Refrigerant leak study – A data-driven insight from Australia

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REFRIGERANTS AUSTRALIA

EXPERTGROUP

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Dedicated to Pat McInerney

The existence of the Cold Hard Facts research series, now in its 19th year, and the basis of this report, is in great part due the support and direction provided by Pat McInerney. Pat worked over much of the past two decades in his position as Director of the team in the Australian Federal Government that implements the *Ozone Protection and Synthetic Greenhouse Gas Management Act*.

Pat was always clear that 'if you can't measure it, you can't do anything about it'. He valued the data and the insights the Cold Hard Facts series has provided to policy makers and the refrigeration and air conditioning industry alike. Through the support he organised, reveals what was once an almost entirely invisible industry. Its activities and impacts that, in the Australian Bureau of Statistics general economic data series, is usually attributed to those industries that are dependent clients of the refrigeration and air conditioning industry.

Pat was Australia's representative to the Meeting of the Parties to the Montreal Protocol for many years, serving in senior positions in that body and often attributed with having a central role in the design of and support for the Kigali Amendment. Pat believed that Australia could also usefully contribute to the objectives of the Montreal Protocol by improving methods for modelling the market for refrigerants and the equipment that relied on them and understanding the complex supply chains and multitude of end uses of refrigeration and air conditioning technology. This report, drawn from the data underpinning the Cold Hard Facts research series is an example of that contribution to the global objectives of the Montreal Protocol.

CONTENTS

TABLES

FIGURES

1 Executive summary

This report provides an in-depth analysis of refrigerant leak rates across Australia's refrigeration and air conditioning (RAC) industry from 2006 to 2022.

Australia is a leading participant in the Montreal Protocol, which aims to reduce the use of ozone-depleting substances (ODS) and hydrofluorocarbons (HFCs) which are widely used in the RAC sector. Under this international agreement, Australia has committed to phasing out 85% of its HFC consumption by 2036.

The report's data, supported by Australia's Cold Hard Facts research series (DCCEEW 2024a, DCCEEW 2023a), reconciles refrigerant usage for system charging and maintenance with service demands, and end of life residual refrigerant charges. This date enables accurate calculation of leak rates in many product categories.

The findings in this report underscore the importance of a shift in focus from simply reducing refrigerant imports to actively managing refrigerant leaks throughout the lifecycle of RAC equipment. This includes improving technician training, eliminating preventable refrigerant leaks, recovering refrigerants, and destroying or reconditioning them for re-use at the end-of-equipment life.

Refrigerant leaks are a critical issue, as they contribute to both greenhouse gas emissions and inefficiencies in system performance that result in greater electricity use. In 2022, refrigerant leaks in Australia were responsible for 6.9 Mt of CO_2-e emissions and caused further energy-related emissions through additional electricity usage.

When evaluating average economy-wide leak rates, it is important to acknowledge that as older equipment retires and is replaced with newer designs, leak rates of new equipment have been consistently lower. As a result, the average leak rates across a product category tend to decrease over time.

In the past, leak rate estimates have varied over time for several reasons, but primarily due to limited availability of primary data. Many early estimates were based on the expert opinions of engineers and technicians in the field, and thus were to some extent subjective. More recently in Australia, fundamental research has provided hard data on leak rates of equipment in operation, and on refrigerant charge remaining at the end of equipment life. This research underpins the much higher confidence we have in the leak rates published in this report.

The report confirms that, while some common causes of leaks have been effectively eliminated over the last decade, the majority of the remaining causes of direct emissions are preventable. These causes are largely due to poor-quality equipment and materials, use of components that are susceptible to leaking, substandard installation practices, inadequate maintenance, and failure to correctly remove refrigerants when equipment reaches the end of its service life.

The report reviews the key sources of emissions from the leakiest category of equipment - commercial refrigeration equipment - caused by failures of containment in condensers, evaporators, joints, valves, connection points and pipework.

Although direct emissions from this equipment category have improved significantly in the course of the last 20 years, the cold chain sector could still deliver sustained reductions in largely avoidable leaks in the lead up to the 2036 HFC phase down target.

The findings underscore the importance of continuous monitoring, clear regulatory measures, and skilled maintenance as key to further reducing leak rates across the RAC industry. These changes would minimise the environmental impact of equipment while improving equipment efficiency. Table 1 provides a summary of the current leak rate estimates in Australia for the main product categories.

Table 1: Summary of annual leak rates in Australia

	Annual leak rate
Mobile air conditioning	
Small MAC [1]	7.5%
Large MAC [2]	9%
Stationary air conditioning	
Window/wall units	3%
Non-ducted single split systems	4%
Ducted split systems and light commercial	4%
Chillers	5%
Cold chain	
Domestic refrigeration [3]	<1%
Self-contained commercial refrigeration	<1% to 3%
Remote condensing units	15%
Supermarket: Major chain	11%
Supermarket: Independent	15%
Industrial refrigeration and cold storage	15%
Road transport refrigeration	17.5%
Marine refrigeration [5]	17.5%

Notes:

1. Small MAC comprises passenger and light commercial vehicles; compartments of rigid, articulated and non-freight trucks; and small buses with a GVM less than 4.5 tonnes.
2. Large MAC includes larger buses and coaches, locomotives, passenger trains and trams.
3. Domestic refrigerators are no longer repaired, meaning that once the refrigeration system stops functioning, they are not economical to repair and service consumption is zero.
4. There is a wide variety of self-contained commercial refrigeration equipment ranging from devices that have similar technical characteristics to domestic refrigerators with minimal leak rates of less than 1% that are not economical to repair to equipment that is economical to repair that have higher leak rates of up to 3% per annum. There are also numerous varieties of low cost, poor quality self-contained equipment types that have short lifespans of less than seven years that cannot be repair and are typically discarded. As a result, service consumption and leak rates are zero.
5. Portable air conditioners are non-serviceable appliances, meaning that once they stop functioning, they cannot be repaired and are typically discarded. As a result, service consumption and leak rates are zero. However, in most cases, the entire refrigerant charge is eventually released, either immediately upon disposal or gradually over time as the unit deteriorates.

2 Introduction

2.1 Background

The Montreal Protocol on Substances that Deplete the Ozone Layer (the Montreal Protocol) is an international agreement made in 1987. It was designed to stop the consumption of ozone depleting substances and reduce their concentration in the atmosphere to protect the earth's ozone layer. In 2016, the Parties to the Montreal Protocol agreed to set binding, progressive phase down obligations for the 18 primary hydrofluorocarbons (HFCs). While these HFCs do not deplete the ozone layer, they are potent greenhouse gases commonly used as replacements for ozone depleting substances.

Australia takes an active role in ongoing Montreal Protocol negotiations, ensuring that actions are scientifically based and technically feasible, and that developing countries are supported in their efforts to phase out ozone depleting substances and phase down HFCs. Australia commenced its phase down of bulk HFC imports in 2018 through new measures that will reduce consumption of HFCs by 85% of a baseline of 10.6 Mt CO_2-e by 2036.

Over the last several years, the Montreal Protocol and the broader international community have increasingly focused on how activities within countries influence emission rates. This focus on 'lifecycle refrigerant management' includes ensuring there is a trained workforce, the banning of disposable cylinders, refrigerant recovery from operating equipment during servicing and repairs, and reclamation/destruction of refrigerant in equipment that has reached the end of its life.

Understanding the benefits of these activities implicitly relies on knowing how much refrigerant is lost from operating equipment and thus how much remains in systems throughout their life and at the point of disposal. Concerningly, global knowledge of leak rates is poor. There is little robust data on losses from operating equipment or on residual refrigerant charges in the large stocks of equipment that reach the end of their useful life.

For the past 20 years, Australia has been actively developing and verifying data in this area, including tracking imports of refrigerant in equipment and as bulk refrigerant imports into Australia for the past 20 years. Additionally, we have an annual assessment of the industry through the Cold Hard Facts research series. This series underpins a detailed and world class assessment of the bank of HFCs employed in the Australian RAC sector.

2.2 Objectives of this report

The objectives of this report are to provide an insight into the Australian leak rate data. This report also aims to consider the methods which are employed to establish leak rates across the stock of RAC equipment in the Australian economy. The hope is by making this information widely available others can use it as a basis for modelling and addressing direct emissions of refrigerant in their own economies. In this report we:

- Provide detail on the data and data collection processes. These data processes underpin estimates of leak rates of various equipment types in Australia, both currently and in the past. Examining how the data is derived and assessed for quality is important to ensure accurate estimates.

- Explain the methodology for how the leak rates are calculated from the collected data and how this process has been adapted over time.
- Utilise data from Cold Hard Facts 4 (DCCEEW 2024a) and its previous editions to present longitudinal analysis of leak rates across the primary product segments.

This document provides the basic framework of data and methods required to model refrigerant emissions as it has been done in Australia. To apply this framework to another national economy or region, participants will require an inventory of equipment stocks similar to the inventory that underpins the Australian research series. That said, there are likely similarities in leak rates across various economies, particularly given the predominance of a number of equipment manufacturers.

2.3 Definition of refrigerant leaks

The annual leak rate of a particular type of equipment is expressed as a percentage of the initial charge that is lost per annum and is calculated as the sum of:

- Refrigerant that is lost during installation and commissioning.
- Gradual leaks during normal operation.
- Losses during service and maintenance.
- Catastrophic losses caused by a result of a breakdown or failure of containment, amortised over the life of the equipment.
- Refrigerant lost along the supply chain while being decanted, transported or handled.

For mobile air conditioning systems, the annual leak rate includes losses resulting from vehicle collisions, which are categorised as catastrophic losses.

The annual leak rate does not include losses at end of equipment life. Total direct emissions include leaks from operating equipment plus end-of-life (EOL) emissions, less any amount that is recovered and destroyed. In Australia a volume equal to around 20% of refrigerant estimated to be contained in equipment at end of life is recovered and either destroyed or reclaimed every year (DCCEEW 2024a).

The service rate of a particular type of equipment is the refrigerant consumed (leaks or catastrophic losses) to maintain the equipment in service, expressed as a percentage of the initial charge per annum. This does not include refrigerant consumed charging, or adding to a partial charge, for new equipment at point of installation.

2.4 Main factors that influence leak rates

It is considered a truism that a significant proportion of refrigerant losses arises from a small number of systems. These losses are primarily due to failures caused by poor design, installation, or maintenance. However, refrigerant leakage can occur in all refrigeration and air conditioning systems during normal operation. Without regular maintenance, these leaks can result in systems becoming undercharged over time.

The rates that different types of equipment leak over a period vary significantly depending upon (*inter alia*);

- Type of equipment (i.e. self-contained versus remote).
- Design of equipment (i.e. flared connections, schrader valves, type of condenser, flexible hoses, mechanical connections, leak detection).
- Quality of the equipment (i.e. poor quality/design evaporators or condensers, thin or pitted copper).
- Operating conditions (i.e. vibration, corrosion, heat).
- Age of equipment.
- Pressure of refrigerant.
- Maintenance routine.
- Skill and workmanship of the technician installing, commissioning and maintaining the equipment.
- Correct tools (i.e. flaring tools).
- Price of refrigerant can directly influence the rate of recovery and recycling, and indirectly equipment leaks.
- Government policies, environmental stewardship and economic incentives.

Slow leaks can often continue undetected for extended periods of time where automatic leak detection systems and/or preventative maintenance are absent. These undercharged systems lead to poor plant performance and a significant energy penalty due to long hours of operation of an undercharged system. This makes the compressor work harder for longer to deliver the required temperature conditions. With a medium to large refrigeration system, the trigger for a leak is generally a temperature alarm. In many instances 30% of the charge can be lost by the time the alarm is tripped.

In 2022 the Australian Government undertook a series of laboratory bench tests under a controlled environment. The aim of these tests was to assess the excess energy used when common faults, such as undercharged systems were applied. The tests ultimately demonstrated the benefits of regular equipment maintenance. The tests included a refrigerated display cabinet, walk-in cool room, non-ducted split AC system and ducted light commercial rooftop packaged unit. The results indicated up to 20% energy losses across most faults tested (see DCCEEW 2022 for test reports and further details).

2.5 Leak rate improvements over time

When considering average economy-wide leak rates it is important to recognise that as older equipment retires and is replaced with new designs leak rates of new equipment are nearly universally found to be lower. An effect of replacing equipment is that the average leak rates across a product category reduces over time.

The evolution of wall-hung and ducted split air conditioning equipment demonstrates this design evolution. For instance, the older generation equipment from the 1990s and the 2000s, contained HCFC-22 and had average annual leak rates in the order of 8% to 12%. In contrast, the current generation of models in the fleet have leak rates of around 4% per annum. New equipment recently installed will have lower leak rates than the current fleet, particularly for the first five years. Another factor that contributed to the reduced leak rates was the refrigerant transition from HCFC-22 to HFC-410A. This new refrigerant required an improved flaring angle. This meant that technicians had to upgrade their old flaring tools. The shift in angle improved the strength of the flared connection and helped prevent leaks under the higher pressures that HFC-410A systems operate at.

