can further compromise temperature stability. This stage is frequently overlooked in food safety strategies, yet it plays a critical role in maintaining product integrity.

To mitigate these risks, consumer education and good practices are essential. Refrigerated and frozen products should be selected at the end of the shopping process to minimise exposure to ambient temperatures. Consumers should check expiration dates and avoid items with visible frost, which may indicate prior temperature abuse. For transport, insulated bags are recommended to preserve cold temperatures. Upon arrival at home, products should be promptly stored in the refrigerator or freezer to prevent further temperature fluctuations.

Policymakers can support these efforts by promoting public awareness campaigns, encouraging retailers to provide guidance at point-of-sale, and integrating cold chain continuity into broader food safety and sustainability policies.

### 4.1.4 Domestic refrigerator temperature control

Temperature control of food in the home is vital to limit the risk of growth of pathogenic organisms and ensuing cases of food poisoning. Despite a recommended temperature set below 4 °C, a UK survey of 671 domestic refrigerators found that the overall mean internal temperature was 5.3 °C (Gemmell et al., 2017). A Europe-wide survey found an average temperature of 6.4 °C, with no significant differences among the 16 countries despite their different weather conditions (ANSES, 2025).

These findings raise concerns not only for public health but also for energy efficiency and climate impact. Poorly maintained or inefficient refrigerators often struggle to maintain consistent low temperatures, leading to both higher energy consumption and increased risk of food spoilage. Enhancing the performance of domestic refrigeration appliances through better insulation, smart temperature controls, and user guidance can deliver a triple benefit: improved food safety, lower household energy use, and reduced greenhouse gas emissions. Public awareness campaigns, updated standards for minimum performance, and better consumer information on correct usage could play a key role in addressing this issue globally.

## 4.2 Energy consumption

The environmental impact of refrigeration systems is primarily associated with the energy consumed during their operation. Over the lifetime of the equipment, this energy use contributes to greenhouse gas emissions, mainly $CO_2$ and, to a lesser extent, methane ($CH_4$), when electricity is generated from fossil fuel sources. This impact, known as the indirect effect, is often greater than the direct effect, which results from the release of refrigerants into the atmosphere.

While detailed data is available for regions such as the USA, the UK, and the EU, there remains a significant lack of reliable information on energy consumption from commercial refrigeration in other parts of the world (➔ Figure 4). Many countries in Asia, Africa, and Latin America do not regularly publish sector-specific energy use statistics, making it difficult to assess the scale of refrigeration-related emissions or identify opportunities for efficiency improvements.

### 4.2.1 Energy consumption in food service establishments

According to the U.S. Commercial Buildings Energy Consumption Survey, refrigeration accounts for 15% of the annual energy consumption in a food service building (U.S. Energy Information Administration, 2022). However, without appropriate use or maintenance of refrigeration equipment, energy use can be substantially higher, as illustrated in a

