Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee

2022 Assessment Report

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Montreal Protocol
on Substances
that Deplete the
Ozone Layer

UNEP

2022 REPORT OF THE
REFRIGERATION, AIR CONDITIONING AND HEAT PUMPS
TECHNICAL OPTIONS COMMITTEE

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The names of chapter lead authors, co-authors and contributors are given at the start of each chapter. Names and contact emails of the chapter lead authors and all other authors of the UNEP TOC Refrigeration, A/C and Heat Pumps can be found in Chapter 14.

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Acronyms

AC	Air Conditioning
AHRI	Air-Conditioning, Heating and Refrigeration Institute
AREP	Alternative Refrigerant Evaluation Program
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATEL	Acute Toxicity Exposure Limit
CARB	California Air Resource Board
CFC	Chlorofluorocarbon
COP	Coefficient of Performance
DX	Direct Expansion
ECM	Electronically Commutated Motor
EER	Energy Efficiency Ratio
EEV	Electronic Expansion Valve
EGYPRA	Egyptian Project for Refrigerant Alternatives
EPEE	European Partnership for Energy and the Environment
EU	European Union
FRA	Flammability Risk Assessment
GCC	Gulf Cooperation Council
GHG	Greenhouse Gas
GIZ	Gesellschaft fuer Internationale Zusammenarbeit, Germany
GWP	Global Warming Potential
HAT	High Ambient Temperature
HC	Hydrocarbon
HCC	Hydrochlorocarbon
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HP	Heat Pump (and also Horsepower)
HPCD	Heat Pump Clothes Dryer
HTF	Heat Transfer Fluid
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
IHX	Internal Heat Exchanger
IIR	International Institute of Refrigeration
ISO	International Standard Organisation
JRAIA	Japan Refrigeration and Air Conditioning Industry Association
K-CEP	Kigali Cooling Efficiency Programme (name changed to CCC)
kW	Kilowatt
LAT	Low Ambient Temperature
LCA	Life Cycle Analysis
LCCP	Life Cycle Climate Performance
LCWI	Lifecycle Warming Impact
LED	Light Emitting Diode
LFL	Lower Flammability Limit
LVC	Low Volume Consuming Country
MAC	Mobile Air Conditioner
MAT	Medium Ambient Temperature

MCII `	Multilateral Fund Climate Impact Indicator
MEPS	Minimum Energy Performance Standard
MLF	Multilateral Fund under the Montreal Protocol
MVC	Mechanical Vapour Compression
NIK	Not-In-Kind
ODP	Ozone Depletion Potential
ODS	Ozone Depleting Substance
OEM	Original Equipment Manufacturer
OEWG	Open-ended Working Group
ORNL	Oak Ridge National Laboratory
PED	Pressure Equipment Directive
PFAS	Perfluoroalkyl & Polyfluoroalkyl Substances
POE	Polyol Ester
PRAHA	Promoting Low-GWP Refrigerant Alternatives for the Air Conditioning Sector in High Ambient temperature Countries
PTAC	Packaged Terminal Air Conditioner
PVE	Polyvinyl Ester
R&D	Research and Development
R/AC	Refrigeration and Air Conditioning
RACHP	Refrigeration, Air Conditioning and Heat Pumps
RTOC	Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee
SAE	Society of Automotive Engineers
SDG	Sustainable Development Goal
SEER	Seasonal Energy Efficiency Ratio
SNAP	Significant New Alternatives Policy
SSC	Small Self Contained
TEAP	Technology and Economic Assessment Panel
TEWI	Total Equivalent Warming Impact
TFA	Trifluoroacetic Acid
TR	Ton of Refrigeration (12,000 BTU per hour)
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organisation
VRF	Variable Refrigerant Flow
W	Watt

Key Messages

- The Montreal Protocol has shown to be successful in phasing out HCFCs with essentially a complete phaseout in non-Article 5 parties and strong progress in Article 5 parties.
- The Kigali Amendment to the MP has provided the signal to mobilize the RACHP sector into a transition towards lower GWP refrigerants.
- Ultralow-, low-, and/or medium-GWP alternative refrigerants are available for all RACHP applications and are being widely applied in some RACHP applications and regions.
- Accessibility is still a major hindrance for the widescale adoption of lower GWP refrigerants and progress towards goals of the Kigali Amendment phasedown schedules.
- Most ultralow-, low-, and medium-GWP refrigerants have different flammability classes (lower flammability, flammable, and higher flammability). As such, the RACHP sector continues to update the relevant safety standards to enable their use. Most recent updates reduced the restrictions on flammable refrigerants and increased the allowable flammable refrigerant charge limits for self-contained commercial refrigeration, air-to-air AC , and heating only heat pump applications.
- Trifluoroacetic acid, TFA, one of the decomposition products of some refrigerants, is a chemical that is included within the OECD definition of per- and poly-fluoroalkyl substances (PFAS). The OECD PFAS definition does not include HFC-32, HFC-152a, HFO-1132 and HFO-1123. Information on TFA is provided in the 2022 EEAP Assessment Report. There is a proposal from five European countries to update their own PFAS definition, which may impact RACHP applications in some countries.
- While high-GWP HFC phasedown focuses on the direct GHG emissions from the RACHP sector, the indirect GHG emissions are equally or more impactful to climate change. The indirect GHG emissions are due to energy consumption from the RACHP applications and can be reduced significantly through improved equipment energy efficiency, reduced demand using high-performance buildings and cold-chain, and reduced carbon intensity of the electricity network.

Sustainability in the RACHP sector

- RACHP applications play a key role in sustainable development.
- RACHP equipment contribute to climate change through direct emissions of GWP refrigerants and indirect emissions from energy consumed during lifetime operation.
- Standards and methods are available to perform sustainability assessments for RACHP applications.
- The RACHP sector uses refrigerants with a range of potential adverse effects. Some adverse effects are real and immediate (e.g., flammability and toxicity) and may be avoided by design measures at an additional cost. Some are near term on climate (e.g., high-GWP) and may be avoided by proper refrigerant selection. And others are currently under further evaluation (e.g., TFA) as discussed in the 2022 EEAP Assessment Report.
- It is important to balance the benefits and risks of refrigerant selection, including known safety and environmental impacts, being mindful of areas of scientific uncertainty.
- Sustainability issues should be balanced with technical issues for RACHP applications.

Refrigerants

- Two new single component refrigerants (FIC-13I1 and HFO-1132(E)) and 23 new refrigerant blends have received designations and classifications by ASHRAE Standard 34 and/or ISO 817 since the publication of the 2018 RTOC Assessment Report.
- There is no single "ideal" refrigerant. Refrigerant selection is a balanced result of weighing several factors which include, environmental issues, suitability for the targeted use, availability, cost of the refrigerant and associated equipment and service, energy efficiency rating, safety, and ease of use.
- The HFC phasedown under the Kigali Amendment as well as regional regulations are driving the industry towards the use of low-GWP refrigerants. Ultralow-, low- and medium-GWP alternatives to high-GWP refrigerants exist and are used in many applications, where new ones are being continuously introduced.
- Many of the alternative refrigerants that are now being used are expected to only play a temporary role in the phasedown process, as their GWP may still be high for future applications.
- Refrigerants with low direct impact on climate change are often flammable (e.g., HCs) and may have higher toxicity (e.g., ammonia). In order to maintain the current safety levels, safety standards are being updated, new technologies are being developed and an increased level of training will be required.
- Refrigerant emissions into the atmosphere can result in decomposition products which could be harmful to the Earth's eco-system. Some of the current and alternative synthetic fluorinated refrigerants, (HCFCs, HFCs, and HFOs) produce varying amounts of TFA (formula $C_2HF_3O_2$) during their atmospheric decomposition. Understanding the TFA budget in the different parts of the environment is key for evaluating future environmental impacts of all anthropogenic TFA (WMO, 2022).
- Article 7 reported data give no sector-specific consumption information on HFCs and are difficult to interpret. One can consider Multilateral Fund and other survey data, but availability of reliable data is limited.
- Five different types of models exist for the calculation of HFC consumption, inventories, and emissions of which three are bottom-up based models. With different ways of calculating refrigerant consumption, banks, and emissions, they have become key for the future understanding of the impact of refrigeration, AC, and heat pump systems on the environment.

Sealed domestic and commercial refrigeration appliances and heat pump tumble dryers

- Around 2 billion refrigerators are installed worldwide, with 200 million new domestic refrigerators and freezers being sold each year dominated by the HC-600a refrigerant technology.
- Due to Kigali amendment, stand-alone commercial refrigeration appliances are moving to more efficient HC-290 technologies in both non-A5 and A5 parties following the revision of safety and equipment standards in 2019.
- Domestic heat pump tumble dryers (HPTDs) use 40 to 50 % of energy of conventional dryers, they continue to gain market share. Common refrigerants are HFC-134a, R-407C, and R-410A but transition to HC-290 is seen in Europe.

Food retail and food service refrigeration

- The shift to ultralow- and low-GWP in new systems and retrofit to low- or medium-GWP in existing systems, while also maintaining or improving the energy efficiency, is critical in the expansion of a sustainable cold chain to reduce food loss and waste.
- Food Retail and Food Service refrigeration conversion to ultralow-, low- and medium-GWP refrigerants is progressing well in all regions, but high-GWP refrigerants are still being used in many countries.
- The most common ultralow- and low-GWP refrigerants being applied are R-744, HC-290, and HFO blends such as R-454C, R-454A and R-455A.
- There is a continuing effort to improve energy efficiency while transitioning to ultralow- and low-GWP systems through refrigeration load reduction and improved vapour compression system design and component efficiency.
- Existing high-GWP R-404A and HFC-134a systems are being proactively converted to medium-GWP A1 refrigerants (e.g., HFO blends such as R-448A, R-449A, R-450A, and R-513A).

Transport refrigeration

- Transport refrigeration is an important part of cold chain systems. To ensure safe and reliable operation, the knowledge, competency for safe service, spare parts, as well as relevant safety processes and procedures, must be available all along the transport routes.
- The majority of trucks and trailers still use R-404A but new equipment in Europe and in North America uses R-452A with a significant reduction in GWP. Furthermore, HFC-134a are being converted to R-513A or HFC-1234yf.
- Light commercial vehicles use mainly HFC-134a, while some begin to use HFO-1234yf.
- The majority of marine container refrigeration units still use HFC-134a.
- Air conditioning in cruise liners air conditioning which has used HFC-134a is being replaced by HFC-1234ze(E). R-717 is returning in fishing vessels.
- The GWP of the refrigerants used is expected to come down consistently with present and future legislation. Future systems may be based on HC-290, R-744, A2L or A1 refrigerant blends.
- A scarcity of qualified people to maintain and service systems with various levels of complexity along the transport routes, combined with availability problems of spare parts including refrigerants, can slow down the transition to the ultralow-, low- and medium-GWP alternative refrigerants or new solutions.
- Progress has been made in the area of design standards, which are becoming available for the subsectors.

Air-to-air air conditioners and heat pumps

- The phaseout of HCFC-22 in non-Article 5 parties is complete for new equipment.
- The phaseout of HCFC-22 is progressing well in Article 5 parties where some have already completed HCFC-22 phaseout.
- In addition to HFC-32, there are several medium-GWP HFC/HFO blends being adopted, such as R-454B, R-452B and R-463A.
- In addition to these refrigerants, transition also includes adoption of HC-290 for single split and portable AC units, which is underway in China, South-East Asia, and Latin America.

- Component and system optimisation remain a design challenge over and above those with conventional refrigerants, such as HCFC-22 and R-410A. Availability and accessibility of certain components and technologies and in some regions are a major hindrance to uptake of medium- and particularly low-GWP alternatives. Also, the high price of some low- and medium-GWP blends is a strong deterrent.