The Australian market has demonstrated that as the cost of refrigerant increases, and as field practices improve, leak rates decline. This decline can happen rapidly. Such trends were amply demonstrated by the market response to the rapid rise in the price of HCFC-22 and HFCs after the introduction of the equivalent carbon tax in Australia in 2012. Dramatic price increases delivered an immediate market focus on switching to lower GWP equipment, recovery and recycling of refrigerant, leak reduction and minimisation of handling losses. The repeal of the equivalent carbon tax less than 18 months later was followed by an increase in refrigerant usage, as the economic driver for improved containment vanished from the market.

The Australian supermarket industry is another example of the capacity of the industry to reduce direct emissions. Leak rates in the early 2000s were above 20% per annum. Additionally, the leak rates published by the Australian Greenhouse Office in 2008 for commercial refrigeration applications were 23%. Current market intelligence and reconciliation of usage now indicates that leak rates of HFC 404A and HFC-134a are likely to be less than half this within the main supermarket chains. This trend has likely been driven by a combination of cost control, greenhouse emissions reporting obligations, and adoption of emissions reduction policies by the corporations involved. One major supermarket chain in Australia achieves leak rates in single digits because they adopt the F-Gas service regulation approach. The corporation also makes the contractor accountable to achieve low leak rates and penalise them if they are not achieved.

2.6 Sources and causes of mechanical refrigerant losses

Expert Group conducted a comprehensive study in 2010. The study investigated the sources and causes of mechanical refrigerant losses in medium-sized refrigeration systems operating at the time of publication.

The report, titled *"Refrigerant Emissions in Australia: Sources, Causes, and Remedies"* provides in-depth insights into these mechanical losses (DCCEEW 2010). The study surveyed over 150 refrigeration technicians and contracting businesses engaged in the installation, servicing, and repair of refrigeration equipment. Participants were asked to identify and discuss the primary sources and causes of leaks they had encountered or repaired within the preceding 24 months.

The study found that sources of leaks are generally components that fail and cause refrigerant loss. Causes of leak, however, are often related to system design, performance characteristics, and workplace practices that increase the likelihood of leaks. The likelihood of leaks is often due to accelerating degradation and eventual failure of equipment components.

Table 2 presents data on sources of mechanical refrigerant leaks, compiled from the 2010 survey and updated with comments from 2024 interviews. Each row identifies a different type of component or connection associated with medium-sized refrigeration systems. These components are accompanied by two key columns:

1. **2010 Survey Result**: A numerical value indicating the percentage of those surveyed that had experienced or repaired leaks associated with the source within the last 24 months based on the 2010 survey.

2. **Comments from Interviews in 2024**: Qualitative feedback that updates or contextualises the 2010 data based on more recent interviews with industry professionals.

This table aims to demonstrate how the sources of refrigerant leaks have evolved over time and identifies ongoing areas of concern within the industry.

The 2024 review indicates that over 25% of the leak sources reported in 2010 have been effectively eliminated through the implementation of new components and processes. A notable example of this progress is the transition from schrader valves, service valves and pressure gauges to electronic sensors and digital controls. Additionally, 45% of the leak sources identified in 2010 have either become less prevalent due to improved practices and upgraded components or are in the process of decreasing as the industry adopts higher-quality components, manufacturing processes, and materials. However, 30% of the causes reported in 2010 continue to be significant or common sources of leaks, such as flare joints and return bends on evaporators and condensers.

Overall, addressing these issues requires a continued focus on ensuring quality installations, combined with good equipment and materials, and preventative maintenance practices. The survey results highlight that effective maintenance and skilled technicians are critical to reducing leaks in existing systems.

Table 2: Sources of mechanical refrigerant leaks on commercial refrigeration equipment

Sources of mechanical refrigerant losses	2010 Survey result	Comments from interviews in 2024
The percentage shown for the 2010 survey results is the portion of those surveyed that had experienced or repaired leaks associated with the source within the last 24 months.		
Flare joints	88%	Still a notable source of leaks. Many technicians now prefer to eliminate them by using soldered joints where possible to reduce leakage.
Return bends on evaporators or condensers	86%	Continue to be a major source of leaks, primarily due to the poor quality of coils. Leaks often occur at the welds on return bends; within the coil where fins are attached to copper tubes; or around the end plates where the copper pipes can be very thin. Evaporators are more prone to failure due to the corrosive environments (i.e. food acids).
Schrader valves	83%	These are no longer considered a significant problem as they are less frequently used. Technicians now access system information via refrigeration controllers, reducing the need to use pressure gauges.
Mechanical joints (e.g. flanges on filter driers)	65%	These joints remain a common source of leaks.
Thermostatic expansion valve	63%	Mechanical thermostatic expansion (TX) valves remain a common source of leaks, particularly at the flared nut on the low-pressure side. However, this issue is expected to diminish over time as electronic TX valves increasingly replace mechanical ones. Electronic TX valves are less susceptible to refrigerant leaks due to their sealed construction and the elimination of flared connections.
Brazed joints	62%	While soldered joints can be problematic on lower-quality equipment, they are generally reliable when installed by skilled technicians who understand proper welding techniques and vibration elimination.
Shaft seals (open type compressors)	58%	The large majority of open-drive compressors with shaft seals have retired and are no longer an issue.
Pressure switch connections	57%	Connection points of pressure switches continue to pose challenges, with additional concerns related to bellow failures.
Condenser failure	54%	Still a notable source of leaks, not as significant as evaporators.
Shut off and ball valves	49%	These components are still potential sources of leaks, though they are less problematic now compared to the past, partly due to less frequent usage.
Copper capillary tubes	45%	Though not as common anymore, when used, they are usually assembled in a controlled environment at the factory, which helps minimise leaks in the field.
Condensate tray pipe work	45%	This issue is reducing as there are more stainless steel pipes used in drain trays.
PVC flexible hose lines on HP/LP	40%	These hoses were initially problematic, but their quality has improved over time. Proper installation to avoid rubbing due to vibration can minimise the risk of leaks. Can be affected by UV with high exposure.
Leakage from a compressor body	35%	This issue is now very rare with the current range of compressors in service.
O-rings	28%	Less problematic now compared to the past, due to less frequent usage.
Pressure relief valves and fusible plugs (over-pressure protection)	19%	The connections of these valves can still be a source of leaks.
Piercing and line tap valves	18%	These are no longer used as service tools, and therefore, are no longer a source of leaks.
Fusible plugs	12%	Fusible plugs have mostly been replaced by pressure relief valves, though the connections of these valves can still be a source of leaks.

(Source: DCCEEW 2010)

3 Data collection and bank mass flows

3.1 Data collection and analysis

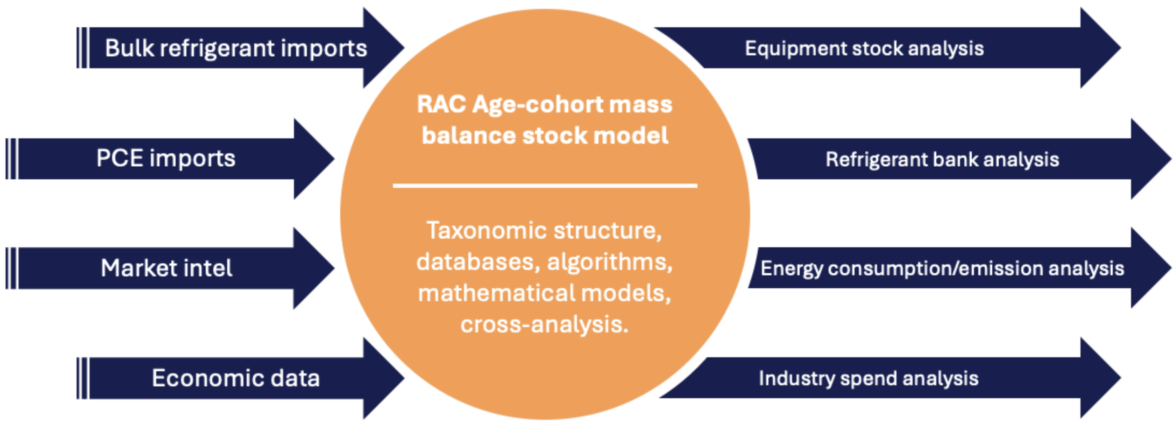
The Cold Hard Facts (CHF) research series includes written reports and an extensive database built on a stock model of all RAC equipment employed in the Australian economy. The Expert Group RAC Age-cohort mass balance stock model (RAC Stock model) has been developed over more than a decade and a half and is among the most comprehensive and extensive stock models of RAC equipment for any economy in the world. The model has provided unique insights into the changes of this industry in Australia, benefitting policy makers and the industry.

The published reports present a technological and economic snapshot of the RAC industry in Australia. The latest publication, Cold Hard Facts 4 (CHF4), is a comprehensive review of industry data from 2022. CHF4 compares the main findings with a similarly extensive study (Cold Hard Facts 3) published in 2017 based on 2016 industry data. More concise and focused reports that provide updates on trends and key aspects of the RAC industry, have been published in 2019, 2020, 2021 and 2022 (see DCCEEW 2024a and DCCEEW 2023a for links to all reports including CHF2 published in 2013 and CHF1 published in 2007).

The CHF4 model reveals that RAC equipment in Australia accounts for approximately 24% of the electricity consumption from the national grid. In 2022, indirect emissions from energy consumed for RAC services were 51.6 Mt CO_2-e (average emission intensity factor of the Australian grid electricity generation 0.73 kg CO_2-e/kWh in 2022), and refrigerant leaks contributed an additional 6.9 Mt CO_2-e. Combined direct and indirect emissions from RAC equipment represented 12.6% of Australia's total emissions in 2022, which amounted to 464.6 Mt CO_2-e.

Figure 4 provides an illustration of the data collection and model framework.

Figure 1: Data collection and model framework



The sources of this data include:

- Bulk refrigerant and pre-charged equipment imports by quantity, mass, species, licence holder, and product category from 2006 to 2022.

- Quarterly market intelligence reports since 2012. More than 95% of refrigerant wholesale market participants with monthly sales ($ and quantity) of HCFCs and HFCs by species including reporting of refrigerant recovery and recycled to AHRI700 specification contributed to these reports. Refrigerant recycling (re-use of refrigerant without reprocessing to a known standard) data that occurs at trade level is not captured.
- Quarterly market intelligence reports conducted by Expert Group since 2012 with monthly equipment sales ($ and quantity) of refrigeration condensing units, evaporators, compressors, and remote condensers by capacity.
- Refrigerant Reclaim Australia data including volume recovered and destroyed and reclaim volumes.
- Annual sales of air conditioning units by capacity and type including wall hung, cassette, and consoles, and ducted split systems.
- Mobile air conditioning aftermarket survey of HFC-134a usage since 2014.
- Data collected during more than 50 independent technical studies undertaken by Expert Group. These studies investigated aspects of the heating, ventilation, air conditioning and refrigeration (HVAC&R) industry since 2005.
- Analysis of the registered equipment models on the Greenhouse and Energy Minimum Standards (GEMS) data base. This database includes all models legally approved to be sold, along with their associated refrigerant types.
- A broad array of data from Australian Government agencies, including the Australian Bureau of Statistics (ABS) and the Bureau of Infrastructure and Transport Research Economics (BITRE). This data encompasses vehicle registrations, housing, agricultural activity, construction and industry sectors such as food retail and hospitality. Additionally, reports that were developed for Australian Government energy efficiency programs, were utilised.
- Equipment retirement rates that were developed using knowledge of manufacturers' warranty conditions, interviews with suppliers, designers and engineers.
- Reviews of large datasets created for models of energy consumption and Australian energy production.
- Interviews with industry associations and professional bodies for the purposes of other industry and government programs. On occasion, seminars with industry bodies were used specifically for testing the assumptions and parameters of the RAC Stock model.
- Personal communications and interviews with manufacturers and importers of HVAC&R equipment and contractors installing/servicing equipment.

All assumptions inherent to the RAC Stock model, such as retirement rates, are reviewed when new information becomes available to support or improve the assumptions. For example, a field trial recovering and recording refrigerant charge remaining in 1,152 split systems at end-of-life (EOL) by Refrigerant Reclaim Australia (RRA 2021) provided hard data that validated or amended conclusions reached from indirect and small data sets.

Environmental Impacts of Refrigerant Gas in End-of-Life Vehicles in Australia, prepared for the Department of the Environment and Energy (now DCCEEW) 2014, is another report that provided some direct data applicable to the modelling and the entire vehicle fleet in Australia.

Due to the broad range of sources and capacity for the Expert Group researchers to validate various data, deductions and market reports with other sources the RAC Stock model ultimately incorporated estimates of equipment stocks across all major equipment classes and primary applications. This date traces back as early as 1996.