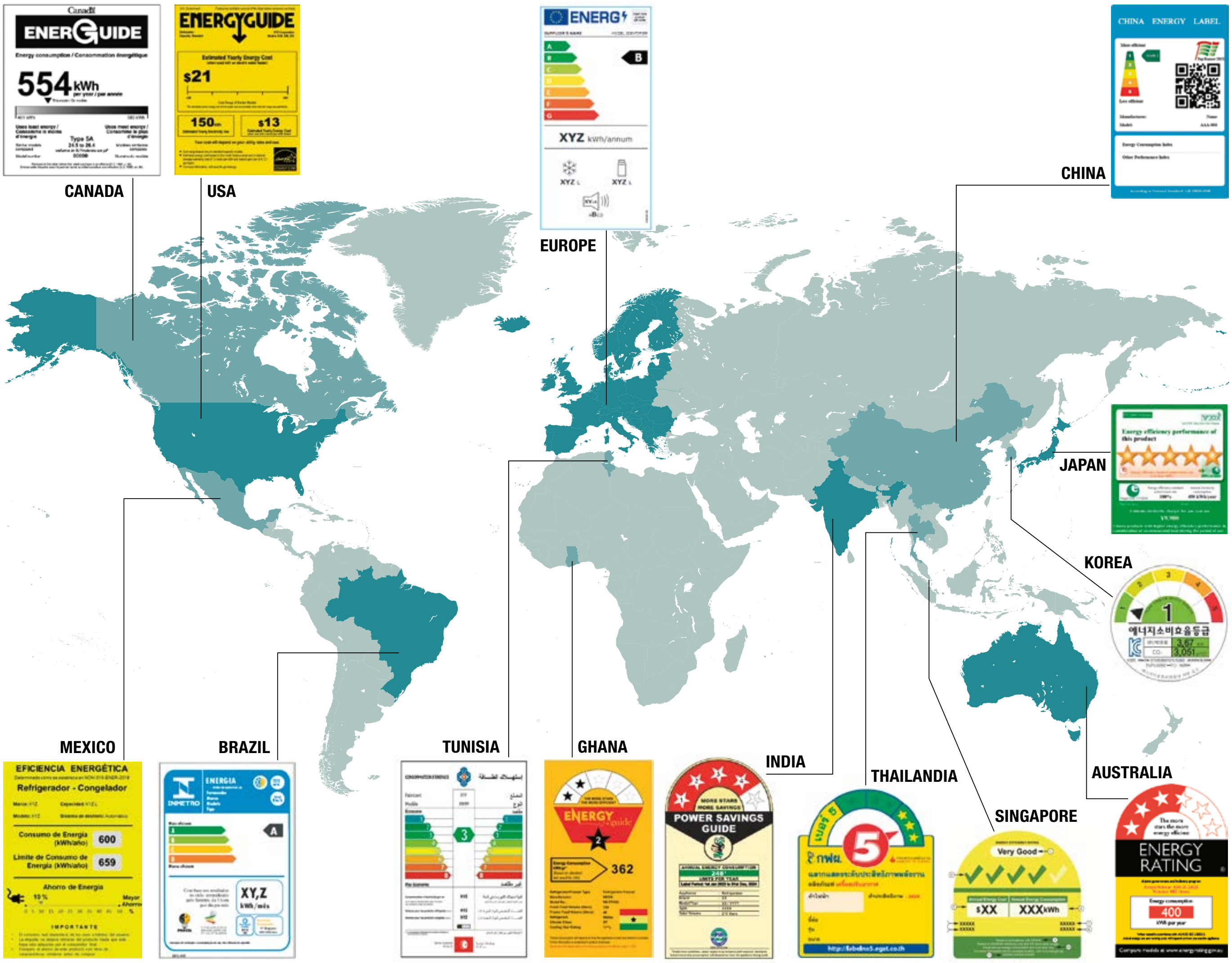


Figure 4 | Typical energy efficiency labels across the globe.

survey of fourteen public house-restaurants, or gastro pubs, in the UK, where refrigeration represented 41% of the daily electricity use due to poor practices (Mudie et al., 2016). Significant energy savings could be achieved by investing in best available technologies and implementing planned preventive maintenance.

In the EU, professional refrigeration was estimated to consume approximately 118 TWh/year of electricity in 2020 (European Commission, 2024). The implementation of the 2015 Ecodesign and Energy Labelling measures led to 40% reduction of the average annual energy consumption per storage cabinet (from 1.5 MWh to 2.5 MWh).

### 4.2.2 Energy consumption in retail supermarkets

Refrigeration is often the largest energy consumer in a supermarket, accounting for 40% to 60% of the electricity used (Mylona et al., 2018), depending on business practices, store format, product mix, shopping activity and the equipment used for in-store food preparation, preservation and display. The annual electrical energy consumption can vary widely from around 444 kWh/m$^2$ sales area in hypermarkets to over 800-1,200 kWh/m$^2$ sales area in convenience stores (Kolokotroni et al., 2019).

Depending on the outdoor climate, significant energy savings can be achieved in supermarkets by implementing technological solutions such as installing doors and efficient lighting on medium-temperature cabinets, upgrading the refrigeration system with overfeed evaporators and parallel compressors, integrating $CO_2$ refrigeration system with heat recovery (more effective in colder climates) or integrating renewable solar energy with thermal energy storage (Thanasoulas and Molinari, 2025).