- Larger, more complex, and distributed systems pose the greatest challenges to adoption of medium- and low-GWP alternatives, although larger ducted and VRF systems with medium-GWP alternatives are becoming available.

- Revised safety standards (e.g., IEC 60335-2-40) enable more extensive and cost-effective application of low-GWP refrigerants in smaller systems and medium-GWP refrigerant in larger systems. Risk assessment for all stages of the equipment lifetime is important.

- Improving energy efficiency for air-to-air air conditioners is an important challenge linked to the Kigali Amendment. Many countries have ambitious minimum energy performances rules. Although some alternative refrigerants are conducive to improvements in efficiency, availability of certain system components is crucial, such as high efficiency compressors, heat exchangers, advanced controls, and energy recovery systems.

Applied building cooling systems

- The phaseout of ozone-depleting refrigerants in chillers, namely CFCs (e.g., CFC-11), is essentially complete. CFCs have been completely phased out for new equipment in non-Article 5 parties, and the CFC banks are decreasing in existing chillers. Some Article 5 parties are still using HCFC-22 in new equipment, but global production of such chillers is very small.

- The installed base within buildings will remain in service due to the long equipment lifetime, with continued HFC servicing needs.
- A complete range of new chillers that use refrigerants with lower GWP, compared with the original HCFC or HFC refrigerant, is available in all major markets. The new chillers maintain or improve full and part load performance.
- Even though new products have been introduced, products using refrigerants with high GWP have not be discontinued and are in fact the dominant products being sold today in most market except Europe. Regulations being adopted in other regions will accelerate the changes.
- Non-fluorinated refrigerants, namely R-717 and HC-290, are used in applications of specific sizes

- Life cycle climate performance analyses indicate that the GHG emissions from chillers are dominated by their energy use, not the direct effect caused by leaking refrigerant.

Mobile AC/HP

- Currently, there are still several refrigerants in use. HFC-134a is used globally. Where regulations require low GWP refrigerants, HFO-1234yf and R-744 provide market options. HFO-1234yf is widely adopted, especially for passenger vehicles. It remains unclear when other mobile AC applications, such as buses and heavy-duty trucks, will follow the light-duty vehicle trends.

- Vehicle refrigerant use is shifting from being an optional feature for passenger cooling to a requirement for total vehicle thermal management. The progressive electrification of road transport in Europe, China and North America requires a new generation of refrigerants that can deliver thermal management in addition to passengers' cooling. Hence, electrification is broadening the technical options leading to reconsider the current refrigerant choices to include R-744, HFOs and blends s as viable options.

- European regulations investigating PFAS are very broad and not product-specific at this time. This could lead to HFO-1234yf re-evaluation.
- R-744 is a market alternative to HFO-1234yf for light duty vehicles and buses. Class A2 and class A3 (e.g., R-152a, hydrocarbons) refrigerants are being investigated, considering that secondary-loop architectures are an option for the electrified vehicle thermal systems.

Industrial refrigeration, heat pumps and heat engines

- Industrial refrigeration, heat pumps, and heat engines are used in a range of industries such as food and beverage, fisheries, pharmaceuticals, petrochemicals, district cooling and heating systems, etc.
- Industrial heat pumps are suitable for use in industrial applications because they provide heat at high temperatures and will be important in decarbonizing the industry.
- Industrial refrigeration and heat pumps traditionally use R-717 but R-744 is also increasingly being used. There is also an emerging trend for the use of HCs and HC mixtures – especially for low temperature applications.

Heating only heat pumps

- Heating only heat pumps have a role in buildings decarbonisation replacing fossil-fuel powered heating systems. Cost effectiveness remains an important consideration with a trade-off between increased capital cost versus lower operating cost when compared with fossil-fuel powered heating systems.
- Water heating heat pumps newly installed today use high-GWP R-410A, HFC-134 and R-407C, medium-GWP HFC-32 and low-GWP R-454C, HC-290, HC-600a, R-744 and R-717. The majority of new equipment installed uses R-410A and HFC-32. In some Article 5 parties HCFC-22 is still being used.
- At present, the main markets for water heating heat pumps are China, the EU, and Japan, and the market will increase rapidly - several states in the US have decarbonization plans that will increase the adoption of heat pumps.
- Since heat pumps are more material intensive than fossil fuel combustion boilers or direct electric heating, the material resource efficiency has to be considered carefully as this will influence the affordability. The selection of a refrigerant for a certain water heating application will influence both the material resource and energy efficiency as well as the life cycle climate impact.

Not-In-Kind technologies

- Not-In-Kind (NIK) technologies could play an important role in sustainable cooling and heating, especially in niche applications.
- Widely available NIK include absorption technologies, direct/indirect evaporative cooling (IEC), hybrid IEC systems, and desiccant cooling.
- NIK technologies can provide lower operating lifecycle cost compared with mechanical vapour compression in some specific conditions.
- Deep sea, lake, and ocean cooling have been investigated and few installations have been implemented. Studies have shown potential for low lifecycle operating cost.
- Other NIK technologies, including magnetocaloric, are in emerging and research and development phases. Some of these technologies, e.g., solid state cooling, are relatively successful in niche markets.

Servicing and refrigerant conservation

- In most Article 5 parties especially in low- and very low- volume consuming countries (LVCs and VLVCs), the majority of refrigerants is used for servicing.
- Proper servicing, described in codes and applied by trained and certified technicians, reduces direct emissions of refrigerants, and minimises the degradation of energy efficiency in RACHP equipment over time.
- Capacity building in Article 5 parties, comprising LVCs and VLVCs includes training programmes (e.g., training of trainers, infrastructure), the provision of appropriate tools, and improved access to spare parts.
- Refrigerant conservation is an effective part of reducing consumption of virgin refrigerants and limiting emissions. The creation of a market mechanism with financial incentives for recovery and recycling is essential to sustain a circular economy.
- While the Montreal Protocol explicitly encourages parties to minimize emissions, refrigerant banks are currently not explicitly managed or controlled as an obligation for Parties under by the Protocol.
- The potential to change the economic viability/affordability of destruction exists with the strengthening of source based Extended Producer Responsibility (EPR) schemes, the imposition of usage fees, and by directing carbon finance revenues back to the refrigeration servicing sector.

Executive Summaries

Sustainability in the RACHP sector

The RACHP sector will continue to play an important role into the sustainable future of mankind, with a focus on efficient cold chains and comfort applications. There is a wealth of information about the impact of refrigerants on the environment. For different RACHP applications, it is important to balance the benefits and risks of refrigerant selection, including known safety and environmental impacts, being mindful of areas of scientific uncertainty. Based on these considerations, standards have been developed as listed in Table 2-1.

CO_2 equivalent emissions include direct and indirect emissions. Direct emissions relate to the emissions of the GWP refrigerant into the atmosphere. They may be reduced through leak minimisation and technician training. Indirect emissions relate to the energy consumed over the lifetime of the equipment and may be reduced through energy efficiency improvement and renewable energy integration.

Refrigerants

Since publication of the RTOC 2018 Assessment Report, two new single component refrigerants (FIC-13I1 and HFO-1132(E)) and 23 new refrigerant blends have received designations and classifications by ASHRAE Standard 34 and/or ISO 817. These include mixtures of HFCs, HFOs, CO2 (R-744), HCs and two mixtures that include new single component refrigerants, R-466A and R-474A. R-466A (a mixture containing FIC-13I1, ODP < 0.04, GWP100 = 733) is a non-flammable replacement of R 410A with approximately a third of its GWP. However, the use of FIC-13I1 (ODP < 0.09) raises the question of the acceptability of short-lived ozone depleting substances. R-474A is a A2L refrigerant mixture of HFO-1132(E) and HFO-1234yf which largely matches R-407C.

Alternatives to high-GWP refrigerants are available for all RACHP applications. However, there is no single "ideal" refrigerant. As result of the implementation of the Kigali Amendment, ultralow-, low- and medium-GWP refrigerants are being introduced for all applications, sometimes as blends of these refrigerants, even with traditional HFC refrigerants. The large number of new refrigerants being proposed creates a challenge to identify the optimal refrigerant for each application. Many of the proposed alternatives are seen as intermediate solutions for the HFC phasedown.

Selection of the optimal refrigerant for a specific application is a balance between environmental issues, suitability for the targeted use, availability, cost of the refrigerant and associated equipment and service, energy efficiency rating, safety, and ease of use.

Using new refrigerants often requires a system redesign or an update to the system architecture. This can be as simple as changing the lubricant or more complex. For example, the earlier transition from CFC-12 primarily to HFC-134a only required changes of the lubricants and some elastomeric seals. However, the shift from HCFC-22 to R 410A required those changes along with additional and extensive modifications of compressor, heat exchangers, controls, and other items.

One aspect of particular importance is that refrigerants with low direct impact on climate change are often flammable and may have higher toxicity. In order to maintain the current safety levels, new technologies are being developed and an increased level of training will be needed. System and appliance safety standards are being continually updated to enable the use of alternative new refrigerants.

Refrigerant emissions into the atmosphere may result in decomposition products which could be harmful to the Earth's eco-system. Some of the current and alternative synthetic refrigerants, (HCFCs, HFCs, and HFOs) produce varying amounts of trifluoroacetic acid (TFA, formula $C_2HF_3O_2$) during their atmospheric decomposition (EEAP, 2022) and (WMO, 2022).

Data on the production of ODS substances and HFCs are reported by parties under Article 7 of the Montreal Protocol and made available by the Ozone Secretariat in aggregated form. Consumption data are not directly reported by Parties. Article 7 reported data give no sector-specific consumption information on HFCs and are difficult to interpret.

For a better understanding of comprehensive and sector specific HCFC and HFC consumption data, the best approach is the use of "bottom-up stock models". Details and accuracy of these models are described. Bottom-up stock models can be validated by comparing the modelled estimates of refrigerant consumption with "top-down" data such as the Article 7 data reported to the Ozone Secretariat or with specific atmospheric data.

Refrigerant designations or identifiers, as well as physical, safety, and environmental data are tabulated in the Annex to Chapter 3.

Sealed domestic and commercial refrigeration appliances and heat pump tumble dryers

Compact and factory sealed equipment includes domestic refrigerators, a wide variety of self-contained commercial refrigeration applications (e.g., beverage coolers, ice cream cabinets, vending machines, water coolers, ice machines, professional refrigerated under counter storage cabinets or freezers, stand-alone plug-in display cases (horizontal and vertical), and refrigerated drug cabinet), and heat pump tumble dryers (HPTD).

Approximately 200 million domestic refrigerators and freezers were sold with a market value of about US$ 35 to 50 billion annually. In 2019, the global installed domestic refrigerators was estimated to be 2.0 billion and consuming almost 4% of global electricity. The entire global new production of domestic refrigeration appliances is based on non-ODS refrigerants, predominantly HC-600a and to a small extent HFC-134a. Migration from HFC-134a to HC-600a is continuing, driven by the Kigali Amendment schedule or local regulations on HFCs. In the USA, migration to HC-600a is expected to be complete by 2023. Many Article 5 parties including China and India have migrated to HC-600a. The energy efficiency of refrigerators continues to improve worldwide driven by MEPS and increasing consumer awareness.

Self-contained commercial refrigeration (SCCR) appliances mainly use HFC-134a, R-404A, and HCs. With the successful revision of safety and equipment standards in 2019, SCCR appliances are migrating to more efficient HC-290 technologies, and this trend is spreading to some Article 5 parties. In larger charge systems, migration from R-404A to R-744 is occurring but will eventually move to HCs.

Domestic heat pump tumble dryers (HPTD) are more efficient than conventional electrically heated dryers using 40 to 50 % less energy. Some EU manufacturers have ceased production of conventional electrical dryers due to energy label requirements. HPTDs continue to gain market share supported by reduced cost from the economy of scale. The most commonly used refrigerants in HPTDs are HFC-134a, R-407C, and R-410A. Some transition to HC-290 has happened in European countries. HPTDs have yet to make significant penetration into North American or Article 5 markets.