3.2 Refrigerant bank mass flows

The concept of a ‘bank of working refrigerant’ was introduced during the development of the RAC Stock model. This concept was developed a method to represent the entire mass of refrigerant gases employed in installed equipment in the Australian economy.

The ‘full bank’, or fully charged bank, is calculated based on the number of devices in the product category. This value is multiplied by the average original charge of that type of equipment when it is initially installed/purchased.

The ‘partially charged bank’ will be less than the fully charged bank as the charge in individual pieces of equipment in the category declines over time until the equipment retires. The size of the ‘partially charged bank’ is calculated using an age-cohort stock model with survival curves, average retirement ages and EOL charges for each product in the model taxonomy. A ‘partially charged bank’ of refrigerant can be calculated for each product category with varying degrees of confidence depending on some of the characteristics of the product category. In particular, calculations can be influenced by the new sales mix of refrigerants, estimated leak rates and service rates of the different categories.

The ‘partially charged bank’ is generally referred to in this report simply as ‘the bank’, or the ‘refrigerant bank’.

There are 2 means by which the bank of working gas in Australia grows:

1. Imports of equipment that are pre-charged with a refrigerant gas, referred to as pre-charged equipment (PCE) imports. Detailed data on refrigerant contained in PCE is collected at the port of entry by Australian Customs from declarations made by equipment importers.
2. Imports of bulk gas, where the bulk gas is used for charging new equipment that has been manufactured in Australia, or it is used for charging equipment that has been imported without a refrigerant charge. It also occurs where bulk gas is used for installations with longer than usual pipe runs requiring additional charge when being equipment is being installed.

   This data is then aggregated, reviewed, cleaned and verified by the Australian Department of Climate Change, Energy, the Environment and Water (DCCEEW).

Imported refrigerant is used for several purposes including:

- Local equipment manufacturing, particularly in medium commercial AC, large chillers, hot water heat pumps and refrigerated display cabinets. These are equipment segments where Australia retains successful manufacturers. Refrigerant consumption for local manufacturing of stationary AC in 2023 was 219 tonnes of HFC-410A, HFC-32 and HFC-134a compared to 242 tonnes in 2022.

- Charging, or adding to a partial charge, for new equipment at point of installation where the device may have been imported without any refrigerant charge (or a partial charge). Additionally, the equipment may need an increase to its pre-charged volume during installation and commissioning to accommodate longer pipe runs.
- Retrofitting existing equipment with a new refrigerant. For instance, retrofitting occurs in cases where equipment originally designed and installed to operate on HCFC-22 can be retrofitted with drop-in replacements, or equipment operated on HFC-404A is retrofitted with hydrofluoro-olefin (HFO)/HFC blends R449A or R448A.
- Servicing the stock of equipment to maintain charge levels due to leaks or catastrophic losses of refrigerant.
- A small fraction of imports is lost during decanting into small cylinders that are distributed into wholesale supply lines.

Insight into refrigerant usage in the Australian economy has significantly improved over the past decade. This insight is informed by a quarterly survey conducted by Expert Group of refrigerant wholesalers which provides robust data that can be reconciled against annual bulk imports.

Refrigerant also leaves the bank of working gas through equipment retirements and recoveries of sub-standard gas which is destroyed by Refrigerant Reclaim Australia (RRA 2024).

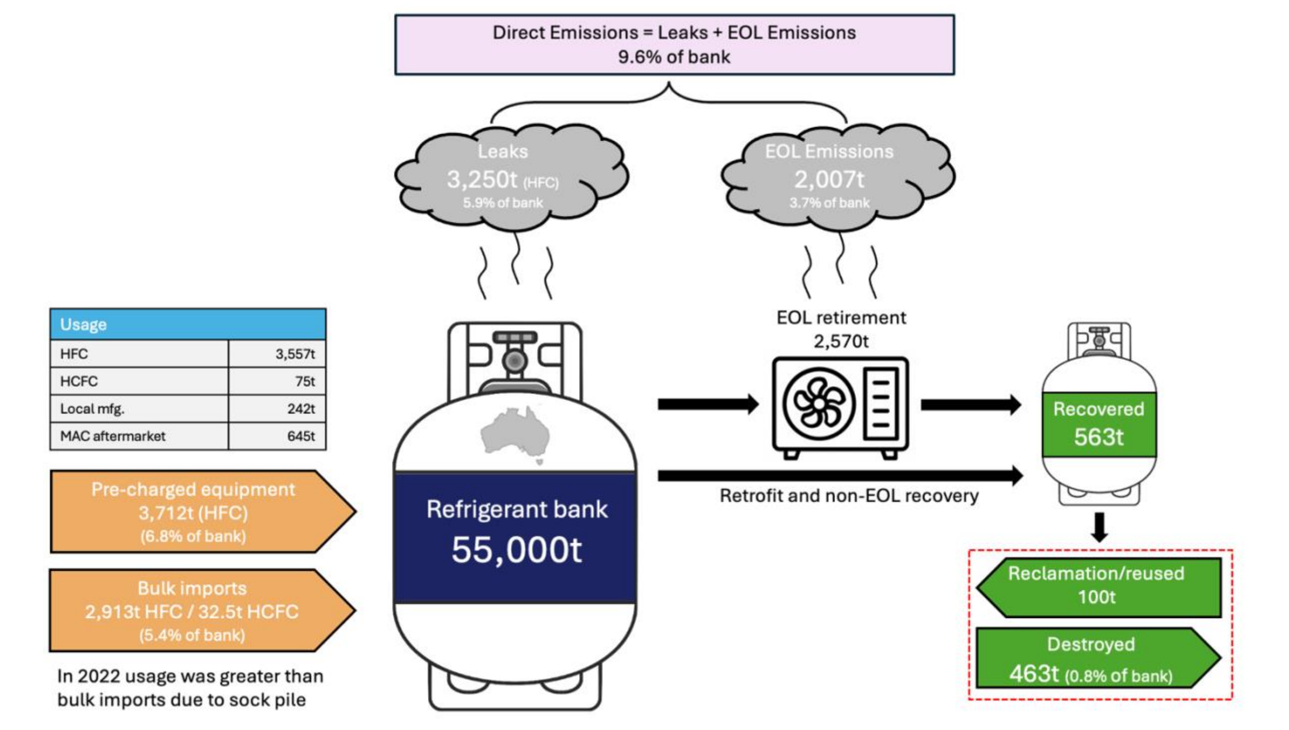
Most of the equipment that is retired would not be fully charged. The RAC Stock model calculates various rates of remaining partial charge for retiring equipment based on observations from the field of the residual charge in various classes of equipment when it is taken out of service.

The model calculates that in 2022 RAC equipment containing an estimated 2,570 tonnes of refrigerant reached the end of its useful life in Australia. Cumulative leak emissions from 2022 to 2036 are estimated at 91.0 Mt CO_2-e. Almost equal to the entire 2022 refrigerant bank emitted over the 15 years of the projection. A further 57.8 Mt CO_2-e of refrigerants estimated to be emitted at EOL over the period. EOL emissions projection assumes approximately 20% of EOL refrigerants are captured.

Figure 2 presents the refrigerant bank mass flows in Australia for 2022. The refrigerant bank in 2022 reached an estimated 55,000 tonnes with an approximate net 2% increase compared to 2021. This trend was likely a result of additions equal to more than 12% of the bank by mass, and losses of around 10% of the total.

These losses from the bank include 5.9% being emitted to the atmosphere as leaks from operating equipment and 4.7% occurring at EOL of which around 20% are captured. These calculations include annual recovery and destruction of refrigerant reported by Refrigerant Reclaim Australia.

Figure 2: Refrigerant bank mass flows in Australia 2022



Source: (DCCEEW 2024b)

HCFC Hydrochlorofluorocarbon **HFC** Hydrofluorocarbon

Notes:

1. 'Reclamation' means the reprocessing of a recovered fluorinated greenhouse gas to the equivalent performance of a virgin substance, taking into account its intended use, in reclamation facilities that have the appropriate equipment and procedures in place to enable the reclamation of such gases and that can assess and attest to the level of the required quality (European Commission 2024, Regulation (EU) 2024/573).
2. 'Recycling' means the reuse of a recovered fluorinated greenhouse gas following a basic cleaning process, including filtering and drying (European Commission 2024, Regulation (EU) 2024/573).
3. 'Recovery' means the collection and storage of fluorinated greenhouse gases from containers, products and equipment during maintenance or servicing or prior to the disposal of the containers, products or equipment (European Commission 2024, Regulation (EU) 2024/573).
4. Refrigerant recycling (re-use of refrigerant without reprocessing to a known standard) data that occurs at trade level is not captured.

4 Leak rates by equipment class

4.1 Mobile air conditioning

Mobile air conditioning (MAC) captures equipment in 2 broad segments. These segments are small MAC and large MAC, which have 13 product categories.

Small MAC

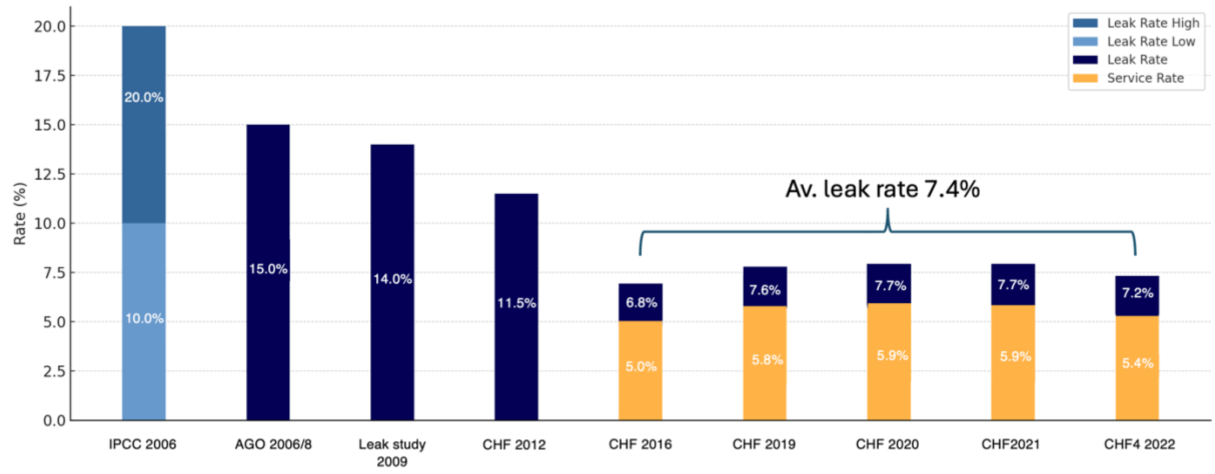
Small MAC comprises passenger and light commercial vehicles; compartments of rigid, articulated and non-freight trucks; and small buses with a GVM less than 4.5 tonnes.

Since 2006, there has been a clear downward trend in the leak rates of small MAC systems. In 2006, international estimates placed leak rates between 10% and 20%, with an average of approximately 15% (as reported by IPCC 2006 and AGO 2006). In 2009, Expert Group conducted an extensive international desktop study of leak rates which resulted in a revised estimated leak rates of 14%. By 2012, the leak rate was further reduced to 11.5%.

In 2016, a new methodology was established to estimate leak rates, based on the service rate and service consumption of the Australian aftermarket. This method, detailed in section 4.1.1, determined that the average leak rate from small MAC was 7.4% over the period from 2016 to 2022.

Figure 3 shows the leak rates and service rates of small MAC systems from 2006 to 2022 for a range of assessments and studies. The data in this chart is tabulated in Table 9 in Appendix A.

Figure 3: Small mobile air conditioning leak rates from 2006 to 2022



Source: (IPCC 2006, AGO 2006, AGO 2008, RA 2009, DCCEEW 2023b, DCCEEW 2024b)
IPCC Intergovernmental Panel on Climate Change **AGO** Australian Greenhouse Office **CHF** Cold Hard Facts series

Notes:

1. The 2006 IPCC data IPCC provided a lower value that was representative of developed countries and higher value of developing countries.
2. The AGO 2006/8 assessment, the Expert Group Leak assessment in 2009 and CHF2 in 2012 specify a single estimated leak rate.
3. The CHF assessments conducted between 2016 and 2022 provide both a service rate and a leak rate. The service rate is determined based on aftermarket usage across the equipment fleet, while the leak rate is derived from the service rate combined with the annual reduction in charge. The calculation methodology is detailed in section 4.1.1.

Large MAC

This segment includes equipment found in a diverse range of registered, unregistered and off-road vehicles. These vehicles include larger buses and coaches; locomotives, passenger trains and trams; recreational vehicles and caravans; boats and pleasure craft; aircraft systems; mobile and fixed cranes; combine harvesters; forklift trucks, military vehicles; mining vehicles and road construction equipment.