### 4.2.3 Energy consumption in domestic refrigerators

Domestic refrigerators account for 14.2% of household electricity use in Japan, 14% in the USA, and 21% in South Korea (Biglia et al., 2020). Implemented in about 120 countries (UNEP, 2023a), energy efficiency standards and labelling programmes significantly contribute to reducing the energy consumed by domestic refrigerators and freezers worldwide. The IEA estimated that energy consumption from new domestic refrigerators and freezers decreases by an average of 2.3% per year across all countries with such programmes in place (IEA/4E TCP, 2021).

Although energy use varies between home and standard test setting, Mavandad and Malinowski (2022) recommended a target annual energy consumption of 279 kWh for a 400-litre frost-free refrigerator-freezer operating at an ambient temperature of 24 °C, based on U4E's Model Regulation Guidelines and the IEA's energy performance indicators. Minimum energy performance standards (MEPS) in Canada, the EU, Japan, the UK, and the USA already meet this target, with India very close (above by 1 kWh/year). Countries with MEPS above the 279 kWh/year target include Indonesia (677 kWh/year), Brazil (524 kWh/year) and South Africa (598 kWh/year) (Mavandad and Malinowski, 2022).

## 4.3 Refrigerant (direct) emissions

The direct environmental impact of refrigeration systems comes from the GWP of the refrigerants used and the amount released into the atmosphere. These emissions can occur through leaks, accidental releases, or improper handling and disposal of the refrigerant. Even small quantities of high-GWP refrigerants can contribute significantly to climate change.

### 4.3.1 Refrigerant emissions in food service establishments

The IPCC (Intergovernmental Panel on Climate Change) estimated direct emissions from food service cabinets at 0.5-3% (IPCC/TEAP, 2005). A review of more recent literature revealed that food service-specific emissions are not disaggregated in newer assessments, preventing an updated assessment. In Europe, refrigerant leakage is relatively low as most cabinets operate using low-GWP refrigerants, such as R-600a or R-290 (Eid et al., 2025; ENOUGH, 2024a). Refrigerant emissions in food service establishments, particularly in catering and restaurant settings, remain an under-researched area, despite their potential environmental impact. While the Carbon Trust highlights that catering operations rely heavily on energy-intensive refrigeration equipment, it does not quantify refrigerant emissions in this sector (Carbon Trust, 2012).

Direct emissions from refrigeration systems can be effectively reduced through a combination of technological and operational improvements. This includes investing in advanced refrigeration technologies that minimise leakage, ensuring operators are properly trained in handling and maintenance procedures, and transitioning to refrigerants with low GWP.

### 4.3.2 Refrigerant emissions in retail supermarkets

Supermarkets and large food retailers have been studied extensively, with data from the U.S. Environmental Protection Agency (EPA) GreenChill Partnership showing that traditional systems can leak up to 25% of their refrigerant charge annually (U.S. Environmental Protection Agency, 2022). Refrigeration racks, walk-in coolers, and display cases have been identified as common leak sources (MSA Safety, n.d.).

Supermarkets in developed countries are rapidly transitioning to natural refrigerants such as R-744 ($CO_2$) (Hines, 2024), R-290 (propane), R-1270 (propylene) (Garry, 2018; Pearson, 2015) or isobutane (R-600a). Reducing refrigerant charge or applying secondary fluids with centralised refrigeration systems can further reduce refrigerant leakage (ENOUGH (European Food Chain Supply to reduce GHG emission by 2050), 2024b). In order to achieve continuing reductions in refrigerant leakage, it is necessary to gain a better understanding of where and why systems leak. Main leaks can come from pipe or joint failures, or a leaking seal/gland/core located in the compressor pack and the high-pressure liquid line (Francis et al., 2017). Good maintenance records can help to identify high risk areas and components within systems and allow operators to prioritise their refrigerant containment activities (Muradi et al., 2024).

### 4.3.3 Refrigerant emissions in domestic refrigerators

The U.S. EPA notes that while domestic refrigerators typically leak very little during operation, dumping or improper disposal can release the entire refrigerant charge into the atmosphere. A study by the City of Seattle found that 92% of refrigerant loss in domestic applications is due to catastrophic leakage events, such as improper disposal or mechanical failure (City of Seattle, 2020).