MEPS drive manufacturers to innovate for better energy efficiency with reduced costs. Many countries with low market volumes are yet to initiate MEPS, possibly due to the risk of short-term rise in cost.

Regulations for mandatory end-of-life refrigerant handling are established in many non-Article 5 parties. They are being introduced in some Article 5 parties, but the small unit charge, the relatively low number of appliances, and their geographical dispersal reduces the commercial opportunities for recovery and recycling.

Food retail and food service refrigeration

Refrigeration applications in food retail and food service are critical to reduce food waste. They have received a lot of attention due to the associated societal and environmental benefits they bring, and the relatively large electricity consumption of operating such systems. The commonly used HFCs in existing food retail and food service are R-404A and HFC-134a and in many Article

5 parties HCFC-22 continues to be used. Globally, several countries and regions are adopting controls on the use of high-GWP HFC refrigerants in food retail and food service applications. These actions by governments have accelerated the development of new lower GWP refrigerants and systems and are being aided by new safety standards for flammable and high-pressure refrigerants. The net effect is that the transition to ultralow- and low-GWP refrigerants is moving at a faster pace in food retail and food service compared to most other RACHP applications.

R-744 are increasingly being used in food retail systems worldwide – both in cascaded systems (R-744 for low temperature cascaded with a second refrigerant such as HFC-134a, R-450A, R513A, HFO-1234ze, or similar, and R-717 or HC-290 in limited cases) and in transcritical all-R744 systems. Transcritical systems are being modified extensively to reduce their energy penalty at high ambient conditions with component and system technologies. R-744 is introduced in food service applications with condensing units.

Meanwhile, several high-, medium- and low-GWP HFC/HFO blends (both A1 and A2L) are being approved for use worldwide in various equipment types with A2L refrigerants in smaller charge systems such as distributed systems and condensing units. High- and medium-GWP A1 blends are important for retrofitting existing R-404A and HFC-134a equipment as transition refrigerants to reduce the CO_2 equivalents of existing equipment. Retrofits are a growing trend in Europe and North America, where the recovered and recycled or reclaimed R-404A and HFC-134a is used for servicing existing equipment. As a result, reclaimed and recycled refrigerant and refrigerant banks within the fleet of equipment are viewed as an asset requiring proper management. This can be achieved using existing leak sensing and mitigation technology that are used primarily for flammable refrigerants.

Energy efficiency increasingly influence the choice of refrigerants that retailers make when selecting new equipment. Equipment in food service and food retail last for 10 to 20 years and as such the life cycle cost of operating and maintaining the equipment is an important factor in the decision making. Reducing the refrigeration load is the first place to start for reducing energy consumption, which is followed by various other efficiency improvement options like the choice of refrigerant, compressors, heat exchangers, etc. The conversion to low-GWP refrigerants in food retail and food service applications is taking place while maintaining or improving energy efficiency.

Transport refrigeration

Transport refrigeration deals with preservation of food, pharmaceutical products, and other temperature-sensitive goods in transit, and is very important for the food and medicine cold chains. It includes refrigeration units for trucks, trailers, light commercial vehicles, marine containers, rail, and air transport. This chapter also covers refrigeration onboard ships, and comfort cooling for passenger railcars and aircraft.

In order to ensure safe and reliable operation, the knowledge, competence for safe service and spare parts, as well as relevant safety processes and procedures, must be available along the transport routes. The latest low-GWP refrigerants are not easily available everywhere and this is slowing the transition for example with transcontinental transport.

The majority of trucks and trailers employ R-404A. New equipment in Europe and in North America uses R-452A offering a significant reduction in GWP. Light commercial vehicles use mainly HFC-134a, while some use HFO-1234yf. The majority of marine container refrigeration units operate on HFC-134a. The latest of these units are being offered as being retrofittable to R-513A. A marine container operating on R-744 is available with limited market penetration.

Legislation is driving lower GWP in transport refrigeration, although the pace and refrigerant options are uncertain. A2L or A1 blends, with GWP levels below 500 such as R-454A and R-454C, present options for the transition. HC-290 or R-744 systems may prevail in the longer term – but still present significant challenges.

Direct emissions are being reduced by design by eliminating leak points, and indirect emissions through alternative ways of powering the refrigeration system, by eliminating diesel engine operation, for example using hybrid or fully electric power trains.

Different types of ships use different refrigerants. HFCs are currently being replaced by alternative systems which are finding their way from other market segments, such as R-744 for food storage systems. For cruise liners air conditioning, HFC-134a is being replaced by HFC-1234ze(E). R-717 was common before 1970 and today is experiencing a revival in many ships and in particular fishing vessels.

Air-to-air air conditioners and heat pumps

Air conditioners, including air-heating heat pumps (sometimes referred to as reversible air conditioners), range in size from 1 kW to 750 kW although the majority are less than 70 kW. The most popular are non-ducted single splits, which are produced in excess of 80 million units per year. All products sold within non-Article 5 countries use non-ODS refrigerants. Around 10% of new systems in Article 5 countries use HCFC-22, with a substantial proportion of the installed equipment still using HCFC-22. In addition to the widespread use of R-410A, the extensive introduction of HFC-32 in residential split air conditioners continues in many countries around the world, accounting for nearly half of the total production of split room air conditioners in 2021.

Manufacturers and research organisations within all regions continue to evaluate and develop products with various HFC/HFO blends, such as those comprising HFC-32, HFC-125, HFC-134a, HFO-1234yf and HFO-1234ze. Products are being introduced with medium-GWP alternatives, R-454A, R- 454B, R-452B and R-463A. Some enterprises within the Middle East still see R-407C and HFC-134a and in some applications R-410A as favourable alternatives to HCFC-22. In addition, transition towards to HC-290 in China, Southeast Asia, and South America is underway, but except for small split and portable units, there is limited market introduction so far because of perceived safety and liability risks.

The adoption of revised international safety standards (e.g., IEC 60335-2-40) with improved requirements particularly and less stringent charge limitations for class A2L, A2, and A3 refrigerants enables greater application of low-GWP refrigerants for this category of products. Numerous research activities are continuing to investigate a variety of aspects related to the application of flammable refrigerants in air conditioning equipment.

Applied building cooling systems

Applied building cooling systems are used in commercial buildings of all types and require engineering services to design and install. The dominant products used in these systems are chillers (that provide comfort through water networks) or packaged commercial unitary product (that provide comfort through air distribution networks).

Existing products using HFC refrigerants have not been discontinued and remain the dominant products sold in most markets. The installed base of these products will remain in service due to the long equipment lifetime. HFC alternatives are currently limited by safety regulations. One of the remaining challenges to their widespread adoption is the standards and codes variations between regions.

Nevertheless, there is a complete range of chillers in all major markets that use refrigerants with lower GWP, while maintaining or improving full and part load performance. Non-fluorinated refrigerants, namely R-717 and HC-290, are used in applications of specific sizes. Absorption chillers, which do not use a vapour compression cycle, are also available but are less efficient in the absence of waste heat.

Life Cycle Climate Performance (LCCP) calculations show that global warming effects from chillers are dominated by energy use over their lifetimes, rather than the direct emissions. Full and part load or seasonal energy consumption is therefore an important factor to consider during the development of new products.

Mobile AC/HP

Currently, there are still several refrigerants in use in mobile AC/HP applications including HFC-134a which is used globally. Low GWP refrigerants options include HFO-1234yf and R-744. HFO-1234yf is widely adopted, especially for passenger vehicles. It remains unclear when other mobile AC applications, such as buses and heavy-duty trucks, will follow the light-duty vehicle trends.

European regulations investigating PFAS are very broad and not product-specific at this time. This could lead to HFO-1234yf re-evaluation as an option for mobile AC. More details about refrigerant decomposition products can be found in Chapter 3 of this report.

Vehicle refrigerant use is shifting from being an optional feature for passenger cooling to a requirement for total vehicle thermal management because heating and cooling is vital for battery performance and lifetime. The progressive electrification of road transport in Europe, China and North America requires a new generation of refrigerants that can deliver thermal management in addition to passengers' cooling. Hence, electrification is broadening the technical options leading to reconsider the current refrigerant choices to include R-744, HFOs and blends s as viable options.

R-744 is increasingly used in fully electrified vehicles due to its overall performance in reversible heat pumps. Some European manufacturers introduced reversible R-744 heat pumps for high-volume BEVs, which are sold in the EU, North America (Canada), and China

Industrial refrigeration, heat pumps and heat engines

Industrial refrigeration, heat pumps, and heat engines are ubiquitous. They are used in a range industries such as food and beverage, fisheries, pharmaceuticals, petrochemicals, district cooling and heating systems, etc. Industrial refrigeration and heat pumps traditionally use R-717 but R-744 is also increasingly being used. R-717/R-744 cascade systems are also being widely adopted to mitigate risks associated with ammonia. There is also an emerging trend for the use of HCs and HC mixtures – especially for low temperature applications.

Heat recovery power-producing-systems, using Organic Rankine Cycles (ORC), may be useful where industrial waste heat is available. However, while the technology is still developing, systems are coming to the market using low-GWP refrigerants, but HFC-245fa is still being used.

Heating only heat pumps

Heating only heat pumps comprise heat pump water heaters, space heating heat pumps, and combined space and hot water heat pumps. They are sought for their potential role in buildings decarbonisation. Cost effectiveness remains an important consideration with a trade-off between capital and operating cost when compared with fossil-fuel powered heating systems. One of the recent innovations is the use of locally installed heat pumps in district heating and cooling systems to reduce typical grid losses.

Refrigerant selection depends greatly on the service water temperature. Heat pumps commercialised today employ a wide variety of refrigerants. The majority of new equipment uses R-410A and HFC-32. R-454B is currently being considered as a replacement for R-410A. In some Article 5 parties, HCFC-22 may still be used; although, there are no technical barriers to its phaseout. The European F-Gas regulations are driving the market towards low- and medium-GWP alternatives such as HC-290 and HFC-32. These refrigerants result in improved performance over R-410A and are cost-effective in small- to medium-sized systems.

Heat pumps are more material intensive than fossil fuel combustion boilers or direct electric heating. Therefore, the trade-off between energy efficiency improvements and material utilization has to be considered carefully.

At present, the main markets for water heating heat pumps are China, the EU, and Japan. China accounted for approximately 60% of the global demand of roughly 3.4 million units in 2019. This market is substantially smaller than the 100 million annual global air conditioner market. This suggests that heat pump market has the potential for rapid expansion. It is important to note that several states in the US have decarbonization plans that will increase the adoption of heat pumps.

Not-In-Kind technologies

Not-In-Kind (NIK) technologies could play an important role in sustainable cooling and heating. Absorption technologies operated using waste heat, direct/indirect evaporative cooling (IEC), hybrid IEC systems, desiccant cooling, and fossil-fired absorption systems are widely available. NIK technologies can provide lower operating lifecycle cost compared with mechanical vapour compression in some specific conditions. Typically, NIK technologies have higher capital cost than traditional systems.

Deep sea, lake, and ocean cooling have been investigated and few installations have been implemented. Studies have shown potential for low lifecycle operating cost, but at capital costs are higher than traditional IK systems. It has also been implemented in limited installations.

Other NIK technologies, including magnetocaloric, are in emerging and research and development phases. Some of these technologies, e.g., solid state cooling, are relatively successful in niche markets.

Servicing and refrigerant conservation

Refrigerants used in the servicing sector constitute the majority of consumption in many Article 5 parties, especially low- and very low- volume consuming countries (LVCs and VLVCs). Servicing and refrigerant conservation have an important role in the global efforts to reduce direct and indirect emissions. It is important to address the responsible use of refrigerants during the lifetime of products. Furthermore, proper servicing minimises the gradual degradation of energy efficiency in RACHP equipment over time.