Leak rates of the current fleet of large MAC are estimated to range from 7.0% to 9.0% with the main applications being 'buses, coaches and rail air conditioning' on the upper end of this scale. This estimate is deduced from a range of industry sources and research reports as there is no field data from equipment operators.

The leak rates of buses and coaches are expected to decrease over time as the equipment transitions to newer designs with enhanced containment capabilities. Typically, air conditioning units in buses and coaches are either roof-mounted or, in older models, rear-mounted, with compressors driven by the vehicle's engine. The stock model assumes that bus and coach air conditioning systems have an average operational lifespan of 20 years which aligns with the common contractual lifespan of 25 years for new bus purchases (BIC 2017, BITRE 2016).

Given the extended service life of passenger buses, it is reasonable to expect that the air conditioning systems will undergo complete refurbishment at least once during their operational lifespan. The newer systems feature advanced containment designs and employ microchannel condensers. These reduce the refrigerant charge by approximately 50% compared to earlier systems which enhances the overall efficiency and reduces potential leakage.

Rail air conditioning units typically feature self-contained hermetic circuits for driver comfort and passenger thermal comfort systems. These systems are customised for various types of vehicles and are typically imported as pre-charged equipment as part of a complete train set, or separately for local assembly or replacement. The average product life of these systems is 30 years (some 40-year-old systems are in operation), and systems will typically have a major overhaul every 10 to 15 years. Overhauls involve rebuilding the refrigerant circuit. Under these circumstances the refrigerant is usually replaced with new refrigerant, particularly if charged with HFC-407C as this is a blend that is susceptible to fractionation. The leak rates of the fleet are expected to decline over time due to improved designs and practices.

Estimated leak rates of all large MAC product categories are provided in Table 7, Appendix A.

4.1.1 Method of calculating small MAC leak rates

The service rates for small MAC are calculated from:

- Bank of equipment (stock of equipment x original average charge).
- Refrigerant usage of the aftermarket (annual survey conducted since 2014 with the assistance of the Australian Government).

The estimate of the 2022 service usage for small MAC of 644.6 tonnes of HFC-134a is a very robust value based on 9 consecutive years of surveys of aftermarket participants. The 2022 usage corresponds to a service rate of approximately 5.4% of the small MAC bank, which totals 12,023 tonnes of HFC-134a. This is the full bank based on the original charge sizes.

The assessment includes 3% small MAC fleet charged with HFO-1234yf, with an assumption that 4% of the fleet are charged with hydrocarbon retrofits.

The leak rates for small MAC are calculated from:

- Service rate of 5.4%.
- End of life charge of 66.6% of the original charge.
- The average lifespan of 18.6 years.

The average leak rate across the fleet of small MAC vehicles is 1.8% (33.3% divided by 18.6 years) plus a service rate of 5.4% equating to 7.2% in 2022.

In a quantitative study of automotive wreckers in Australia, the end-of-life charge was found to be 66.6%. This value represents the average remaining charge at the time of dismantling or crushing, based on a data sample of 28,000 vehicles (DoEE 2015). The 33.3% is the amount lost over and above the service rate.

The RAC Stock model uses both sales data (ABS 2018, FCAI 2018, FCAI 2023b) and registration data (BITRE 2023b) from the Bureau of Infrastructure, Transport and Regional Economics (BITRE) to calculate the current fleet of small MAC. This data includes passenger and light commercial vehicles; rigid trucks; articulated trucks; non-freight trucks; and small buses with a

GVM less than 4.5 tonnes. The data assumes that 100% of these vehicles manufactured after the year 2000 contain air conditioning.

The RAC Stock model uses a polynomial function to estimate average charge by year of manufacture. The collection of refrigerant charge values of over 10,000 vehicles conducted over several years by an industry participant was provided to Expert Group for analysis. This information provided excellent primary data on average charges of vehicles by year of make. This study shows that in the early 1990s small MAC was manufactured with an average of 1,100 grams of refrigerant charge. By the year 2000 this average charge of new vehicles had reduced to about 800 grams and continued to decline to the current average charge in the 2020s of just 620 grams. These charge sizes are the original or specified manufacturer's charge.

The RAC Stock model uses a survival curve which is a normal distribution with a mean retirement age of 18.6 years and a standard deviation of 6.2 years. This produces a survival curve that simulates actual vehicle registrations in the Australian Bureau of Statistics Census of Motor Vehicles in 2014.

Based on five CHF evaluations conducted from 2016 to 2022, the average leak rate is calculated at 7.4%. If the proportion of vehicles charged with hydrocarbons is assumed to be 8%, the leak rate would be 7.4% in 2022, resulting in an average leak rate of 7.6% over the five assessments.

Table 3: Summary of current registrations that are classified as small MAC

	2021	2022
Passenger vehicles	15,052,913	15,327,612
Campervans	89,171	93,513
Light commercial vehicles	3,805,726	3,951,792
• *Rigid trucks*	*544,574*	*574,567*
• *Articulated trucks*	*115,649*	*120,337*
• *Non-freight trucks*	*36,463*	*37,934*
Total trucks	696,686	732,838
Commuter buses (GVM <4.5 tonnes)	70,305	72,457
BITRE Total vehicles	19,714,801	20,178,212
RAC Stock model: Small MAC: 2022	**19,855,300**	

Source: (BITRE 2022, BITRE 2023b)
MAC mobile air conditioning

Notes:

1. The 2021 data presented above has been published by BITRE as the 2022 registration data, as it reflects registrations recorded at the end of January 2022. Similarly, the 2022 data above is based on the end of January 2023 and was published by BITRE in July 2023. The RAC Stock model: Small MAC for 2022 is calculated at the midpoint of the calendar year, and only includes those vehicles with air conditioning (i.e., approx. 99% passenger and light commercial vehicles; 100% articulated trucks; 95% rigid and other trucks; and 99% commuter buses). Electric vehicles are included in these small MAC values.
2. The assessment assumes 4% of small MAC are charged with hydrocarbon retrofits and 3% are charged with HFO-1234yf.

4.2 Stationary air conditioning and heat pumps

Stationary air conditioning and heat pump equipment contains the largest portion of the bank of refrigerant. This equipment also uses the largest portion of annual bulk refrigerant imports and consumes more electricity than any of the other classes of equipment in the RAC industry.

Stationary air conditioning and heat pumps includes equipment that can operate in reverse cycle (heating and cooling) or cooling only or heating only, on single phase or three phase power. Equipment in this class ranges in capacity from small 2 kW domestic portable air conditioners, with a refrigerant charge of less than 600 grams, to very large 4,000 kW commercial space chillers containing more than a tonne of refrigerant in a single machine.

The most common type of heat pump is the air-to-air heat pump (air source heat pump), which transfers heat between the air conditioned space and the outside air. In earlier decades these devices were referred to as reverse cycle air conditioners.

Air-to-water heat pumps are an emerging application. When connected to a water tank, this type of heat pump can transfer heat from the outside air to a water storage tank which supplies hot water to residential and commercial premises. Air-to-water heat pumps are commonly called hot water heat pumps.

In recent years heat pump technology has also made strong inroads into several new applications including heat pump clothes dryers and heat pump water heating.

Figure 4 illustrates the leak rates for stationary air conditioning systems and heat pumps from 2006 to 2022. The chart highlights the substantial variation in leak rates among different AC types, with self-contained units like window/wall systems exhibiting the lowest rates. Figure 4 also demonstrates a significant improvement in leak rates across all AC categories since 2006. The data in this chart is tabulated in Table 10 in Appendix A.

The starting point of that data set was derived from the IPCC 2006 assessment of the contribution of industrial gases to global warming. Leak rates as low as 1% are typically associated with sealed air conditioning systems, such as window/wall units. Higher leak rates of 10%, however, are attributed to split systems and commercial AC systems. The quality of split systems and commercial AC in the early 2000s was relatively inferior compared to the mass-produced equipment and appliances available today. While some systems were mass-produced, many products and components, such as coils, were manufactured in small-scale workshops. There was limited emphasis on refrigerant containment in their design.

The low leak rate of 2% quoted for chillers in the IPCC 2006 assessment is likely referring to low pressure HCFC-123 chillers, and the higher leak rates are mostly attributed to HCFC and some HFC chillers.

The Australian Greenhouse Office (AGO) also published leak rates in their AGO Factors and methods workbooks (AGO 2004, AGO 2006, AGO 2008). The 2004 assessment estimated leak rates for window/wall units at 2%, domestic split systems at 20% and all commercial AC including chillers at 15%. This assessment was simplified in 2006 with all varieties of chillers (scroll, screw and centrifugal) and the full range of chiller capacities being attributed a leak rate of 8.5%, while all other AC equipment was claimed to have a leak rate of 3.0%. In 2008, the AGO assessment was further simplified by adopting a 9% leak rate for all commercial air conditioning.

A leak study conducted by the Expert Group in 2009 (RA 2009) revealed a wide range of industry and practitioner opinions as to the sources and causes of leaks and provided an assessment of the lower leak rates reported with newer designs of that era that were operating on HFCs. In contrast, higher leak rates reported were typically linked to older equipment and designs using HCFCs. For instance, the estimated leak rate for HFC-based split systems was 3.0%, while older wall-hung split systems operating on HCFCs had a leak rate of 10.0%, and ducted systems exhibited a rate of 12.0%.

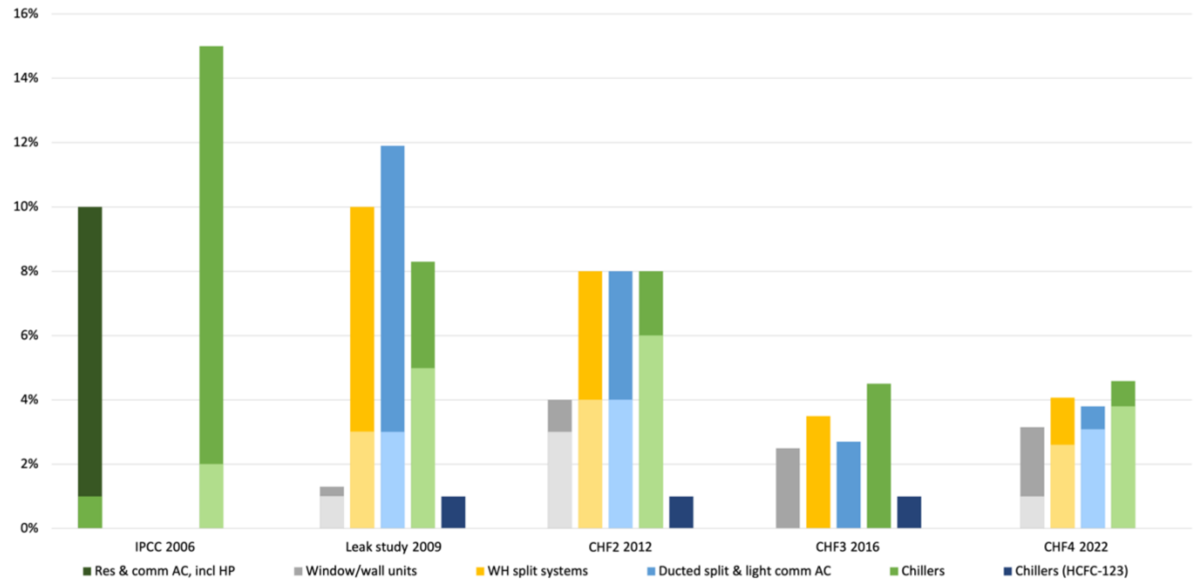
The leak rates across all classes of stationary AC were revised again when undertaking research for CHF2 in 2012. Leak rates of split systems and light commercial AC were set at a low of 4.0% and a high of 8.0%.

The next major review was undertaken for CHF3 in 2016 which saw many leak rates reduce further, in part due to the majority of the older HCFC equipment retiring, and a better understanding of the service consumption across the stock of equipment. The leak rates of the main classes serviced, non-ducted single split system (wall hung, cassette and consoles), ducted split systems and light commercial AC, and chillers were revised down to 3.5%, 2.7% and 4.5% respectively.

The most recent assessment CHF4 for the 2022 year includes a review of service rates and leak rates. This method, detailed in section 4.2.1, determined that the average service rate of non-ducted single split systems was 2.4% with a leak rate of 4.1%. Ducted split systems and light commercial AC were revised back up to a service rate of 2.6% and leak rate of 3.8%.

Portable air conditioners are non-serviceable appliances, meaning that once they stop functioning, they cannot be repaired and are typically discarded. In earlier assessments, a leak rate of 1% was typically used; however, as understanding of this equipment improved and it became clear that these are treated as disposable appliances, the leak rate was adjusted to zero for the life of the equipment. Noting that all the evidence points to the fact that in the majority of cases, 100% of the refrigerant charge is released upon disposal.