Assuming that refrigerant is removed and destroyed at the end of the life of the appliance, refrigerant leakage rates from domestic refrigerators is low, consistent with earlier estimates of 0.1-0.5% (IPCC/TEAP, 2005). For instance, the UK Department for Environment, Food & Rural Affairs (DEFRA) estimates an annual leakage rate of approximately 0.3% for domestic refrigeration, assuming that refrigerant is removed and destroyed at the end of the life of the appliance.

In developing countries where servicing and at the end of life are poorly controlled due to lack of regulation, the leakage rates may be as high as 10% or more (Kumar et al., 2023).

# CURRENT REFRIGERANTS USED AND POTENTIAL ALTERNATIVES

## 5.1 Refrigerants used in food service establishments

Traditionally, the hydrofluorocarbon (HFC) refrigerant R-134a was used in food service cabinets. More recently most manufacturers have moved to R-290, partly due to its low GWP but also because it is an efficient alternative. With cooling systems integrated into single units as opposed to centralised units, meeting hydrocarbon charge limitations around the world has proven to be feasible with commercialised units. In addition, in 2023 the refrigerant charge limits, limited by the safety standard 60335-2-89:2019/COR3:2023, have been increased from 150 g to 500 g for the higher flammability A3 refrigerants. For lower flammability alternatives (A2 and A2L), the limit has been increased from 150 g to 1.2 kg. This increase in the permitted charge satisfies the capacity requirements of food service cabinets by using hydrocarbons.

## 5.2 Refrigerants used in supermarkets

Existing supermarket refrigeration systems are predominately based upon Hydrochlorofluorocarbons (HCFCs), such as R-22, and HFC refrigerants, such as R-404A and R-407C, although use of R-744, hydrofluoroolefins (HFOs) and hydrocarbons (HCs) is increasing. Supermarkets are going through a transition, but it is a slow process due to the high number of stores worldwide. Alternative systems, such as secondary systems, where a fluid such as glycol is cooled by a primary refrigeration system and is then pumped to the cabinets, are often used in Scandinavian countries. Other systems include the use of water to cool the condensers of integrated cabinets and deliver cold air in a central location that is then used to directly cool chilled cabinets. In general, the trend is toward adopting refrigerants with a GWP of less than 150, replacing those previously used. The most used low-GWP replacements are R-744, R-290, R-1270, and some HFO blends such as R-454C, R-454A, or R-455A.

## 5.3 Refrigerants used in domestic refrigerators

With stringent regulations coming into force, the use of hydrocarbon refrigerants has reached broad acceptance among manufacturers of domestic refrigerators worldwide. According to UNEP's 2022 RTOC report, 75% of newly sold domestic refrigerators operate on R-600a, an efficient hydrocarbon refrigerant with a GWP of 3 (Official Journal of the European Union, 2024b), with the rest operating on R-134a (UNEP, 2023b). Generally, refrigerators operating on a hydrocarbon will be helium leak tested prior to being charged with refrigerant at the factory. This leak testing process has been shown to provide a high level of leak detection and, as a result, there have been few instances of leakage of refrigerant in consumer homes. A summary of refrigerants and low-GWP alternatives can be found in ➔ Table 2 with IPCC AR6 values where attainable (Intergovernmental Panel on Climate Change (IPCC), 2023).

**REFRIGERANTS FOR COMMERCIAL, PROFESSIONAL, AND DOMESTIC REFRIGERATION**

| **Types of refrigeration** | Current higher GWP refrigerants ($GWP_{100}$ $kg \cdot CO_2$) | Alternative lower GWP refrigerants ($GWP_{100}$ $kg \cdot CO_2$) |
|---|---|---|
| **Commercial** | Centralised and integrated:<br>HFC-134a (1530);<br>HFC-404A (3920),<br>HCFC-22 (1960) | Centralised: R-744 (1)<br>Centralised and secondary loop: HC-290 (0.02), HC-1270 (1.8)<br>Centralised and integrated: wide range of HFO and HFO blend refrigerants (R-454C, R-454A, R-455A) |
| **Professional** | HFC-404A (3920), HFC-134a (1530) | HC-290 (0.02), HC-600a (3), wide range of HFO and HFO blend refrigerants (R-454C, R-454A, R-455A) |
| **Domestic** | HFC-134a (1530) | HC-600a (3) |

Table 2 | Summary of current and alternative refrigerants.