The application of proper servicing techniques by trained and certified technicians, using proper tools, is crucial for the conservation of refrigerants as well as for the safety of the technicians and end users. Proper servicing techniques are described in codes. Capacity building activities in LVCs and VLVCs include training programmes, e.g., training of trainers, infrastructure, tools, and improved access to spare parts. The continuity of training, along with the application of the principals learned in daily work environments, is a major pillar for the introduction and the proliferation of low-GWP, energy-efficient refrigerants.

Refrigerant conservation is based on reducing leakages and emissions during the lifetime of equipment as well as the recovery and recycling of refrigerants during servicing and at the end-of-life. Predictive and preventive maintenance contribute to the reduction of emissions, while awareness on recovery and the provision of the tools to perform recycling and reclamation ensure the success of the programmes related to these efforts.

Chapter 1

Introduction

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1 Introduction

1.1 The Refrigeration, Air Conditioning and Heat Pump (RACHP) Sector - Current status

Refrigeration, air conditioning and heat pump (RACHP) applications form the sector that uses by far the largest amount of the remaining ODSs and their replacement substances. It is also one of the important electricity using sectors in the total. According to the IIR (2019), the RACHP sector consumes about 20 % of the overall electricity used worldwide, which is substantial. The global demand for refrigeration and air conditioning could more than double by 2050. IIR (2019) also estimates that the total number of RACHP systems in operation worldwide amounts to roughly 5 billion, including 2.6 billion air conditioning units and 2 billion domestic refrigerators and freezers. Global annual sales of all the RACHP equipment amounts to roughly 500 billion USD. Over 15 million people are employed worldwide in this sector, where the need for engineering and technical staff increases due to the growing demand for RACHP capacities along with the unique skills required of RACHP related professionals (IIR, 2019). That is why the IIR (IIR, 2019) states*:* *"Refrigeration is of paramount importance for mankind and must become a priority for policy makers".* The economic impact of RACHP technology is much more significant than generally believed. This is one of the reasons that the economic impacts of the phaseout of CFC refrigerants (in the past), HCFC refrigerants -and of the current and near future phasedown of high GWP HFC refrigerants- have been difficult and are still difficult to estimate.

RACHP applications vary enormously in size and temperature level. A domestic refrigerator has an electrical input in the range of 50 to 200 W and contains about 30 to 150 g of refrigerant (dependent on the type of refrigerant and the size of the appliance), whereas industrial refrigeration and cold storage is characterised by temperatures between -40 and -10 °C, with electrical inputs of up to several MW and refrigerant contents of up to 1000 kilograms. Air conditioning and heat pumps normally operate with higher evaporation temperatures, significantly different from refrigeration applications, while they also vary enormously in energy input, capacity, and size.

In principle one can therefore discriminate between four main areas each with corresponding subsectors:

a) the food chain in all its aspects, from cold storage via transport to commercial and domestic refrigeration,
b) process air conditioning and refrigeration,
c) comfort air conditioning, from unitary equipment to centralised systems using water chillers, including heat pumps, and
d) mobile air conditioning, with different, specific aspects.

In all applications, or sub-sectors, as described in the separate chapters in this report, the attention is focused on the technology based on the vapour compression cycle. Options and aspects for this technology are described since it is unlikely that during the next 10 to 20 years other technologies may take over a substantial part of the market. Vapour compression cycle technology has so far provided the simplest, most economic, efficient, and reliable way to provide refrigeration capacity and is supported by virtually all manufacturers and associations. One of the growing RACHP application is the heating only heat pumps due to their role in buildings' decarbonisation efforts. This is discussed in detail in Chapter 11 of this report. Chapter 12 of this report provides information about non-vapour compression cycle technologies, called "Not-In-Kind", which have become commercially available for certain applications, particularly absorption technology, which is a mature technology serving an important niche market. However, most of the technologies described are in the research or development stage. They may be able to improve the energy performance in different ways.

1.2 Montreal Protocol Reporting Developments - the Kigali Amendment

At the 31st Meeting of the Parties (Rome, 4-8 November 2019), parties decided, through Decision XXXI/2, to request the three Montreal Protocol Assessment Panels to prepare quadrennial assessment reports in 2022, to submit them to the Secretariat by 31 December 2022 for consideration by the Open-ended Working Group and the Meeting of the Parties 2023, and to present a synthesis report by 30 April 2023, noting that the panels should continue to exchange information during the process of developing their respective reports in order to avoid duplication and to provide comprehensive information to the parties to the Montreal Protocol.

For the Technology and Economic Assessment Panel, the decision mentioned explicitly:

1. That, in its 2022 report, the Technology and Economic Assessment Panel should include an assessment and evaluation of the following topics:
2. Technical progress in the production and consumption sectors in the transition to technically and economically feasible and sustainable alternatives and practices that minimize or eliminate the use of controlled substances in all sectors;
3. The status of banks and stocks of controlled substances and the options available for managing them so as to avoid emissions to the atmosphere;
4. Challenges facing all parties to the Montreal Protocol in implementing Montreal Protocol obligations and maintaining the phaseouts already achieved, especially those on substitutes and substitution technologies, including challenges for parties related to feedstock uses and by-production to prevent emissions, and potential technically and economically feasible options to face those challenges;
5. The impact of the phaseout of controlled ODSs and the phase-down of HFCs on sustainable development;
6. Technical advancements in developing alternatives to HFCs suitable for usage in countries with high ambient temperatures, particularly with regard to energy efficiency and safety

1.3 The Kigali Amendment ratification

At the 28th Meeting of the Parties in October 2016 in Kigali, Rwanda, the parties adopted the Kigali Amendment. Since the Amendment was designed to address high GWP HFCs, unsaturated HFCs and HCFCs, i.e., HFOs and HCFOs with low GWP, were not included.

The HFC phasedown under the Kigali Amendment is a production-consumption phasedown expressed in CO_2 equivalents (and not in metric tonnes). In the reporting under the Montreal Protocol, all data regarding production, imports, exports (not the emissions) of HFCs shall be given in CO_2 equivalents and not in HFC mass quantities.

Under the Amendment, non-Article 5, and Article 5 parties (parties) are each subdivided in two Groups (Groups 1 and 2) (see Fig. 1-1). Non-Article 5 parties will start to phase down HFCs by 2019. A large amount of Article 5 parties will follow with a freeze of HFC production and consumption levels in 2024 (Group 1), with some Article 5 parties (defined in Group 2) that will not freeze HFC production and consumption until 2028.

The baselines used consist of various combinations of HCFC and HFC production or consumption (in certain years) expressed in CO_2-equivalent units. The Kigali Amendment has entered into force on 1 January 2019. 147 parties have ratified the Amendment by 1 January 2023, including the USA and Brazil (where 65 parties had ratified the Amendment by 1 January 2019). See Figure 1-1.

***Figure 1-1: World map highlighting the current status of the Kigali amendment acceptance, approval, or ratification (January 1st, 2023).*[1]**

Table 1-1: The various HFCs as controlled under the Kigali Amendment

HFCs (Group I)		HCFCs	
Substance	GWP (100 yr)	Substance	GWP (100 yr)
HFC-32	675	HCFC-21	151
HFC-41	92	HCFC-22	1810
HFC-125	3500	HCFC-123	77
HFC-134	1100	HCFC-124	609
HFC-134a	1430	HCFC-141b	725
HFC-143	353	HCFC-142b	2310
HFC-143a	4470	HCFC-225ca	122
HFC-152	53	HCFC-225cb	595
HFC-152a	124		
HFC-227ea	3220		
HFC-236cb	1340		
HFC-236ea	1370		
HFC-236fa	9810	CFCs	
HFC-245ca	693	Substance	GWP (100 yr)
HFC-245fa	1030	CFC-11	4750
HFC-365mfc	794	CFC-12	10 900
HFC-43-10mee	1640	CFC-113	6130
HFCs (Group II)		CFC-114	10 000
HFC-23	14 800	CFC-115	7370

The Kigali Amendment has different years for HFC production and consumption in the baseline and various phasedown schedules for the two groups of Article 5 parties (developing countries) and two groups of non-Article 5 parties (developed countries). Table 1-2 and Figure 1-2 as presented below show the baseline (freeze) and the phasedown schedules (all expressed in CO_2-tonnes equivalent units).

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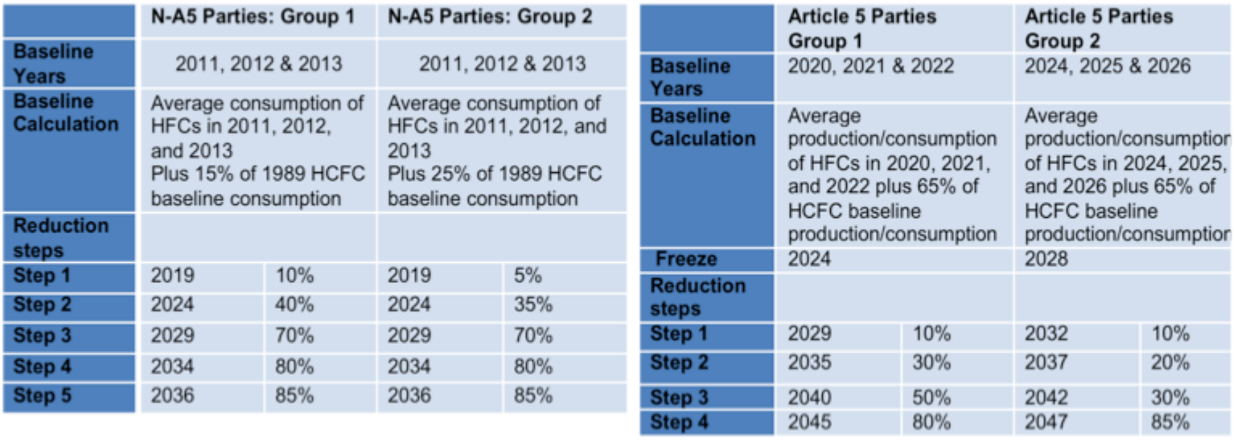
[1] https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-2-f&chapter=27&clang=_en, January 1st, 2023.