Figure 4: Stationary air conditioning and heat pump leak rates from 2006 to 2022



Source: (IPCC 2006, AGO 2006, AGO 2008, RA 2009, DCCEEW 2023b, DCCEEW 2024b)

IPCC Intergovernmental Panel on Climate Change **AGO** Australian Greenhouse Office **CHF** Cold Hard Facts series

Notes:

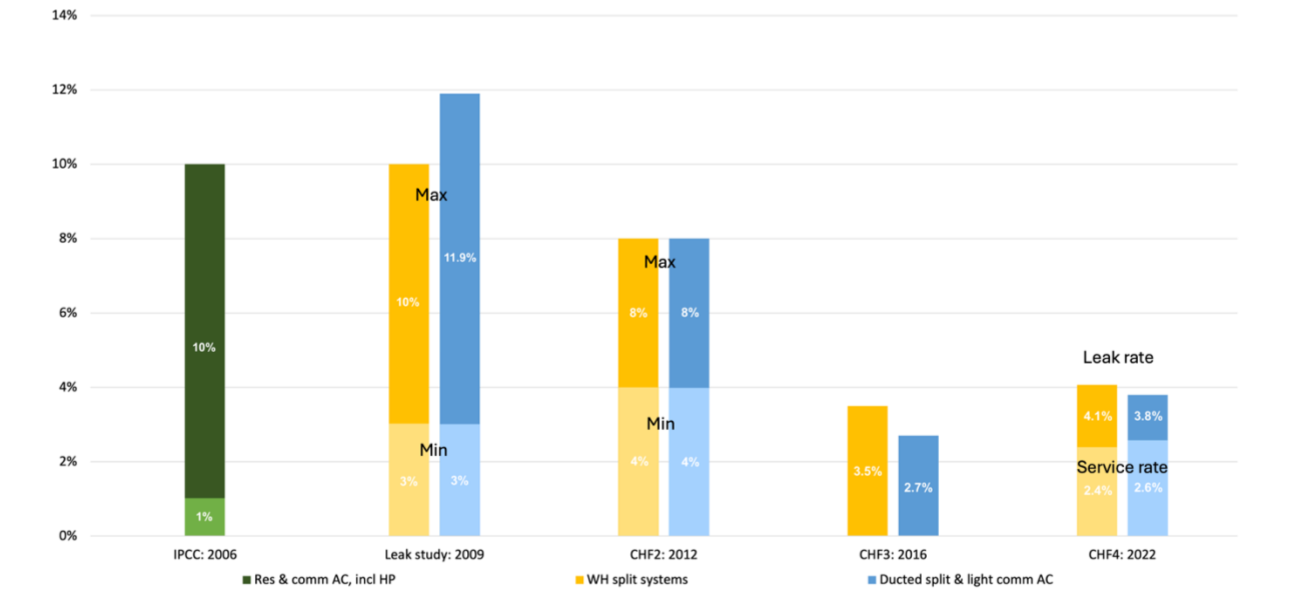
1. The 2006 IPCC data provided a lower value that were representative of developed countries and higher value of developing countries.
2. Residential and commercial air conditioning including heat pumps is a broad category assigned by the IPCC 2006 assessment to all air conditioning equipment except chillers.
3. The 2009 Leak study and CHF2 2012 data provide a lower value that were typically representative of HFC systems and the higher value older HCFC systems.
4. The CHF4 2022 assessment provides both a service rate and a leak rate. The service rate is determined based on service consumption across the equipment fleet, while the leak rate is derived from the service rate combined with the annual reduction in charge. The calculation methodology is detailed in section 4.2.1.
5. Window/wall units are self-contained packaged room air conditioning units intended to be inserted through a hole in a wall or through a window aperture of a home, shop or worksite demountable building.
6. WH split systems are non-ducted single systems and include wall hung, cassette and consoles indoor units.
7. Ducted split systems and light commercial AC includes single ducted split systems, multi-head split systems, variable refrigerant volume/variable refrigerant flow (VRV/VRF) systems, and close control or precision air conditioning systems.
8. Chillers includes all varieties of chillers (scroll, screw and centrifugal) and the full range of chiller capacities.

Figure 5 presents leak rates for split systems and light commercial air conditioning systems from different studies spanning from 2006 to 2022.

The chart highlights the leak rates of the earlier generations of equipment in the 2000s at around 10% to 12%. These leaks are mostly attributed to many products and components, such as coils, which were manufactured in small-scale workshops with limited emphasis on refrigerant containment in their design.

In contrast, the more recent CHF studies (2016, 2022) indicate that leak rates have stabilised at approximately 4.0% per annum. This is likely due to the retirement of older generations of equipment and the improved skills associated with installing higher quality mass-produced systems.

Figure 5: Split systems and light commercial air conditioning rates from 2006 to 2022



Source: (IPCC 2006, AGO 2006, AGO 2008, RA 2009, DCCEEW 2023b, DCCEEW 2024b)
IPCC Intergovernmental Panel on Climate Change **AGO** Australian Greenhouse Office **CHF** Cold Hard Facts series

Notes:

1. The 2006 IPCC data provided a lower value that were representative of developed countries and higher value of developing countries.
2. The 2009 Leak study and CHF2 2012 data provide a lower value that were typically representative of HFC systems and the higher value older HCFC systems.
3. WH split systems are non-ducted single systems and include wall hung, cassette and consoles indoor units.
4. Ducted split systems and light commercial AC includes single ducted split systems, multi-head split systems, variable refrigerant volume/variable refrigerant flow (VRV/VRF) systems, and close control or precision air conditioning systems.
5. The CHF4 2022 assessment provides both a service rate and a leak rate. The service rate is determined based on service consumption across the equipment fleet, while the leak rate is derived from the service rate combined with the annual reduction in charge. The calculation methodology is detailed in section 4.2.1.

4.2.1 Method of calculating stationary AC leak rates

The main product categories in this equipment class include non-ducted single split system (wall hung, cassette and consoles) and ducted single split systems. Average service rates for these categories is deduced by reconciling service demand against the known volumes refrigerant sold by species.

As a result, the refrigerant usage in the service of these equipment segments sector is known with a high level of confidence. For example usages in 2022 were:

- HFC-410A: 801 tonnes
- HFC-32: 97 tonnes
- The mix of refrigerant species and usage in local manufacturing is also known.

The refrigerant composition and charge size by equipment type within the stock of equipment is accurately known based on pre-charged equipment import data and domestic manufacturers data.

The equipment inventory has been modelled by type by the Expert Group for CHF and by other consultants for the Australian Government. This was done to support energy efficiency programs since the 2000s. This modelling is based on actual annual sales data and well established lifespans and survival curves.

The refrigerant usage from the two largest product category banks, non-ducted single split system and ducted single split systems are reconciled. The reconciliation accounts for installations with extended pipe runs requiring additional refrigerant charge. It also accounts for the local manufacturing of split ducted systems and rooftop packaged systems.

Using these various data points the leak rates for non-ducted single split system are calculated from:

- Service consumption of 2.3% across the stock of HFC-410A charged equipment.
- EOL charge of 80% of the original charge.
- The average lifespan of 12.0 years.

Therefore, the average leak rate for the bank of equipment operating on HFC-410A is calculated as 4% per annum.

This calculation is based on 1.7% decline in annual average operating charge over the life of the equipment (i.e. 20% of total charge lost across the average equipment life to arrive at the 80% average EOL charge, divided by the 12.0 years of service) plus a service rate of 2.3%. This equates to total losses from this stock of equipment of 4.0% in 2022. Table 4 provides a summary of the reconcile analysis for HFC-410A.

Using the same array of data, a much newer cohort of HFC-32 equipment is estimated to be less than 2.5%.

Table 4: HFC-410A refrigerant bank and usage in tonnes

	Bank	Service rate	Service usage	Local charge	Local mfg	Total HFC-410A usage
Window/wall units	340.9	2.0%	6.8	0.0	0.0	6.8
Portable AC and other	183.5	0.0%	0.0	0.0	0.0	
Non-ducted single split systems	9,753.6	2.3%	223.1	1.5	0.0	224.5
Ducted split systems	8,522.6	2.6%	221.6	15.3	182.1	528.2
Light commercial AC	4,197.7	2.6%	109.1			
Chillers	230.7	3.8%	8.8	2.6	0.0	11.4
HP	448.0	2.6%	11.6	0.0	0.0	11.6
Other applications	-	-	-	-	-	18.4
Total HFC-410A usage	**-**	**-**	**581.0**	**19.4**	**182.1**	**801.0**

Source: (DCCEEW 2024b)

4.3 Cold chain

The refrigerated cold chain plays a crucial role in supporting modern urban life. The cold chain ensures the supply of fresh and frozen food, as well as pharmaceuticals, medical supplies, and scientific applications. Without an extensive and reliable cold chain, cities would struggle to maintain the volume of essential products needed to sustain their populations.

The cold chain encompasses a broad array of equipment used throughout the process of handling perishable goods, from primary food production, such as on farms and fishing vessels, to retail outlets and hospitality venues. This equipment cold rooms, milk vats, blast freezers, and various stationary and mobile refrigeration formats. Additionally, residential refrigerators and freezers, as well as portable and vehicle refrigeration systems, are part of the cold chain.

Small commercial refrigeration typically uses self-contained units with hermetically sealed systems. These range from small water coolers with small refrigerant charges, with as little as 40 grams of HFCs to a five door low temperature display case with a charge of over 1 kg of HFC (or 450 grams of hydrocarbon). Medium sized commercial refrigeration equipment employs remote condensing units with capacities from 1 kW to 20 kW, located outside the cooled space. Larger systems may include racks with multiple compressors.

Supermarkets rely on a wide variety of refrigeration equipment, including large central plant systems, remote condensing units, and self-contained merchandisers. This equipment is necessary to maintain different temperature ranges for various products like meat, dairy, and frozen foods. This infrastructure is essential to efficiently manage the storage and display of perishable goods.

The medium and large stationary refrigeration applications, transport refrigeration and marine systems in the cold chain are found to have the highest leak rates of all RAC applications and in many instances use refrigerants with the highest GWPs (i.e. HFC-404A GWP of 3922).

The 2006 IPCC assessment provided a broad range of estimated leak rates, including 1% to 15% for self-contained systems, 10% to 35% for remote condensing units and supermarkets, 7% to 25% for industrial refrigeration, and 15% to 50% for transport and marine systems. The lower values were indicative for developed countries and higher value of developing countries.

In the 2000s, older refrigeration equipment faced several issues that contributed to high refrigerant leak rates. A major source of leaks was from condensers and evaporators, particularly at return bends, where leaks frequently occurred. Additional leaks were observed on end plates due to the expansion and contraction, leading to wear of copper tubes. Corrosion and failures in the evaporator condensate tray pipework, often caused by food acids in the condensate, also contributed to the problem.

Mechanical components were also major contributors to leaks. Flared joints and schrader valves were widely recognised as key leakage points, while mechanical joints, such as flares on driers, frequently leaked. Brazed joints were another common source of leaks and often suffered from poor brazing techniques, lack of vibration elimination, and inadequate pipe support.

Service valves, including shut-off and ball valves, were identified as additional points of failure, particularly when uncapped. Older refrigeration systems also employed open drive compressor designs with shaft seals. These were especially problematic and prone to leakage. These design and component weaknesses, coupled with corrosion, vibration and mechanical failures, as well as inadequate technical skills, significantly contributed to the high refrigerant leak rates seen in older commercial and industrial refrigeration equipment.

The Australian Greenhouse Office (AGO) in their 2008 AGO Factors and Methods Workbook, estimated that leak rates were 23% for all commercial refrigeration applications, and 16% for industrial refrigeration including food processing and cold storage.

The leak rate estimate of 23% was formed to some extent from a study of actual data from a major supermarket chain in Australia across 134 stores in 2002 and 2003 with an average charge per store of 886 kilograms. The study found the average leak rate across the stores was 20% per annum, and that 38% of the stores had a leak rate greater than 20% per annum, accounting for 71% of the losses. This leak data demonstrated that a significant proportion of refrigerant losses often arise from a small number of systems.[1] Leak rates in independent stores and other hard working and high vibration applications (transport, marine and milk vat refrigeration) were known to have even higher leak rates.

In 2009, the Expert Group's leak study involved extensive international research, and interviews with contractors, equipment owners and wholesalers of refrigerant and parts. The study presented a broad spectrum of opinions and more detailed insights into assigning leak rates across various applications.

While many leak rates for individual equipment types were adjusted downward, the majority remained extremely high due to the age of the equipment and poor field practices. For example, the leak rates for supermarkets were calculated at 15% to 21% for major chains, and 15% to 30% for independent stores. Transport refrigeration exhibited rates of between 15% and 30%, while marine refrigeration ranged from 25% to 35%. Leak rates for remote condensing units were estimated at 10% to 15%, though this was likely underestimated given equipment designs in service at the time. Similarly, leak rates for what were thought at the time to be better designed self-contained units, reported at 2% to 5%.