# EMERGING TECHNOLOGIES IN REFRIGERATION

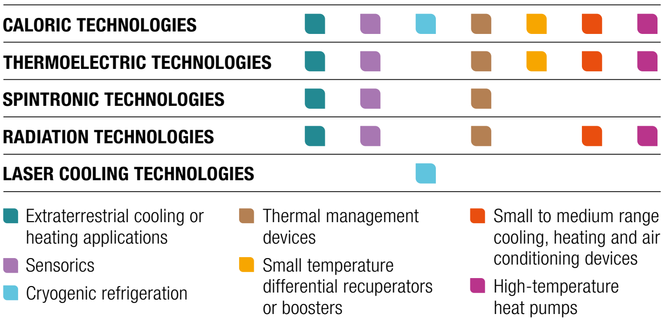
While conventional vapour-compression systems dominate domestic, commercial, and professional refrigeration, emerging technologies are being explored to address environmental and energy efficiency challenges. One promising area is solid-state refrigeration and heat pump technologies, which use refrigerants in the solid state that respond to external stimuli, such as magnetic or electric fields, mechanical stress, or voltage potentials, to produce a cooling or heating effect. These materials can be integrated into thermodynamic cycles to create refrigerators, heat pumps, or even energy harvesting systems.

Although still in the early stages of development, solid-state systems offer the potential for low-noise, compact, and environmentally friendly alternatives to traditional systems. However, significant research and development efforts are still needed to improve performance, scalability, and cost-effectiveness before these technologies can compete in mainstream refrigeration markets.

➔ Figure 5 illustrates solid-state refrigeration and heat pump technologies. It also highlights some of their most promising applications, both those already in use and those expected in the future. A major advantage of these technologies is that solid refrigerants cannot leak into the environment and, in many cases, can be recycled for use in new devices. These refrigerants are often environmentally friendly and are readily available. Some of the technologies allow silent operation without moving parts or vibrations. They also enable operation at temperature levels that cannot be reached by conventional technologies. Significant research efforts have been dedicated to certain solid-state approaches because of their potential to achieve efficiencies comparable to, or even exceeding, those of commercially available systems. In other cases, their scalability to miniaturised devices opens possibilities for novel thermal management solutions that traditional technologies cannot address.

Caloric technologies for cooling and heat pumps can be further distinguished as: magnetocalorics (Kitanovski, 2020; Klinar et al., 2024), electrocalorics, mechanocalorics (Lloveras, 2023; Mañosa and Planes, 2017; Wang et al., 2023), ionocaloric (Lilley and Prasher, 2022) and multicalorics (Hou et al., 2022). Thermoelectrics based on the Peltier effect is a well-established technology, relying on the continuous flow of charge carriers through multiple p- and n-type semiconductors (Shi et al., 2020). As a result, heat is continuously pumped from the heat source to the heat sink. This technology is particularly attractive for the thermal management of electronics and sensors, although it is known for its very low efficiency. Nevertheless, thermoelectric devices can achieve very high-power densities, surpassing those of many existing cooling methods (Chen et al., 2022). Spintronics is an emerging field that exploits various physical phenomena (e.g. spin Peltier effect, Ettingshausen effect), capable of generating temperature gradients, which can, in principle, be used for cooling or heat pumping (Uchida and Iguchi, 2021).