Table 1-2: Kigali Amendment baselines and the reduction percentages for groups of countries (UNEP, 2016)



	N-A5 Parties: Group 1		N-A5 Parties: Group 2	
Baseline Years	2011, 2012 & 2013		2011, 2012 & 2013	
Baseline Calculation	Average consumption of HFCs in 2011, 2012, and 2013 Plus 15% of 1989 HCFC baseline consumption		Average consumption of HFCs in 2011, 2012, and 2013 Plus 25% of 1989 HCFC baseline consumption	
Reduction steps				
Step 1	2019	10%	2019	5%
Step 2	2024	40%	2024	35%
Step 3	2029	70%	2029	70%
Step 4	2034	80%	2034	80%
Step 5	2036	85%	2036	85%

	Article 5 Parties Group 1		Article 5 Parties Group 2	
Baseline Years	2020, 2021 & 2022		2024, 2025 & 2026	
Baseline Calculation	Average production/consumption of HFCs in 2020, 2021, and 2022 plus 65% of HCFC baseline production/consumption		Average production/consumptior of HFCs in 2024, 2025, and 2026 plus 65% of HCFC baseline production/consumptior	
Freeze	2024		2028	
Reduction steps				
Step 1	2029	10%	2032	10%
Step 2	2035	30%	2037	20%
Step 3	2040	50%	2042	30%
Step 4	2045	80%	2047	85%

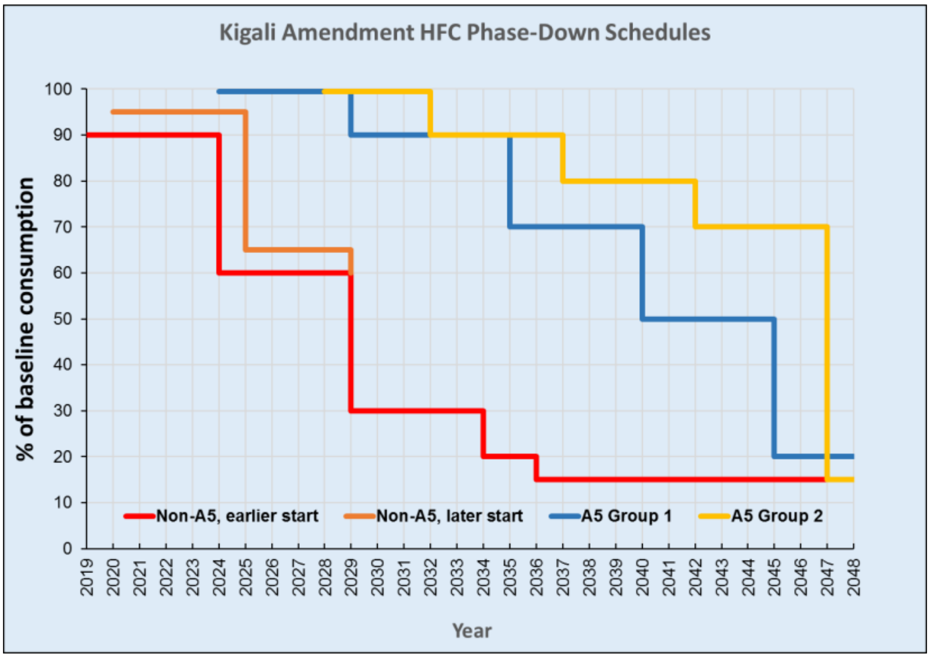


Figure 1-2: Phasedown schedules for (a) two groups of non-Article 5 parties and (b) two groups of Article 5 parties (UNEP, 2016)

The reason for including both HFC consumption values and a percentage of the HCFC consumption value (all expressed in CO_2 equivalents) in the calculation of the baseline is due to the fact that HFCs are considered to be used as alternatives for a certain portion of HCFCs still to be phased out. The HCFC component in the baseline calculation is assumed to take this HCFC portion into account. The reduction schedules for non-Article 5 and Article 5 parties are supposed to lead to a reduction in the consumption of high GWP HFCs and to an uptake of low or zero GWP replacement chemicals (CCAC, 2022; GIZ, 2022; IPCC, 2022; Kuijpers et al., 2017, Peixoto et al., 2017, Peixoto et al., 2017b). Under the provisions of the Kigali Amendment, current trends in consumption and emissions, and national policies, the contribution of HFCs to global annual average surface warming is projected to be 0.04 °C in 2100. This is substantially lower than under the scenario without HFC control measures, for which a contribution of 0.3 to 0.5 °C was projected. So, the global warming from HFC emissions (via the consumption reduction) will be decreased to about 0.04 °C by 2100 (Velders et al., 2022).

In the discussion of the HFC Amendment proposals, high ambient temperatures were addressed as they relate to the issues above. The solution agreed on was found in a different phasedown schedule for the countries experiencing high ambient temperatures, specifically India, Iran, Pakistan and the Gulf States, and others. This exemption allows for a delay in the HFC freeze date and following phasedown obligations by a period of four years.
It is important to mention that considerations for the operation of equipment at HAT conditions must not only be based on the selection of the refrigerant but also have to consider overall system design, aimed to obtain an optimum and reliable performance, and that also under HAT conditions.

1.4 Structure of the RTOC 2022 Assessment Report

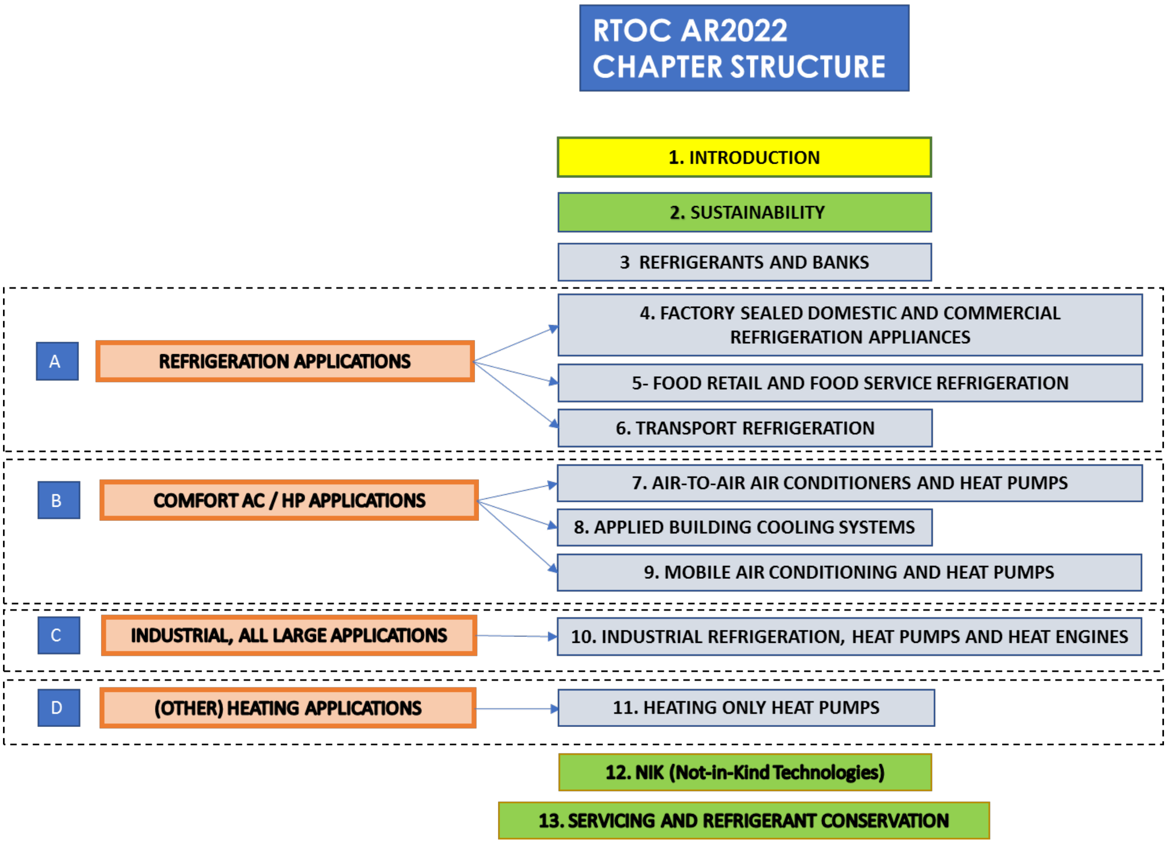


Figure 1-3: AR 2022 structure

For the 2022 Assessment, the RTOC Assessment Report (AR 2022)[2] was restructured. New chapters were included, and the titles and scope of some chapters were changed. Additionally, the sequence of chapters adopted for the AR 2022 slightly differs from the 2018 Assessment Report, AR 2018 (UNEP, 2018). Figure 1-3 presents the AR 2022 structure.

Chapters 2, 3, 12, and 13 are cross cutting chapters focusing on sustainability in RACHP applications, refrigerants, not-in-kind technologies, and service, respectively. The Annex to chapter 3 provides a comprehensive list of all refrigerants listed in ASHRAE 34 / ISO 817 standards since the year 2000 along with relevant properties including safety designation, GWP, and ODP values. In the AR 2022, RACHP application chapters have been grouped in 4 (four) main groups:

I. Refrigeration applications (Chapters 4, 5, and 6)
II. Comfort air conditioning and heat pumps applications (Chapters 7, 8, and 9)
III. Industrial refrigeration and all other large applications (Chapter 10)
IV. Other heating applications (Chapter 11)

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[2] This and former RTOC Assessment reports can be accessed at the UNEP Ozone Website: https://ozone.unep.org/science/assessment/teap

1.5 Current and Future Trends

1.5.1 Energy Efficiency

The RACHP sector is responsible for 80 to 85 % of the global HFC CO_2-eq. emissions. As such, it continues to increase energy efficiency (reduce energy use per unit of capacity) in an effort to combat the anthropogenic environmental impact of this sector. Furthermore, the improved equipment and system efficiency have the potential to double the global warming mitigation of the Kigali Amendment. In an effort to further understand the potential of energy efficiency in the RACHP sector, the Technical and Economic Assessment Panel (TEAP) has produced eight (8) reports[3], which respond to the following decisions:

- Decision XXVI/9; (UNEP, 2015)
- Decision XXVII/4; (UNEP, 2016)
- Decision XXVIII/3; (2017)
- Decision XXIX/10; (UNEP, 2018a; UNEP, 2018b)
- Decision XXX/5; (UNEP, 2019a; UNEP, 2019b)
- Decision XXXI/7; (UNEP, 2020), (UNEP, 2021) and
- Decision XXXIII/5. (UNEP, 2022)

These reports focused primarily on the two largest refrigerant consuming sectors: room air conditioners and self-contained commercial refrigeration equipment. The most recent Energy Efficiency Task Force Report in 2022 was expanded to cover additional sectors, including heat pumps, commercial air conditioning, and commercial refrigeration.

These reports reveal that the evidence for climate change is increasing. The Parties to the Montreal Protocol have a unique opportunity to minimise global warming (and resulting climate impact) by harnessing the synergies with energy efficiency (EE) during the HFC phasedown. These reports also highlighted that many energy-efficient technical innovations by using lower GWP refrigerants in RACHP equipment are widely available and increasingly accessible. In general, EE may be enhanced or increased through equipment design optimization, load reduction, good operation, and adequate maintenance of the RACHP equipment.

Integrated modelling of the direct (refrigerant-related) GHG emissions and indirect (energy-related) GHG emissions from RACHP operation provides valuable insights into the importance of linking improvements in energy efficiency with the HFC phasedown. Early outputs from the UNEP DTIE used HFC Model (see chapter 3) suggest that indirect energy related GHG emissions represent around 70 % of total GHG emissions from the RACHP sector. They also imply that combining a faster phasedown of high GWP HFCs with further improving efficiency provides substantial additional benefits in reducing total, cumulative emissions. These results further suggest that there is a large potential to reduce both direct (>90 %) and indirect emissions (>98 %) by 2050, compared to a business-as-usual scenario. This is not taking into consideration any further measures on decarbonization as planned globally to different degrees.

The ODS phaseout has avoided 1.1 °C of warming over the Arctic by 2021 and is expected to contribute to roughly 25 % of the mitigation of global warming by 2050 (Goyal et al., 2019). The HFC phasedown through the Kigali Amendment can mitigate 0.3 to 0.5 °C of the global temperature increase by 2100 with a potential to double this impact through EE improvements (Velders et al., 2022). An effective implementation of EE in the cooling sector may result in up to 20 % reduction in future global electricity consumption which may contribute between 9 and 16 % air pollution reduction (Purohit et al., 2020). Hence, synergistic integration of EE and HFC phasedown activities can be the most cost-effective warming mitigation measure. As such, the EE in the RACHP sector is especially relevant to the reduction of the growth in electricity demand as it may contribute to up to 50 % of this growth as shown in Figure 1-4:.