More recent studies for the CHF series found that while the extremely high leak rates observed in remote and supermarket systems, transport refrigeration and marine of 25% to 50% per annum during the 2000s have significantly decreased. Average leaks in the 2020s remain notably high. For instance, remote condensing units, cold storage below 1,000 m^3 and independent supermarket applications are estimated at 15%. Larger cold storage and distribution facilities have predominantly migrated to ammonia systems and are no longer included in these studies as they are not employing reportable refrigerants.

The equipment at the very end of the cold food chain, domestic refrigerators and freezers, have always been assessed as having very low leak rates, below 2%. This equipment category also includes a growing number of portable and vehicle refrigeration systems that are used in caravans, trucks, and as camping systems.

[1] Ray Gluckman, who peer-reviewed the report, identified a similar pattern of significant variability in leakage rates within large supermarket refrigeration systems. While some systems exhibited minimal leakage (<5%), others experienced multiple severe leaks, leading to annual leakage rates exceeding 200%, well above the fleet average. It is recommended that supermarkets create a 'league table' to benchmark leakage rates across different systems and focus maintenance efforts on those with the highest leakage levels.

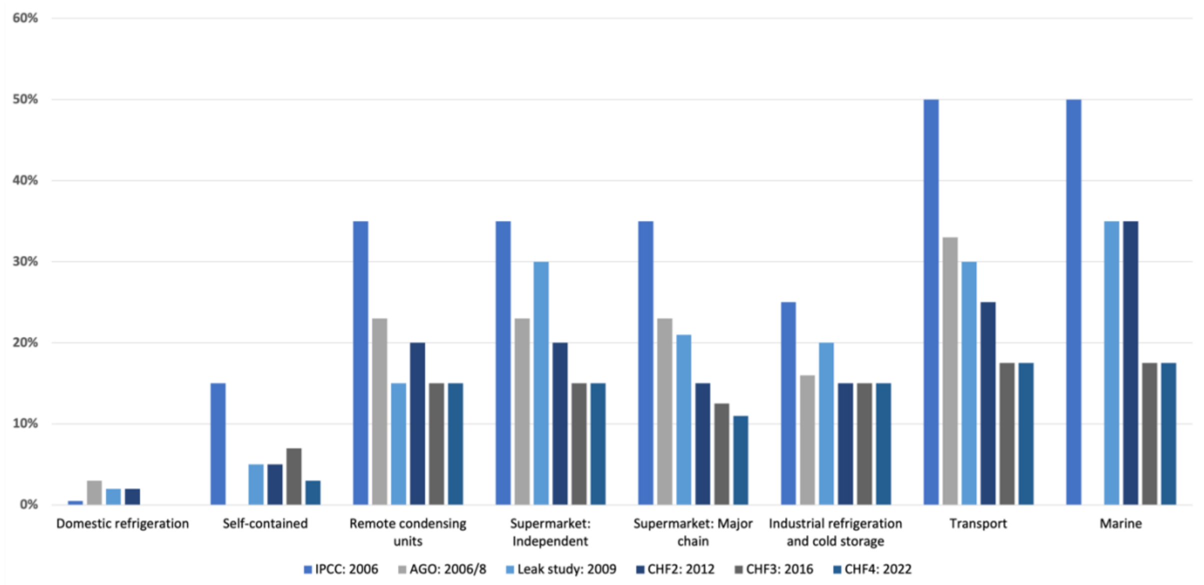
There was some service consumption of primarily HFC-134a in past decades as older models of these small appliances were repaired. However, most domestic refrigerators are no longer repaired. Instead, once the refrigeration system fails, they are typically discarded due to the lack of economic viability for repairs. Consequently, service consumption and leak rates are regarded to be effectively zero.

It should be noted however that it is assumed that all remaining refrigerant charge in EOL equipment is released during disposal other than in those locations where refrigerant from equipment is properly captured at disposal facilities. In these instances, the refrigeration recovered is counted when returned via Refrigerant Reclaim Australia for destruction.

This issue is diminishing as an increasing number of devices in operation are utilising hydrocarbon-based systems. By 2022, approximately 62% of the stock, equivalent to around 12.9 million devices, employed hydrocarbon refrigerants. Surveys conducted in 2020 across sales channels indicated that over 99% of the models available for sale were charged with HC-600a.

Figure 6 presents the leak rates assumed, reported and observed in the cold chain between 2006 and 2022. The corresponding data is detailed in Table 11, located in Appendix A. The chart emphasises the significant variation in leak rates across different types of equipment, with self-contained units (such as service and display cases, beverage coolers, ice makers, vending equipment and water dispensers) exhibiting the lowest rates ranging from zero to 3%. The leak rate of 7% for self-contained equipment in the CHF3 2016 assessment appears to be an over statement. These categories of self-contained equipment are also becoming less of a concern as a source of emissions as the majority of these devices, particularly the smaller ones, are transitioning to hydrocarbon refrigerant.

Figure 6: Cold chain leak rates from 2006 to 2022



Source: (IPCC 2006, AGO 2006, AGO 2008, RA 2009, DCCEEW 2023b, DCCEEW 2024b)

IPCC Intergovernmental Panel on Climate Change **AGO** Australian Greenhouse Office **CHF** Cold Hard Facts series

Notes:

1. The IPCC 2006, 2009 Leak study and CHF2 2012 assessment had higher and lower values. This chart only shows the higher values to illustrate the trends in each equipment class. The lower and higher values are tabulated in Table 11.
2. Self-contained equipment includes service and display cases, beverage coolers, ice makers, vending equipment and water dispensers.
3. The most common applications for remote condensing units are mostly remote display cases and cold rooms.
4. An independently owned supermarket refers to a grocery store managed by an individual or a small group of owners. In contrast, a corporate-owned supermarket chain is operated by a larger company, characterised by standardised processes and adherence to environmental corporate responsibility practices.

Medium to large refrigeration

In 2022, the cold chain accounted for more than 50% of Australia's wholesale refrigerant volumes, measured in Mt CO_2-e. This high consumption is primarily attributed to the elevated leak rates of very high GWP refrigerants in medium and large commercial refrigeration systems. Without regulatory intervention, refrigerant usage in the cold chain is projected to remain at these levels (greater than 50%) through to 2036.

Figure 7 illustrates the assumed, reported, and observed leak rates in the cold chain from 2006 to 2022. A breakdown of the data over this period is as follows:

Remote condensing units:

- In 2006, leak rates ranged from 10.0% to 35.0%.
- The AGO assessment (2006/2008) reported a 23.0% leak rate.
- The 2009 study estimated a lower range of 10.0% to 15.0%, though this was likely underestimated given equipment designs in service at the time. These estimates were increased to 17.5% to 20.0% in 2012.
- The estimated leak rate remained at 15.0% from 2016 to 2022 with no improvements observed in this application.

Supermarket: Independent:

- The leak rates assigned to independent supermarkets are very similar to those of remote condensing units.
- Leak rates in 2006 were 10.0% to 35.0%.
- In 2009, the range increased to 15.0% to 30.0%.
- In 2012, this reduced to 15.0% to 20.0%.
- The rate opinion stabilised at 15.0% by 2016 and remained the same in 2022.

Supermarket: Major chains:

- The 2006 data shows a wide range from 10.0% to 35.0%.
- By 2009, this narrowed slightly to 15.0% to 21.0%.
- By 2012, the range decreased to 12.0% to 15.0%, further reducing to 12.5% in 2016.
- The leak rate fell further to 11.0% by 2022.

Industrial refrigeration and cold storage:

- Leak rate estimated started at 7.0% to 25.0% in 2006.
- By 2009, this range was 7.0% to 20.0%, further reducing to 10.0% to 15.0% in 2012.
- From 2016 to 2022, the leak rate opinion stabilised at 15.0%.
- Most of the older, larger facilities greater than 1,000 m^3 have been upgraded to ammonia systems.

Leak rate estimates have varied over time for several reasons, primarily due to limited availability of primary data. Many estimates are subjective and based on expert opinions, which can lead to variability. Updates in references, new observations, and shifts in expert perspectives also contribute to adjustments in leak rates. Additionally, regulations or initiatives by key industry participants can influence these rates.

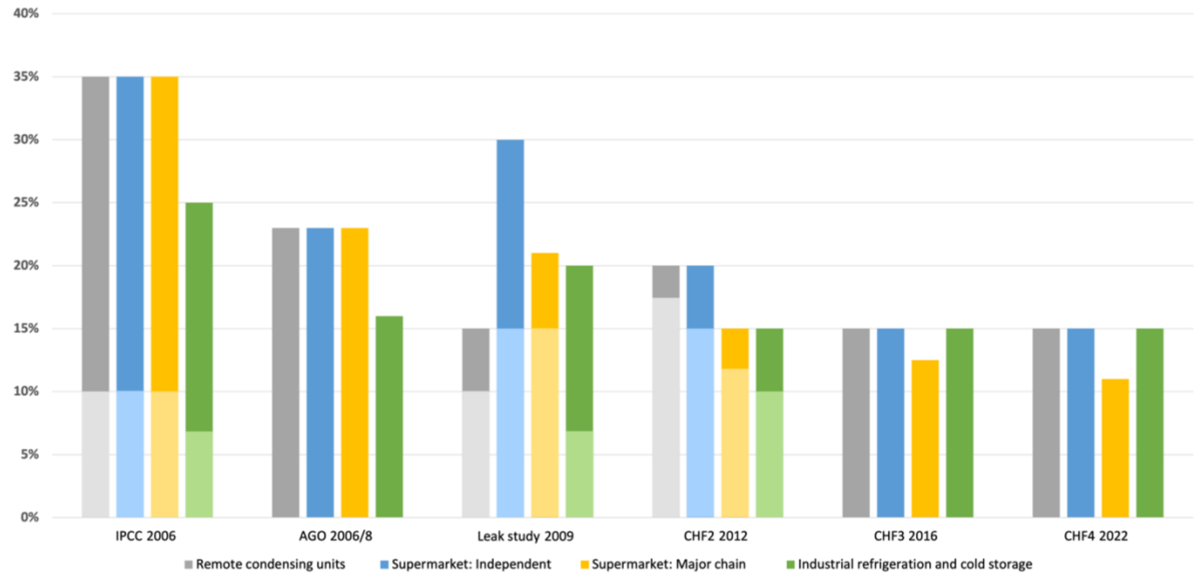
The Expert Group observed a decline in the usage of the primary commercial refrigeration refrigerant, HFC-404A (GWP of 3922), during the one to two years following the introduction of the equivalent carbon tax in 2012. This decline was driven by a 4 to 5 fold increase in the price of HFC-404A for end users. However, this trend was short-lived and leak rates increased again after the repeal of the equivalent carbon tax.

Over the past decade, CHF assessments have found that major supermarket chains generally experience lower leak rates compared to independent supermarkets. This is attributed to several factors:

- Remote supervisory systems: These systems allow for continuous performance monitoring of refrigeration equipment with built-in alarms, enabling early detection of issues before they escalate.
- Automated leak detection systems: Major chains often utilise advanced automated leak detection technology, enabling quick identification and repair of leaks.
- Key Performance Indicators (KPIs): Supermarket chains regularly track and optimise KPIs for refrigeration systems. This promotes better maintenance and efficiency to reduce product losses, energy consumption and refrigerant consumption.
- Newer equipment: The refrigeration systems in major chains tend to be newer, averaging 15 year lifespans compared to 25 years in independent supermarkets. This newer equipment leads to fewer failures and leaks.
- NGERS Reporting Compliance: Major chains are subject to the National Greenhouse and Energy Reporting Scheme (NGERS), which mandates accurate reporting on emissions and therefore encourages proactive leak management.

One leading supermarket chain in Australia maintains single-digit leak rates by implementing the F-Gas service regulation approach. The company holds contractors accountable for achieving these low leak rates, with penalties imposed if targets are not met.

Figure 7: Medium to large refrigeration leak rates from 2006 to 2022



Source: (IPCC 2006, AGO 2006, AGO 2008, RA 2009, DCCEEW 2023b, DCCEEW 2024b)
IPCC Intergovernmental Panel on Climate Change **AGO** Australian Greenhouse Office **CHF** Cold Hard Facts series

Notes:

1. The 2006 IPCC data provided a lower value that were representative of developed countries and higher value of developing countries.
2. The 2009 Leak study and CHF2 2012 data provide a lower value that were typically representative of HFC systems and the higher value older HCFC systems.
3. The most common applications for remote condensing units are remote display cases and cold rooms.
4. An independently owned supermarket refers to a grocery store managed by an individual or a small group of owners. In contrast, a corporate-owned supermarket chain is operated by a larger company, characterised by standardised processes and adherence to environmental corporate responsibility practices.