However, it is more likely that these technologies will find practical applications in sensing and in the thermal management of electronic devices. Radiative cooling is based on the manipulation of surface properties. Within this context, one can distinguish between approaches such as thermionics (Bescond and Hirakawa, 2020) and daytime radiative cooling (Su et al., 2023). Thermionic cooling relies on heat removal through thermionic emission, in which electrons are emitted from a heated electrode into a vacuum or low-pressure environment. Solid-state laser cooling is a technique that uses laser light to reduce the temperature of solid materials, in some cases reaching well below room temperature. The process is based on the principle of optical refrigeration, in which specially engineered materials, often doped with rare-earth ions, absorb laser photons and then re-emit them in a way that produces a net cooling effect. Recent advancements in this field have achieved remarkable results, including cooling materials to cryogenic temperatures below 100 K (Pant et al., 2020; Thomas et al., 2021).



| | Extraterrestrial cooling or heating applications | Sensorics | Cryogenic refrigeration | Thermal management devices | Small temperature differential recuperators or boosters | Small to medium range cooling, heating and air conditioning devices | High-temperature heat pumps |
|---|---|---|---|---|---|---|---|
| **CALORIC TECHNOLOGIES** | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **THERMOELECTRIC TECHNOLOGIES** | ■ | ■ | | ■ | ■ | ■ | ■ |
| **SPINTRONIC TECHNOLOGIES** | ■ | ■ | | ■ | | | |
| **RADIATION TECHNOLOGIES** | ■ | ■ | | ■ | | ■ | ■ |
| **LASER COOLING TECHNOLOGIES** | | | ■ | | | | |

**Figure 5** | **Some of the most representative solid-state cooling and heat pump technologies and related potential applications.**

# CONCLUSIONS AND RECOMMENDATIONS

The cold chain is a vital logistical and technical system that ensures temperature-sensitive products, such as food, medicines, and vaccines, are kept within safe temperature ranges from production to consumption. The cold chain includes multiple stages: production, transport, storage, and final use. However, the complexity and variety of these stages make the system vulnerable to breakdowns and its technology faces growing environmental pressures.

The final stages of the cold chain rely on commercial, professional, and domestic refrigeration systems. These systems face several technical challenges, including maintaining uniform product temperatures and reducing energy consumption. Studies show that approximately one-third of products exceed recommended temperature limits, highlighting the need for improved temperature control. Doored cabinets have demonstrated better performance in maintaining consistent temperatures.

Energy consumption in refrigeration is also a major concern. The sector is energy-intensive and reducing its carbon footprint requires two key strategies: improving system efficiency to lower indirect emissions and reducing direct emissions by minimising refrigerant leaks and using low-GWP refrigerants. Leak rates are particularly high in commercial refrigeration and addressing this requires better monitoring, maintenance, and technician training. The transition to natural refrigerants is also helping reduce direct emissions.

In domestic refrigeration, progress is already underway. The widespread adoption of R-600a, a natural refrigerant with low environmental impact, shows that the industry is moving ahead of regulatory requirements. Consumers increasingly demand appliances that combine energy efficiency with smart features and reliable temperature control.

Despite ongoing improvements, the cold chain still faces reliability issues and high leak rates in some segments. These challenges call for continued technological innovation and supportive legislation to ensure refrigeration systems can operate safely, efficiently, and sustainably while fulfilling their essential role in protecting public health and food security.

Guidelines and decision-making frameworks for selecting cold chain technologies that are environmentally sustainable, energy-efficient, and economically viable are currently fragmented across various institutions and stakeholder groups within the same country. This fragmentation can lead to inconsistent implementation, missed opportunities for harmonisation, and slower progress toward national and international climate goals.

To address this, the IIR recommends establishing a national governance model, such as national refrigeration committees (IIR, 2025), to structure the sector and ensure that its cross-cutting nature is addressed effectively. These committees can coordinate policies, integrate refrigeration into climate and energy strategies, and align national efforts with global sustainability goals such as the Paris Agreement and the Kigali Amendment.

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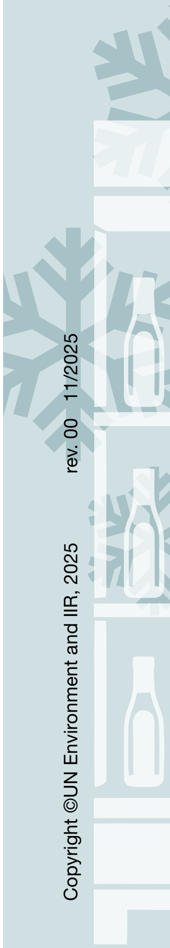

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