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[3] These reports are available on UNEP Ozone Website at: https://ozone.unep.org/science/assessment/teap

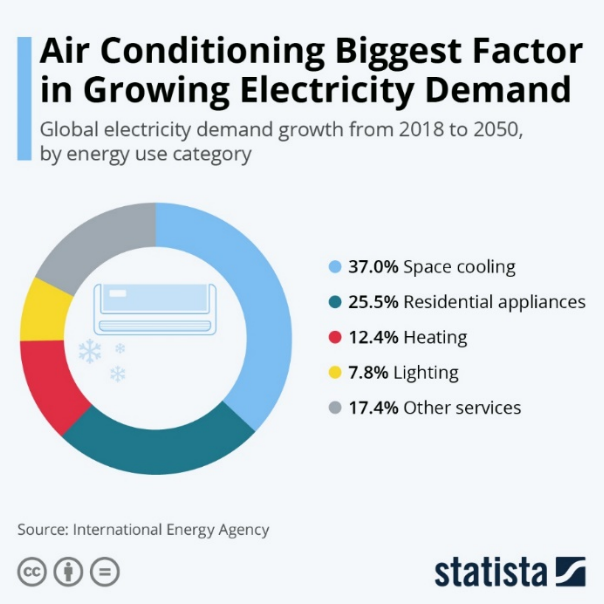

Figure 1-4: Energy end uses impact on global electricity demand growth from 2018 to 2050 [4]

Due to the importance that the energy consumption from the RACHP sector is attaining, several reports have been developed and released this year, including the TEAP XXIX/10 report on energy efficiency issues. In 2018, an IEA report presented statistics related to the numbers of equipment installed and sold, as well as the energy consumption associated, and developed predictions for 2050 based on scenarios modelling (IEA, 2018). Another recent report addressed specific issues related to the impact of available refrigerants on equipment energy efficiency (AFCE, 2018).

1.5.2 Refrigerants

The process of selecting a refrigerant to provide the optimum operation for a specific design of a vapour compression cycle is rather complex, since a large number of parameters need to be investigated including environmental, safety, thermophysical, technical, and implementation challenges. This is described in detail in section 3.2.3.

In the long term, the role of non-vapour compression technologies such as adsorption, Stirling and air cycles etc. may become more important. However, refrigeration using the vapour compression cycle is considered to remain the most important method for the foreseeable future.

For the longer term, there remain five important refrigerant options[5] for the vapour compression cycle in all refrigeration, air conditioning and heat pump sectors:

- ammonia (R-717);
- carbon dioxide (R-744);
- hydrocarbons and blends (HCs, e.g., HC-290, HC-600a, HC-1270 etc.);
- hydrofluorocarbons (unsaturated HFCs (fluoro-olefins or HCFOs and HFOs) with a four-digit number, a number of lower GWP HFCs and low GWP HFC-HFO blends with 400 and 500 numbers);
- water (R-718) (plus evaporative or other ways of cooling with water, and devices using a variety of physical methods to generate a refrigerating effect); plus, a number of Not-In-Kind, non-vapour compression methods.

Refrigerant emissions from RACHP systems into the atmosphere result in decomposition products which could be harmful to the Earth's eco-system. Some of the current and alternative synthetic

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[4] https://www.statista.com/chart/14401/growing-demand-for-air-conditioning-and-energy/

[5] Ammonia is toxic, the use of certain HFCs and HFOs is currently under scrutiny, see below

refrigerants, (HCFCs, HFCs, and HFOs) produce varying amounts of trifluoroacetic acid (TFA) during their atmospheric decomposition; see the EEAP 2022 Assessment Report, section 6.3 (EEAP, 2022) for detailed estimates and conclusions. Because of the short lifetime of HFOs, TFA generated as a breakdown product of HFOs will be deposited nearer to the location of emissions. Further research is expected on how the TFA deposits will be geographically distributed.

The Science Assessment Panel Report 2022 states in its chapter 7 (WMO, 2022): "While all global averages in concentration and depositions of TFA are still far below the toxic values for aquatic organisms, regional studies focused in highly populated and industrialized areas have projected areas of higher impact and high concentrations in precipitation and in the atmosphere". Growing TFA concentrations are not expected to harm the environment over the next few decades, although some regional concerns are being raised. Periodic re-evaluation is expected because of the persistence of TFA in the environment.[6]

TFA is a chemical that is included within the OECD definition of the per- and poly-fluoroalkyl substances (PFAS). The OECD PFAS definition does not include HFC-32, HFC-152a, HFO-1132 and HFO-1123 (EEAP, 2022). In July 2021, five European countries (D, DK, NL, NO, SE) published their intention to propose a REACH based restriction for PFAS. As a next step, they submitted this PFAS proposal to the European Chemical Agency (ECHA) on 7 February 2023 (ECHA, 2023) for further study and consultations. Final decisions for possible regulations may be expected in the course of 2025. This may already create some uncertainty at present for the long-term use of several HCFO/HFOs.

1.5.3 Safety Standards

A recent study (McLinden, 2017) (for further details see Section 3.5) showed that the number of chemical compounds possessing the local and global environmental requisites listed in the previous section, and able to cover future refrigerants demand, is very limited.

As a consequence, it is likely that most of the refrigerants that will be allowed for application in the future will fall into the domain of flammable fluids. This poses a series of problems for the design, manufacturing, installation, and servicing of RACHP equipment that can only be overcome if a number of safety standards to be complied with is available to accompany the equipment throughout its life cycle.

The Montreal Protocol has already tackled this issue via Decision XXVIII/4 and the reporting in 2017 by the relevant TEAP Task Force (UNEP, 2017) as well as via a series of follow-up initiatives summarized in section 3.3.

Considering the importance of this issue for the future of the RACHP applications, the same section 3.3 reports in detail the state-of-the-art of the several initiatives that Standard bodies throughout the world are currently taking into account to cope with it. Moreover, the applications chapters describe the development of safety standards that are inherently connected with the corresponding application.

1.6 Technical Note on the Vaccine Cold Chain

During the AR 2022 assessment period, the RTOC published a technical note on the vaccine cold chain (issued September 2021 (RTOC, 2021)) focused on the 2021 situation, related to the specific needs for refrigeration and cooling of vaccines (and Covid-19 vaccines, in particular) in the distribution chain. The technical note therefore also deals with refrigerant options and technologies for vaccine storage and transport with a link to the issues posed by specifics of the distribution chains.

This implies the consideration of energy consumption issues, the availability of refrigerants and refrigeration means, as well as the link to the distribution chain, particularly in Article 5 parties. Of

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[6] The EEAP reports can be accessed at: https://ozone.unep.org/science/assessment/eeap

course, the distribution chain needs to be addressed in tandem, but that has not been considered a major issue for the vaccine note. One also needs to consider that, in specific regions of the world, the available and stable electric grid to supply cooling for medical applications is in question.

1.7 The Technical Options Committee Refrigeration, A/C and Heat Pumps

The 2022 RTOC committee includes 41 representatives from Asian, European, Middle East, Latin and North American companies, universities, and governments, as well as independent experts. Affiliations and respective parties of the members are listed in Table 1-5.

The names and contact details of all members are as chapter 14 in this RTOC assessment report.

Table 1-5: Affiliations and respective parties of the members of UNEP's Technical Options Committee on Refrigeration, A/C and Heat Pumps

1	A/genT Consultancy Ltd.	Netherlands
2	AHRI	U.S.A.
3	American University in Cairo	Egypt
4	Anna University	India
5	Bhambure, Jitendra, independent expert	India
6	Braunschweig University	Germany
7	Calm, James M., engineering consultant	U.S.A.
8	CRT Cambridge	UK
9	Daikin Europe N.V.	Belgium
10	Danish Technological Institute	Denmark
11	DeVos, Rick, independent expert	U.S.A.
12	Devotta, Sukumar, independent expert	India
13	Elassaad, Bassam, independent expert	Lebanon
14	Emerson Climate Technologies	U.S.A.
15	Gluckman Consultancy	UK
16	Ingersoll Rand	Czech Republic
17	Johnson Controls	Brazil
18	Johnson Controls	Denmark
19	JRAIA	Japan
20	Karlsruhe University of Applied Sciences	Germany
21	Maua Institute of Technology	Brazil
22	MHM Consultancy Ltd.	Saudi Arabia
23	Nelson, Horace, independent expert	Jamaica
24	Oak Ridge National Laboratories	U.S.A.
25	Olama, Alaa, independent expert	Egypt
26	PAWHT	Indonesia
27	Petra Industries	Jordan
28	Re/gent Ltd.	Netherlands
29	ref-tech engineering	Germany
30	Re-phridge Consultancy Ltd.	United Kingdom
31	SINTEF Energy Research, Trondheim	Norway
32	Stellartis, Torino	Italy
33	Sun Yat-sen University, Guangzhou	P.R. China
34	Toshiba	Japan
35	Trane Co.	U.S.A.
36	U.S. Environmental Protection Agency	U.S.A
37	Università Politecnica delle Marche, Ancona	Italy
38	University of Zagreb	Croatia
39	UTC Carrier	U.S.A.

40	Vonsild Consulting	Denmark
41	Zhejiang University, Hangzhou	P.R. China

1.8 Peer review process

After the online April 2022 RTOC meeting, Third Order Drafts of all chapters were developed. After an internal review, the various chapters were combined into the draft RTOC Assessment Report for peer review. This draft report has been peer reviewed by a number of institutions and associations (sixteen in total); each of them reviewed (via their experts) the different chapters sections in a coordinated effort. This took place between the beginning of September 2022 and mid November 2022 (see Table 1-7 for the organisations that have been involved in the peer review). As a result, about 2100 comments were received in total (related to all chapters).

All peer review comments received were collected, sorted out per chapter, and subsequently sent to the separate RTOC chapters (to both CLAs and members) for further study and for addressing the review comments before the last (final plenary) RTOC Assessment Meeting in December 2022. During this December meeting in Luxor, Egypt, the RTOC members present decided in small chapter meetings (as well as in plenary) on whether and how to amend chapter texts and particularly the Key Messages and Executive Summaries; this mainly on the basis of the peer review comments received.

The RTOC greatly acknowledges the voluntary support given by the peer review institutions and their experts. The experts were in principle involved in their personal capacities and reported their findings and comments back to the associations and institutions, who then submitted them to the RTOC co-chairs via the review coordinator's email address.

Table 1-7: Organisations that participated in the UNEP 2022 RTOC Assessment peer review

1 AHRI	*Airconditioning, Heating and Refrigeration Institute USA*
2 AiCARR	*Ass. Italiana Condizionamento dell'Aria Riscaldamento e Refrigerazione*
3 CAR	*Chinese Association of Refrigeration*
4 DKV	*German Refrigeration Society*
5 EIA	*Environmental Investigation Agency*
6 EPEE	*European Partnership for Environment and Energy*
7 eurammon	*European Industry - Association for Ammonia*
8 IIR	*International Institute of Refrigeration*
9 IOR	*Institute of Refrigeration, UK*
10 ISHRAE	*Indian Society Heating Refrigeration Air Conditioning Engineers*
11 JRAIA	*Japanese Refrigeration and Air-conditioning Industry Association*
12 NIST	*National Institute of Standards and Technology*
13 NKF	*Norsk Kjøleteknisk Forening (together with NTNU)*
14 SAE	*SAE Interior Climate Control Steering Committee*
15 SAIRAC	*South African Institute for Refrigeration and Air Conditioning*
16 Shecco/ATMO	*R/AC Market Development Expert Organisation Brussels*

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Chapter 2

Sustainability applied to the RACHP sector

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2 Sustainability applied to the RACHP sector

Research by the industry and the scientific community aim to provide the society with solutions to certain issues and challenges to facilitate life and provide comfort and continuity. To respond to an urgent need, products may be required to be put on the market while the long-term side effects on the environment are being assessed through a risk-based approach as mentioned under section 2.2.

Refrigerants are one example where an urgent need to find solutions to ozone depleting substances and those with a high GWP, like HFCs, is driving research on alternatives. Since there is not one ideal refrigerant that meets all the application needs, some of the subsequent solutions might require continuous monitoring for aspects of nature and human health effects that were not the main criteria behind the original research.

Policy, on a national or global scale, is continuously weighing the economic needs of the market with the environmental impacts of the proposed solutions. Policy is informed by experts' views and the direction taken protocols and agreements.

This section offers a view of global and regional policy mechanisms and factors affecting business practices when making refrigerant choices.