Transport, marine and milk vat refrigeration

Road transport refrigeration units (TRUs) have seen considerable advancements over the last decade resulting in lower leak rates. The previous generation systems are equipped with shaft seals and vibra-sorber hoses (stainless steel braided flexible hoses). These components frequently fail during the equipment's lifespan which leads to significant refrigerant loss, particularly from shaft seal and hose failures. Compressor replacements are also common, typically requiring the replacement or reuse of refrigerant. The current TRU designs, particularly those from Europe and the USA, are self-contained systems that come pre-charged and ready for installation and with smaller refrigerant charges (about 75% of previous charge sizes). As these newer designs become the dominant design in the fleet, leak rates are expected to reduce.

Refrigeration systems on fishing vessels greater than 15 metres and coastal shipping are simply called ‘marine’ refrigeration. The refrigeration equipment on fishing vessels typically comprises specialised chilling and often very high-capacity blast freezing equipment. They have one of the most demanding tasks for refrigeration equipment. They operate in constrained spaces, under heavy load, in high ambient temperatures. This equipment is also required to snap freeze of tonnes of sensitive product using equipment operating in a moving vessel, with heavy vibration and exposed to corrosive salt spray and water.

Average leak rates in Australia's fishing fleet have decreased significantly, from 25% to 35% per annum in 2012 to approximately 17.5% per annum by 2022. This reduction is primarily attributed to rising refrigerant costs and advancements in practices and equipment design. A key challenge for the fishing fleet is the aging equipment, most of which are around 40 years old. While major components may have been replaced, the interconnecting pipework (insulated mild steel) often remains original and is a primary source of leaks.

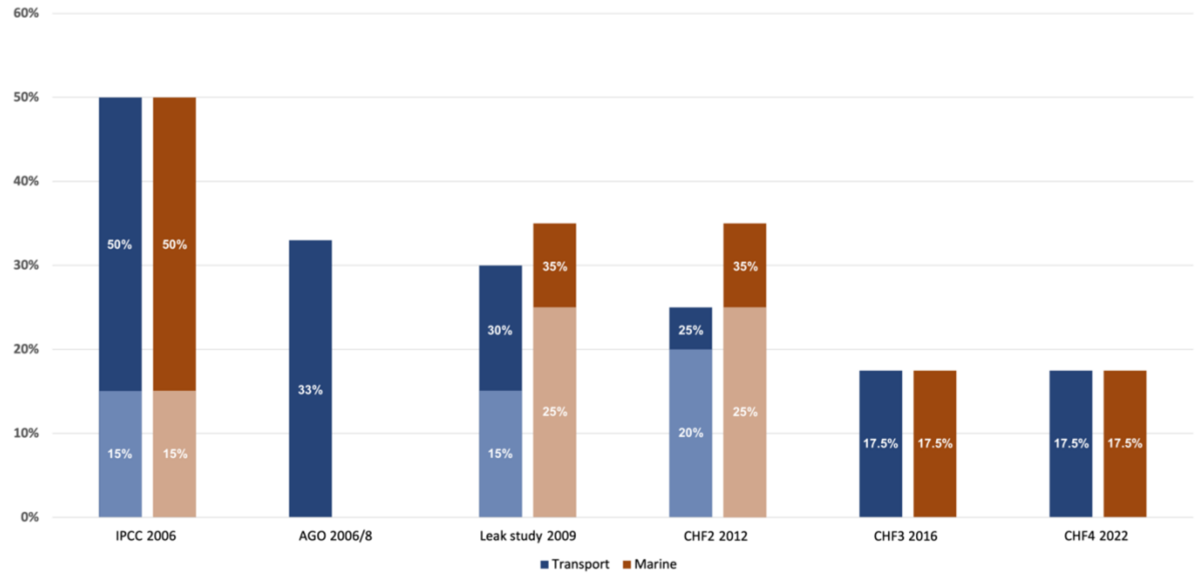
While these high rates are representative of the industry, there is one fleet operator with eleven vessels that participates in Climate Active[2] reporting to claim carbon neutral status after purchasing carbon off-sets. This company claims to achieve leak rates ranging from 5% to 10% and considers the occasional catastrophic failure. At the same time, they have transitioned most of their vessels to R438A and R448A with only one HFC-404A vessel in operation at the end of 2024.

Direct expansion milk vat chilling systems exhibited exceptionally high leak rates in the early 2000s, exceeding 25% per year. Around 2010, over half of these systems utilised outdated belt-drive technology and were charged with the ozone depleting HCFC refrigerants. The drive shaft seals and the poor maintenance practices on farms contributed to the high refrigerant leak rates. Most of these systems have since been decommissioned, with many larger farms transitioning to indirect cooling systems, which have significantly lower leak rates, estimated at approximately 7% per year.

Figure 8 illustrates the variation in leak rates for transport and marine refrigeration systems from 2006 to 2022, showing a reduction from 50% annually in 2006 to approximately 17.5% in recent years.

[2] https://www.climateactive.org.au

Figure 8: Transport and marine refrigeration leak rates from 2006 to 2022



Source: (IPCC 2006, AGO 2006, AGO 2008, RA 2009, DCCEEW 2023b, DCCEEW 2024b)
IPCC Intergovernmental Panel on Climate Change **AGO** Australian Greenhouse Office **CHF** Cold Hard Facts series

Notes:

1. The 2006 IPCC data provided a lower value that were representative of developed countries and higher value of developing countries.
2. The 2009 Leak study and CHF2 2012 data provide a lower value that were typically representative of HFC systems and the higher value older HCFC systems.
3. Transport refrigeration includes all types of road refrigeration (trailer - inter-modal, diesel drive and off engine).
4. Marine refrigeration refers to fishing vessels greater than 15 metres.

4.3.1 Method of calculating commercial refrigeration leak rates

The following data enables the Expert Group to model the Australian refrigerant bank by application, segmented by refrigerant species, with a reasonable degree of confidence:

- Monthly sales data for refrigeration condensing units, evaporators, compressors, and remote condensers by capacity from 2012 to the present.
- The number of small, medium, and large supermarkets, along with average refrigerant charges by store size.
- The refrigerant mix of new equipment installed across different applications over the past decade.
- Modelled refrigerant mix for the refrigerant bank by application.
- The number of cascade and trans-critical R744 (CO_2) systems currently in operation.
- Average refrigerant charges and typical lifespans of various equipment types.

Industry data collected over the past decade confirm with a high level of certainty that 852 tonnes of HFC-404A were used in 2022. By accounting for the refrigerant utilised in charging new systems, we can reconcile service demand across the supermarket and commercial refrigeration fleet and reliably estimate leak rates.

5 Appendix A

5.1 Technical characteristics by product category

Tables 5 to 8 shows the average refrigerant charges, end-of-life charges, leak rates, service rates and average equipment life span assumptions that are applied in the stock model. These metrics are applied to produce a number of outputs of the RAC Stock model, and ultimately, define the bank of refrigerant.

Table 5: Technical characteristics by product category: Stationary AC

	Product category	Average charge of most common species (kg) a			EOL factors (%) b		Rates (% of original charge) d		Nom. lifespan (years)
					EOL factors	Tech rec c	Service rate	Leak rate	
AC1: Small AC: Self-contained	Non-Ducted: Unitary 0-10 kWr	**HFC-410A**	**HFC-32**	**HC-290**	85%	90%	2.0%	2.5%	12.0
		0.6	0.5	0.18					
	Portable AC and de-humidifiers 0-10 kWr	**HFC-410A**	**HFC-32**	**HC-290**	-	-	Not serviced	-	8.0
		0.470	0.470	0.14					
AC2: Small AC: Split	Single split system: non-ducted (wall hung, cassette, console and under ceiling units)	**HFC-410A**	**HFC-32**		80%	90%	2.3% **e**	4.0%	12.0
		1.40	1.12						
AC3: Medium AC: Ducted and light commercial	Single split system: ducted	**HFC-410A**	**HFC-32**		80%	90%	2.5% to 2.6% **e**	3.5% to 3.7%	16.0
		4.70	3.30						
	RT Packaged systems	**HFC-410A**	**HFC-32**		80%	90%			20.0
		15.0	12.0						
	Multi split	**HFC-410A**	**HFC-32**		80%	90%			20.0
		3.0	2.0						
	VRV/VRF split systems	**HFC-410A**	**HFC-32**		80%	90%			20
		9.0	6.0						

	Close control AC (excl. chillers)	**HFC-407C**	**HFC-410A**		80%	90%			12.5
		30.0	30.0						
	Compressed air refrig. filter/dryers	**HFC-134a**	**HFC-407C**	**R513A**	85%	90%	2.5%	4.0%	12.5
		3.0	3.0	3.0					
	Thermal management systems for batteries and associated electronics	**HFC-410A**	**HFC-134a**		85%	90%	2.5%	4.0%	12.5
		1.40	1.40						
AC4: Large AC: Chillers	Scroll compressor: ≥100 to <350 kW	**HFC-410A**	**HFC-32**		85.0	95.0	3.75%	4.6%	18
		30.0	24.0						
	Screw compressor and medium pressure centrifugal ≥100 to <350 kW	**HFC-134a**	**HFO-1234ze**	**R513A**	85.0	95.0	3.8%	4.6%	18
		55.0	55.0	55.0					
	Screw compressor and medium pressure centrifugal ≥1055 kW	**HFC-134a**	**HFO-1234ze**	**R513A**	85.0	95.0	3.8%	4.6%	25
		500	500	500					
	Low pressure centrifugal ≥1055 kW	**HFO-1233zd**	**R514A**		85.0	95.0	3.8%	4.6%	25
		850	850						

AC air conditioning **EOL** end-of-life. **HFC** hydrofluorocarbon **HFO** hydrofluoro-olefin **HC** hydrocarbon
a Average charge of the most common species found in bank that product category. Charges of other species used in the same product category may differ. **b** EOL factor used to calculate residual EOL charge when retired. EOL factors generally consistent with others cited internationally and in IPCC good practice guides. **c** The EOL technical recovery factor represents the maximum proportion of refrigerant that can be reclaimed from a product during its disposal process. The recovery of refrigerant may face various constraints, such as product design limitations (e.g. absence of service valves, necessitating refrigerant recovery piercing pliers) and field-related challenges. **d** The service rate of sealed units includes usage from repairs or a possibly product recall. If refrigerant is required for a portable air conditioner it is typically retired. **e** The service rates of HFC-32 models is lower than this percentage for HFC-410A as the stock of equipment is much newer.

Table 6: Technical characteristics by product category: Heat Pumps

	Product category	Average charge of most common species (kg) a			EOL factors (%) b		Rates (% of original charge) d		Nominal lifespan (years)
					EOL factors	Tech rec c	Service rate	Leak rate	
HP1: Small HP	Hot water heat pump: domestic, incl. residential and commercial as well as cascade systems	**HFC-134a**	**HFC-410A**	**HC-290**	90%	90%	2.0%	3.0%	10.0
		1.10	0.92	0.53					
	Heat pump clothes dryers	**HFC-134a**	**R450A**	**HC-290**	90%	90%	2.0%	3.0%	15.0
		0.41	0.46	0.14					
HP2: Medium HP	Pool heat pumps	**HFC-407C**	**HFC-410A**	**HFC-32**	80%	90%	2.5%	3.7%	12.0
		2.60	1.60	1.00					
HP3: Large HP	Commercial HP & multi-function chillers	**HFC-410A**	**HFC-32**	**HFC-134a**	85%	95%	3.0%	4.0%	25.0
		110.0	77.0	110.0					

HP heat pump **EOL** end-of-life **HFC** hydrofluorocarbon **HC** hydrocarbon
a Average charge of the most common species found in the bank in that product category. Charges of other species used in the same product category may differ. **b** EOL factor used to calculate residual EOL charge when retired. EOL factors generally consistent with others cited internationally and in IPCC good practice guides. **c** The EOL technical recovery factor represents the maximum proportion of refrigerant that can be reclaimed from a product during its disposal process. The recovery of refrigerant may face various constraints, such as product design limitations (e.g. absence of service valves, necessitating refrigerant recovery piercing pliers, small charge sizes) and field-related challenges. **d** The service rate of sealed units includes usage from repairs or a possibly product recall.