2.1 Global policy mechanisms for carbon emissions reduction

The Paris Agreement has vast objectives with no mandatory schedules. The Paris Agreement is based on a mechanism of submitting Nationally Determined Contributions (NDCs) which outline plans on greenhouse gas reductions by certain target years. Officially, NDCs are submitted to the UNFCCC Secretariat as described by the Paris Agreement. A National Cooling Plan is an example of a framework tool that can be used as part of NDCs.

The successful implementation of emission reduction plans depend on how well the tools are used to implement the reduction strategy to achieve certain emission targets (for the Paris agreement this is a temperature increase by 2100 of < 2 °C, preferably 1.5 °C). Achieving the 1.5 °C goal is considered "ambitious". However, the sum of the effects of the NDCs submitted so far is not considered sufficient to achieve the 1.5°C target mentioned above. Another example of a framework tool is the European Green Deal[7] which is a top-down approach that provides a long-term strategy and a positive signal to the market to invest in innovative technologies.

In the context of the RACHP sector, there are many policy tools available to reduce carbon emissions that are already widely used in the world. To achieve a transformation of the market, these policy tools can be market-disruptive to push the evolution of the market beyond its natural development course. The following can be mentioned as most effective:

1. **Product Bans** are undertaken when the environmental impact of the product is much higher than the benefit and when alternatives already are available on the market. A product ban can either remove an entire product category from the market or a subsection of a product category (i.e., second-hand products). This tool is easily enforceable because banned products can be identified and removed from the market as with the successful elimination and ban of CFC refrigerants.

2. **Minimum Energy Performance Standards (MEPS)** are like bans in the sense that part of the products on the market are banned based on their energy efficiency. MEPS provide a push to improve the energy efficiency of the products on the market. They anticipate the improvement of the product by setting a schedule that defines when they will be tightened. This provides a perspective to manufacturers so that they can plan and develop their

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[7] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

products accordingly. MEPS are a highly effective and cost-efficient way to improve energy efficiency.

3. **Incentive programs** allow for the promotion of the adoption of new products and technologies. At that point, the price to consumers is still high in comparison to the existing alternatives because the new product and its components are not being produced in sufficiently large quantities. The incentive program covers this gap through different financial incentives such as a rebate or a tax reduction. The cost-effectiveness of these programs is positive, especially in countries where the production of electricity is subsidized: the amount of energy and associated subsidy costs saved are higher than the rebate or tax reduction.

Some policy measures can be hybrid and combine the tools listed above. This is the case for example for the European F-Gas Regulation EU 517/2014. The regulation combines a phasedown quota system for HFC refrigerants from 2015 to 2030, procedures for record keeping and specific refrigerant bans based on their global warming potential for specific products until 2025.

Recently, the US EPA (2022) proposed new rules to phase down the production and consumption of HFCs by 85% by 2036. If approved, this would restrict the use of HFCs in specific sectors or subsectors and would prohibit manufacture and import of products containing restricted HFCs by 1st January 2025, in most cases, and would prohibit the sale, distribution, and export of products containing restricted HFCs a year later i.e., 1st January 2026. For the sub-sectors considered in this chapter, the GWP limit is likely to be 150.

In the RACHP sector, policies can tackle two large contributors of CO_2-eq emissions: direct emissions of high GWP refrigerants through a refrigerant policy and indirect emissions for operation of RACHP equipment through energy efficiency enhancement and other measures like reducing the heat load. The measures should be implemented using an integrated approach to not lead to unintended negative consequences (for example maintaining high GWP refrigerants while improving the energy efficiency of the equipment or vice versa).

2.2 Factors affecting sustainability

Products must be developed that meet the concept of sustainability including improved energy efficiency and ensuring product sustainability. Furthermore, products must be evaluated and certified. Product cycles in RACHP technology typically vary between 4-8 years to 15-30 years for durable capital goods. Experience has shown that flammable refrigerants require risk analyses and development cycles greater than 2 years.

The following factors affect business economics and thus the decisions that impact refrigerant selection:

- new environmental legislation and laws,
- funding for new plants/technology and equipment,
- introduction of disruptive technologies which meet future investors, company, and owner's policy requirements to reach a net zero emission target,
- investment funds targeted for converting to sustainable products or industries.

It is therefore necessary to develop and define tools and parameters that assess the sustainability of products over their entire life cycle (see section 2.4).

The increase in energy efficiency ratio has a significant role in a sustainability assessment for the complete RACHP system which might be considered when assessing the sustainability of refrigerants. Improvement in energy efficiency may have additional effects in the circular economy. The impact might include greater demand for material including adopting new material and methods for recycling them.

2.2.1 Stakeholder participation

Societal and political stakeholders try to influence such systems as far as possible through targeted technical or political actions and to align them with goals that are (ideally) formulated and implemented by consensus of those involved. To be objective in the sustainability assessment process, standards are available and can be used ISO 14001, especially ISO 14064[8] and VDI 4605 (König, 2022)), it is necessary to identify the various roles of the stakeholders and to make these roles transparent in the information process. Diverse groups will have different interests to put forward and defend, while some interests are common to several interest groups.

2.2.2 Direct and indirect emissions reduction

CO_2 equivalents include direct and indirect emissions Direct emissions result from leakage of refrigerants during installation, commissioning, operational lifetime of the product, and the end-of-life management. The indirect emissions are resulting from the energy consumption of all energy forms throughout the lifetime of the product. Indirect emissions can also be extended to manufacturing processes across the supply chain.

Policy measures for emission reduction are already in place at various country levels per country, including:

1. Direct emissions
    a. Mandatory requirement of development of installation and commissioning guidelines to be developed by manufacturers and dispatched along with the product.
    b. Self-declaration that the contractors, dealers, and distributors are trained by manufacturers.
    c. Mandatory requirement of certified technicians
    d. Development of guideline and standards for tightness of leaks.
    e. Development of guidelines for end-of-life management as extended manufacturers responsibility
    f. Development of guidelines for recovery, collection, and disposal
2. Indirect emissions
    a. Implementation of progressive MEPS
    b. Programs for super-efficient products
    c. Purchase of higher efficiency products for governmental demand
    d. Replacement programs to phaseout older inefficient units to reduce indirect emissions.

National Cooling Action Plans (NCAP) can include programmes and initiatives to reduce direct as well as indirect emissions. India for example has a requirement for the listed companies to declare steps taken towards the reduction of impact on environment, developed India cooling action plan with targets on reduction on heat load, energy efficiency, reduction in usage of refrigerants, training of service technicians, developing an environment for research by involvement of all stakeholders and taken steps for implementation.

Case Study: Emissions in the cold chain

IIR estimates that, globally, the 400 million tons of food needing refrigeration is being supported by 600 million m^3 of warehouses, 1.5 billion refrigerators, and 90 million commercial refrigeration

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[8] The ISO 14064 standard provides governments, businesses, regions, and other organisations with a complementary set of tools for programs to quantify, monitor, report and to also verify greenhouse gas emissions. The standard supports organisations to participate in both regulated and voluntary programs as e.g., in emissions trading schemes and public reporting using a globally recognised standard.

equipment. In addition, there are 4 million refrigerated trucks, 1.2 million refrigerated containers with 447,000 supermarkets where 45% of the power consumed is for refrigeration equipment (IIR-UN 2018).

Figure 2-1 shows the CO_2 emissions from the current cold chain by stage (or sector) and emission source including refrigerants. Refrigerants contribute to 22% of the total emissions with the largest portion coming from the retail sector (IIR, 2021).

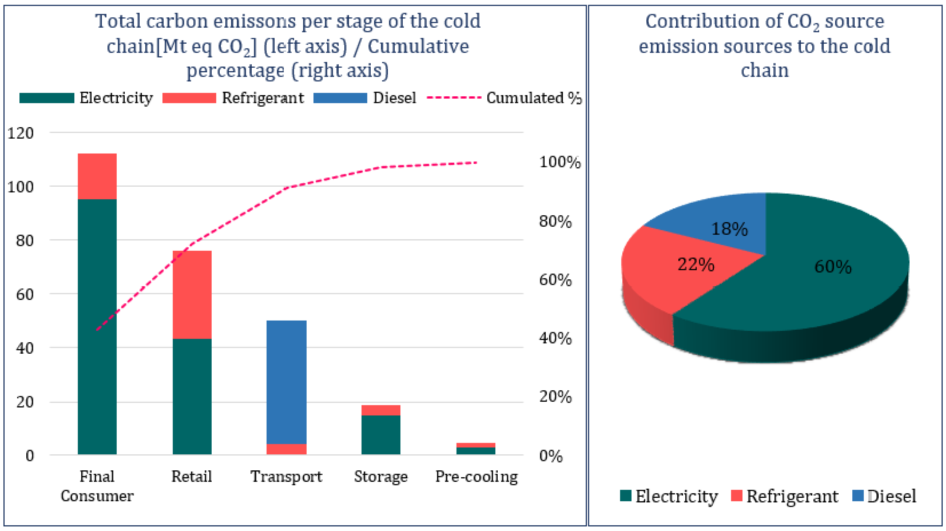

Figure 2-1. Total CO_2 emissions of the current global cold chain per stage and emission sources (IIR, 2021)

Modelling by IIR has shown that an energy efficient cold chain would allow a reduction of 47% of the CO_2 emissions of the current cold chain and avoid 55% of the food losses attributed to the current cold chain a shown in figure 2-2 below (IIR, 2021).

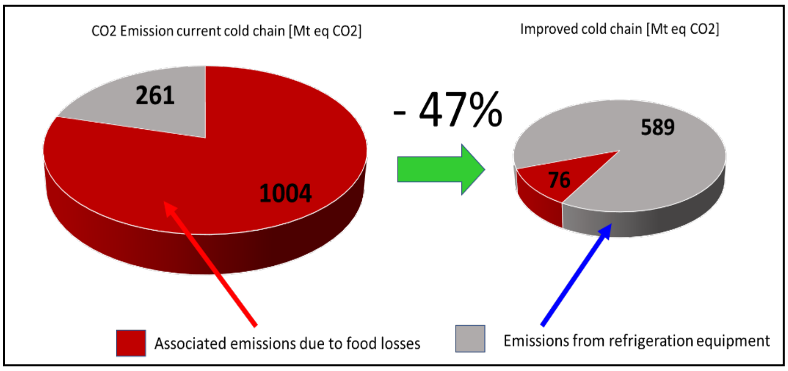

Figure 2-2: Potential for CO2 emission reduction by improved cold chain (IIR, 2021)

CO_2 neutrality in the cold chain

To reach CO_2 neutrality in the cold chain, the direct emissions would need to be totally contained and amounts of refrigerants used for servicing would need to be recycled or destroyed or the contribution to global warming and ecosystem is negligible. To reach CO_2 neutrality in indirect emissions, power would have to be produced from renewables. Reduction of leakage and the probability of recycling and destruction are discussed in more details in chapter 13. Some good practices are being applied and shared globally including regulation and establishing sustainable schemes.

- Regulation is driving the trend towards CO2 neutrality. Presently, there are no estimates as to the number of equipment that are beyond repair and need to be replaced in order to reduce leakage to zero; however, the fact that various regulations are driving a change in technology and restricting access to older refrigerant technologies, is steadily driving towards newer and sturdier equipment that are at the time more energy efficient. Regulation on energy efficiency, which is starting to be coordinated with regulation on refrigerants is helping that trend.

- It takes a concerted effort to reach CO2 neutrality. This relates to dumping of old technologies from developed economies onto developing ones with no, or non-enforced regulation.
- Reducing emissions is costly but the effects on the economies of participating countries are positive. It is a proven fact that green technologies contribute to GDP growth more than dirty technologies.