Table 7: Technical characteristics by product category: Mobile air conditioning

<table>
<tr><th rowspan="2"></th><th rowspan="2">Product category</th><th colspan="3" rowspan="2">Average charge of most common species (kg)
a</th><th colspan="2">EOL factors (%)
b</th><th colspan="2">Rates
(% of original charge)
d</th><th rowspan="2">Nominal lifespan (years</th></tr>
<tr><th>EOL factors</th><th>Tech rec
c</th><th>Service rate</th><th>Leak rate</th></tr>
<tr><td rowspan="4">MAC1: Small Mobile AC</td><td rowspan="2">Passenger vehicles and light commercial vehicle</td><td>HFC-134a</td><td>HFO-1234yf</td><td rowspan="2"></td><td rowspan="2">67%</td><td rowspan="2">90%</td><td rowspan="2">5.4%</td><td rowspan="2">7.2%</td><td rowspan="2">18.6</td></tr>
<tr><td>0.610</td><td>0.610</td></tr>
<tr><td rowspan="2">Electric vehicle: heat pumps</td><td>HFC-134a</td><td>HFO-1234yf</td><td rowspan="2"></td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">1% e</td><td rowspan="2">1%</td><td rowspan="2">16.0</td></tr>
<tr><td>0.840</td><td>0.840</td></tr>
<tr><td rowspan="14">MAC2: Large Mobile AC</td><td rowspan="2">Buses and coach es: Small</td><td>HFC-134a</td><td>HFC-407C</td><td rowspan="2"></td><td rowspan="2">80%</td><td rowspan="2">90%</td><td rowspan="8">8.0%</td><td rowspan="8">8.7%
to
9.0%</td><td rowspan="2">20.0</td></tr>
<tr><td>3.0</td><td>3.0</td></tr>
<tr><td rowspan="2">Buses and coaches: Large</td><td>HFC-134a</td><td>HFC-407C</td><td rowspan="2"></td><td rowspan="2">80%</td><td rowspan="2">90%</td><td rowspan="2">20.0</td></tr>
<tr><td>5.50</td><td>5.50</td></tr>
<tr><td rowspan="2">Passenger rail</td><td>HFC-134a</td><td>HFC-407C</td><td rowspan="2"></td><td rowspan="2">80%</td><td rowspan="2">90%</td><td rowspan="2">30.0</td></tr>
<tr><td>13.0</td><td>13.0</td></tr>
<tr><td rowspan="2">Locomotive</td><td>HFC-134a</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">80%</td><td rowspan="2">90%</td><td rowspan="2">30.0</td></tr>
<tr><td>3.0</td></tr>
<tr><td rowspan="2">RV and caravan</td><td>HFC-410A</td><td>HFC-407C</td><td rowspan="2"></td><td rowspan="2">85</td><td rowspan="2">90.0</td><td rowspan="2">6.0%</td><td rowspan="2">7.0%</td><td rowspan="2">15.0</td></tr>
<tr><td>0.60</td><td>0.60</td></tr>
<tr><td rowspan="2">Off-road, defence and other.</td><td>HFC-134a</td><td>HFC-410A</td><td>HFC-407C</td><td rowspan="2">80.0</td><td rowspan="2">90.0</td><td rowspan="2">6.0%</td><td rowspan="2">7.3%</td><td rowspan="2">15.0</td></tr>
<tr><td>1.25</td><td>1.25</td><td>1.25</td></tr>
<tr><td rowspan="2">Registered marine vessels and pleasure craft.</td><td>HFC-410A</td><td>HFC-407C</td><td rowspan="2"></td><td rowspan="2">80.0</td><td rowspan="2">90.0</td><td rowspan="2">8.0%</td><td rowspan="2">9.0%</td><td rowspan="2">15.0</td></tr>
<tr><td>2.25</td><td>2.25</td></tr>
</table>

MAC mobile air conditioning **EOL** end-of-life **HFC** hydrofluorocarbon **HFO** hydrofluoro-olefin
a Average charge of the most common species found in the bank in that product category. Charges of other species used in the same product category may differ. **b** EOL factor used to calculate residual EOL charge when retired. EOL factors generally consistent with others cited internationally and in IPCC good practice guides. **c** The EOL technical recovery factor represents the maximum proportion of refrigerant that can be reclaimed from a product during its disposal process. The recovery of refrigerant may face various constraints, such as product design limitations (e.g., absence of service valves, necessitating refrigerant recovery piercing pliers, small charge sizes) and field-related challenges. **d** The service rate of sealed units includes usage from repairs or a possibly product recall. **e** The service rate for MAC in EVs is very low as the majority of the fleet is less than 5 years old and still under warranty. The service and leak rate will eventually be consistent with the fleet of internal combustion engines vehicles when the average ages are similar. **f** Based on five CHF evaluations conducted from 2016 to 2022, the average leak rate is calculated at 7.4%. In the summary table this was rounded up to 7.5%.

Table 8: Technical characteristics by product category: Cold chain

	Product category	Average charge of most common species (kg) a			EOL factors (%) b		Rates (% of original charge) d	Nominal lifespan (years
					EOL factors	Tech rec c	Leak rate	
CC1: Domestic refrigeration and freezers, and portable	Domestic refrigerators and freezers	**HFC-134a**	**HC-290**		90.0	80.0	<1% (Replacement rather than service/repair)	15.5
		0.135	0.055					
	Portable	**HFC-134a**	**HC-290**		90.0	80.0		12.0
		0.55	0.35					
	Vehicle refrigeration	**HFC-134a**			-	-		12.0
		0.35						
CC2: Small Commercial Refrigeration	Refrigeration cabinets: self-contained	**HFC-134a**	**HC-290**		85.0	90.0	<1% to 3.0%	11.5
		0.50	0.15					
	Refrigeration beverage vending machines	**HFC-134a**	**HC-290**		85.0	90.0		12.0
		0.30	0.075					
	Beverage cooling (beer and post mix)	**HFC-134a**	**HC-290**		85.0	90.0		8.0
		0.550	0.210					
	Ice makers (flakers and cubers)	**HFC-134a**	**HFC-404A**	**HC-290**	85.0	90.0		11.0
		0.60	0.60	0.30				
	Water dispensers (incl. bottle)	**HFC-134a**	**HC-290**		85.0	90.0		8.0
		0.050	0.015					
	Walk-in coolrooms: small: Slid-in/Drop-in	**HFC-134a**	**HFC-404A**	**HC-290**	85.0	90.0		12.0
		0.75	0.225	0.225				
CC3: Medi	Walk-in coolrooms: small: remote	**HFC-404A**	**HFC-134a**		80.0	95.0	15.0%	12.0

		5.0	5.0					
	Walk-in coolrooms: medium	**HFC-404A**	**HFC-134a**		80.0	95.0		12.0
		17.0	17.0					
	Walk-in coolrooms: large	**HFC-404A**	**HFC-134a**		80.0	95.0		15.0
		23.0	23.0					
	Refrigeration cabinets: remote	**HFC-404A**	**HFC-134a**		80.0	95.0		15.0
		10.0	10.0					
	Beverage cooling (beer)	**HFC-404A**	**HFC-134a**		80.0	95.0		15.0
		40.0	40.0					
	Milk vat refrigeration (direct expansion)	**HFC-404A**	**HFC-407F**	**HFC-134a**	80.0	95.0	17.5%	30.0
		40.0	40.0	40.0				
	Packaged liquid chillers (incl. milk vat)	**HFC-407C**	**HFC-134a**	**HFC-410A**	80.0	95.0	7.0%	20.0
		38.0	38.0	38.0				
CC4: Supermarket refrigeration	Supermarket refrigeration: small	HFC-404A, HFC-134a and HFC/HFO-Blends			90%	95%	11%/15% **e**	15/25 **f**
		160 to 300						
	Supermarket refrigeration: medium	HFC-404A, HFC-134a and HFC/HFO-Blends			90%	95%	11%/15% **e**	15/25 **f**
		160 to 300						
	Supermarket refrigeration: large	HFC-404A, HFC-134a and HFC/HFO-Blends			90%	95%	11%/15% **e**	15/25 **f**
		900 to 1,300						
CC5: Transport refrigeration	Mobile refrigeration: road: trailer - inter-modal	**HFC-404A**	**HFC-452A**		90%	95%	17.5%	**12.5**
		6.0	6.0					
	Mobile refrigeration: road: diesel drive	**HFC-404A**	**HFC-452A**		90%	95%		12.5

		3.6	3.6					
	Mobile refrigeration: road: off engine	**HFC-404A**	**HFC-134a**	**HFC-452A**	90%	95%		10.0
		2.0	2.0	2.0				
	Mobile refrigeration: marine	**HFC-404A**	**HFC-438A**		90%	95%	17.5%	40.0
		130.0	130.0					

CC cold chain **EOL** end-of-life **HFC** hydrofluorocarbon **HFO** hydrofluoro-olefin **HC** hydrocarbon
a Average charge of the most common species found in the bank in that product category. Charges of other species used in the same product category may differ. **b** EOL factor used to calculate residual EOL charge when retired. EOL factors generally consistent with others cited internationally and in IPCC good practice guides. **c** The EOL technical recovery factor represents the maximum proportion of refrigerant that can be reclaimed from a product during its disposal process. The recovery of refrigerant may face various constraints, such as product design limitations (e.g. absence of service valves, necessitating refrigerant recovery piercing pliers, small charge sizes) and field-related challenges. For example, portable and some domestic refrigerators with small charges and/or no service ports have the lowest technical recovery factors. **d** The service rate of sealed units includes usage from repairs or a possibly product recall. If refrigerant is required for a portable or domestic refrigerator it is typically retired. **e** The two leak rates refer to those for a major supermarket chains and independently owned supermarkets. The corporate-owned supermarket chain is operated by a larger company, characterised by standardised processes and adherence to environmental corporate responsibility practices with lower leak rates. **f** The refrigeration systems in major chains tend to be newer, averaging 15 year lifespans compared to 25 years in independent supermarkets.

Table 9 provides the data used for Figure 3.

Table 9: Small mobile air conditioning leak rates from 2006 to 2022

	IPCC 2006		AGO 2006/8	Leak study 2009	CHF2 2012		CHF3 2016	
	Leak rate low	Leak rate high	Leak rate	Leak rate	-	Leak rate	Service rate	Leak rate
Passenger and light commercial vehicles	10.0%	20.0%	15.0%	14.0%	-	11.5%	4.8%	6.7%
	CHF3 2019		CHF3 2020		CHF3 2021		CHF4 2022	
	Service rate	Leak rate	Service rate	Leak rate	Service rate	Leak rate	Service rate	Leak rate
Passenger and light commercial vehicles	5.6%	7.4%	5.7%	7.5%	5.7%	7.5%	5.3%	7.1%

Table 10 provides the data used for Figures 4 and 5.

Table 10: Stationary air conditioning and heat pump leak rates from 2006 to 2022

	IPCC 2006		AGO 2006/8	Leak study 2009		CHF2 2012		CHF3 2016	CHF4 2022	
	Leak rate low	Leak rate high	Leak rate	Leak rate low	Leak rate high	Leak rate low	Leak rate high	Leak rate	Service rate	Leak rate
Res. and com. AC, incl heat pumps	1.0%	10.0%								
Portable				1.0%	1.3%	1.0%	1.0%	1.0%		
Window/wall units			3.0%	1.0%	1.3%	3.0%	4.0%	2.5%	1.0%	3.2%
WH split systems			3.0%	3.0%	10.0%	4.0%	8.0%	3.5%	2.4%	4.1%
Ducted split and light comm AC			3.0%	3.0%	11.9%	4.0%	8.0%	2.7%	2.6%	3.8%
Chillers	2.0%	15.0%	8.5%	5.0%	8.3%	6.0%	8.0%	4.5%	3.8%	4.6%
Chillers (HCFC-123)				1.0%	1.0%	1.0%	1.0%	1.0%		

Table 11 provides the data used for Figures 6, 7 and 8.

Table 11: Cold chain leak rates from 2006 to 2022

	IPCC 2006		AGO 2006/8	Leak study 2009		CHF2 2012		CHF3 2016	CHF4 2022
	Leak rate low	**Leak rate high**	**Leak rate**	**Leak rate low**	**Leak rate high**	**Leak rate low**	**Leak rate high**	**Leak rate**	**Leak rate**
Domestic refrigeration	0.1%	0.5%	3.0%	0.1%	2.0%	1.0%	2.0%	<1%	<1%
Self-contained	1.0%	15.0%		2.0%	5.0%	2.0%	5.0%	7.0%	<1% to 3%
Remote cond. units	10.0%	35.0%	23.0%	10.0%	15.0%	17.5%	20.0%	15.0%	15.0%
Supermarket: Major chain	10.0%	35.0%	23.0%	15.0%	21.0%	12.0%	15.0%	12.5%	11.0%
Supermarket: Independent	10.0%	35.0%	23.0%	15.0%	30.0%	15.0%	20.0%	15.0%	15.0%
Industrial ref. and cold storage	7.0%	25.0%	16.0%	7.0%	20.0%	10.0%	15.0%	15.0%	15.0%
Transport	15.0%	50.0%	33.0%	15.0%	30.0%	20.0%	25.0%	17.5%	17.5%
Marine	15.0%	50.0%		25.0%	35.0%	25.0%	35.0%	17.5%	17.5%

Notes:

1. The leak rate of 7% for self-contained equipment in the CHF3 2016 assessment appears to be an over statement. The leak rate for self-contained equipment in the CHF4 2022 assessment was adjusted to less than 1% to 3%.

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