2.3 Refrigerants lifecycle sustainable assessment

RACHP equipment are vital means for achieving sustainability to address the fundamental needs of humankind in areas such as food conservation, food security, healthcare, water heating, and thermal comfort worldwide. There are, however, negative environmental impacts from the use of this equipment that can be minimised through careful consideration of design, operation, and end of life aspects of these equipment and, especially, the refrigerants they use.

One can say that progress is something that inherently involves risk, and that means that the exploration of new risk areas will be incentivized. Otherwise, constant caution will only lead to fewer solutions and less progress. For refrigerants that are manufactured and applied, there are at least three stages to be looked at:

1. The impact of emissions of feedstocks when manufacturing current refrigerants
2. The environmental risks associated with currently applied refrigerants
3. The potential impact of decomposition products on the environment

A detailed description of the process for conducting a sustainability assessment for refrigeration technology in general and particularly for refrigerants applied can be made. It shows that such investigations are useful in making comparisons and decisions for technologies applied and especially for the comparison of refrigerants uses in terms of sustainability (König, 2022).

Any new substitute refrigerant for CFCs, HCFCs or HFCs has traditionally been compared to the ODP and GWP of the ones it would replace. RACHP systems' indirect emissions associated with energy consumption during operation are increasingly important due to improved equipment sealing and reduced refrigerant leakage. As such, it is important to consider the annually weighted energy efficiency and ensure that new refrigerants result in similar or better energy efficiency compared with refrigerant technologies being replaced.

The atmospheric breakdown of some current and alternative refrigerants (HCFCs, HFCs, and H(C)FOs) is discussed in detail in section 3.4.2 showing that they produce trifluoroacetic acid (TFA). In view of the changing and potential unknown sources for TFA, its deposition in several parts of the biosphere may need to be globally and locally monitored with a special focus on highly populated regions. This is next to the building-up of further scientific knowledge on the impacts of certain TFA concentrations in various parts (soil, aquatic, etc.) of the environment.

A sustainability assessment for refrigerants must be based on a comparison: current versus possible replacement refrigerant. One example of assessment is presented in Table 2.1, where criteria, factors to be considered, rated, and prioritised, as well as the goals to be achieved are shown. This table shows sustainability criteria from a wider sense; however, in this chapter we are mostly concerned with the environmental factors, e.g., life cycle climate performance (LCCP) and total equivalent warming impact (TEWI) measured in metric Tonnes (MT) CO_2 equivalents. In addition, the use of refrigerants in service, maintenance, recycling, recovery, and disposal are key factors to be evaluated also considering social aspects.

It must be noted that design for safe operation can sometimes conflict with the design for energy efficiency and may lead to more CO_2 equivalents if costs are not compensated. As a result, engineers are faced with an analysis of the varied factors when comparing the refrigerant for the application in its local environment. To support the sustainability assessment as a refrigerant selection tool the information in Table 2-2 can be used in combination with Table 2-1. The sustainability assessment is a tool for comparison and should therefore include a rating for high or low impact on sustainability, and prioritization. In addition, the documentation and explanation of the assessment is essential. A more detailed description of the sustainability assessment process applied to RACHP can be found in König, 2022.

It should be noted that the effect of energy efficiency often overwhelms other factors when considering the lifetime of the product, since it affects many sustainable principals in a large way, including resource usage and CO_2 equivalents from the originating energy source.

Tables 2-1 and 2-2 present the complexity of the sustainability assessment for a comparison of refrigerants. The goals, factors, and indicators listed can be used for a sustainability assessment for refrigerants using the comparison method according to e.g., VDI 4605 (VDI, 2017), AHAM 7001 (AHAM, 2012).

Table 2-1: The three dimensions for a sustainability assessment related to refrigerants: Economic, environmental, and social aspects (headings), the main goals to be achieved (2nd column), and indicators (3rd column)

Economic		
1	Economic Efficiency	Refrigerant cost, Labour productivity related to refrigerants, Profits gained from refrigerant charging, Criticality of material used, Energy and operating cost
2	Economic provisions	Shared R & D efforts, market and operational risk, marketability, acceptability, and cost of refrigerant emissions allowance
3	Future viability and sustainability value	Refrigerant life cycle, durability, and serviceability
4	Risk assessment	Application, operational, tolerable, country specific and innovation
Environment		
1	Material efficiency	Quantity, manufacturing energy demand and recycling
2	Energy efficiency	Performance, energy consumption in annual operation, GWP, TEWI, MEPS, local power generation and country specific
3	Sustainability and resource efficiency	Refrigerant recycle, decomposition and deposits, local and global, influence on aquatic systems and impact on flora and fauna
Social		
1	Nutrition	Ensuring cold chain, sufficient nutrition, quality of food, country specific
2	Health of humans, toxicology, and environment	Safety in operation, service risk, deaths and mortality, quantity of hazardous waste, disposal, and decomposition
3	Air and Water	Emissions of harmful substances, local & global water contamination
4	Public perception and society acceptance	Training and education of technicians, competency and procedures, possible legal action, information on policies, acceptance by society
5	Legal certainty	Existing and development of environmental laws, liabilities, business risk and country specific requirements

Table 2-2: Goals, indicators criteria, factors for a sustainability assessment related to refrigerants.

Goal	Indicator for comparison	Area for indicator	Criteria, factor	Potential assessment	Period for evaluation	Explanation, indicative to not exhaustive, to be evaluated
Economic	Energy consumption and operating costs	Full life cycle	Operating costs	Comparison of investment versus operating cost of systems optimized for different refrigerants	Product development	- Indicator depends on initial system costs (investment) and has high influence on operating costs. - A comparison should in addition consider other sustainability factors
	Innovation	Patents, IP Potential	Number of innovations	- Innovation workshops; - Standards and guides for stimulation of innovation	- Product development - Product lifetime	The assessment of different refrigerants may result in innovations, related to the chemical nature of the refrigerant in consideration (e.g., flammability) and impact on environment
	Performance	Testing	Fulfilment of market requirements	- Comparison with market - Compliance to standards	Product development	Testing and certification costs can be high for several refrigerant options
	Risk assessment	Refrigerant	Tolerable risk acceptance level	- ISO 31010 - Safety Data Sheet of refrigerant	- Product development - Refrigerant life cycle	- Assessment for handling, use, toxicity, flammability, decomposition, pressure, disposal - Local requirements for refrigerant handling; typically, as state of the art - Risk evaluation for fluid in consideration
	Risk assessment	Application	Tolerable risk acceptance level	ISO 12100, ISO Guide 51, ISO 13043, ISO 20854	- Product development - Product lifetime	Assessment of tightness in application-related use, hazards from improper use, foreseeable misuse
Environmental	Ecosystem and climate impact	Refrigerant	GWP	- GWP comparison - Decision on time horizon for GWP Values	- Refrigerant life cycle	- Long GWP time horizons enable the differentiation between long lived substances. Examples: R-23, PFC's. - Short GWP time horizons enable the differentiation between short lived substances and addresses short term concerns better. Example: a GWP-20 years is appropriate for climate impact between 2040 to 2060.
	Ecosystem and climate impact	TEWI	Mt $CO_{2.}$ eq	Assessment of direct and indirect emissions of the application, depending on local conditions	- Product lifetime	Assumptions for leakage rates and the emission factors are made locally depending on the selected system configuration and refrigerant, - Conducting an annual operation energy demand calculation and end-of-life management
	Performance	Refrigerant	COP, SEER	- Use of resources; - simulation, - calculation of energy use depending on local operating conditions	- Product operating lifetime	- The energy consumption of a refrigeration system depends on the thermodynamic properties of the refrigerant or working fluid within the ambient conditions. - The optimization of components such as the heat exchanger also depends on the transport properties of the fluid.

Goal	Indicator for comparison	Area for indicator	Criteria, factor	Potential assessment	Period for evaluation	Explanation, indicative to not exhaustive, to be evaluated
	Recourses	Material	Materials used by weight	- Rating, - Evaluating demand, - Recycling rate	Leaks in the lifetime in operation recycling cycle	- Avoiding excessive material use - Considering waste and destruction
	Resources	Energy	Rating, Power consumption	- Annual operational profile, - component selection including refrigerant, - Refrigeration concept and design, - Controls and system integration	Product operating lifetime	Operation of refrigeration systems contribute to global warming by indirect emissions through energy consumption and emission of refrigerants and should be minimized.
Social	Regulations	Regulations to be observed by law	Compliance	- Audit - Considering future regulations and policy direction	Refrigerant lifetime	- Meeting MP, Kigali Amendment, voluntary commitment - Consideration of expected regulations or phasedown, reduction of CO_2.eq
	Risk assessment	Operation	Tolerable risk	- Safety of users, technicians, operators - Standards: ISO 31010, ISO 12100, IEC 62502, IEC 60812, IEC 61025, IEC 61882	Product lifetime	Assessment of operational safety and determination of mitigation strategy, risk management, qualification, competence, training, update, and development of new safety standards
	Serviceability	Simplicity and feasibility, safety	Degree of fulfilment competence level required	- Audit - Self assessment of competence	Product operating lifetime	characteristics of refrigerants in terms of safety, toxicity, decompositions, pressure, colour codes and requirements, operational health, and safety codes; tools and instruments
	Standards and codes	CO2-Emission	MEPS rating labelling	- Testing and certification	Product development	MEPS (Minimum Energy Performance Standards) are like bans in the sense that part of the products on the market are banned based on their energy efficiency rating

2.4 The SDGs as they apply to the RACHP industry

RACHP is not explicitly addressed by the *Sustainable Developments Goals*; however, RACHP and refrigerants are key contributors to achieving the goal of a sustainable population and contribute to many SDGs. Cooling is essential for multiple SDGs: to protect against the risks of extreme heat, provide the cold chains needed for vaccines, to reduce food waste and improve food security, as a pathway for increasing the incomes of rural farmers, and to limit extreme heat in urban developments.

1 NO POVERTY	Refrigerant enabled cold chains are a required element of the economies of the world, enabling chemical processing, manufacturing, food preservation and building environmental conditioning.
2 ZERO HUNGER	Refrigeration helps fight food loss and waste and improves food security. Overall, losses due to a deficient cold chain account for 13% of food production. If all these losses were eliminated, one billion people could be fed, thus significantly meeting the future needs of humanity (IIR. 2021) Inadequate food preservation leads to further tragic consequences: 600 million people, almost 1 in 10 worldwide, fall ill after eating contaminated food. Of these, 420 000 people die each year, including 125 000 children under the age of five years (WHO. 2022). The use of a cold chain increases food safety and the food availability. Fresh meat or fish for example has a shelf life of 1 day or less at ambient storage temperatures (20-30°C). The shelf life can reach 10 days with cooling.
3 GOOD HEALTH AND WELL-BEING	As the world warms, around 30 percent of the global population is exposed to life-threatening heat for at least 20 days a year. Even in a low-emissions scenario, 50 percent of humanity may be exposed to life-threatening conditions arising from extreme heat and humidity by 2100 (IPCC. 2022). As at 2018, less than a third of global households own an air conditioner The combination of rising temperatures and incomes means this figure is growing rapidly; by 2050 it has been projected around two thirds of the world's households could have an air conditioner – more than a billion new units (IEA. 2018). Without subsidies or strict performance standards, low-income consumers will buy the lowest cost and typically least energy-efficient equipment, some still using potent greenhouse gases as refrigerants, locking in their use for a decade or more.
4 QUALITY EDUCATION	The Montreal Protocol, through funding provided by the multilateral Fund, is providing capacity building and training to technicians in A-5 countries contributing to the application of servicing best practices, and safe working environment both for technicians and end users.
5 GENDER EQUALITY	Gender mainstreaming activities in encouraging women to join the RACHP sector and removing barriers to their participation in the workforce will provide opportunities to women in A5 countries and enable their social and economic independence.
6 CLEAN WATER AND SANITATION	Water is used for various cooling processes in RACHP systems. On the one hand for separate re-cooling systems (evaporative cooling systems, cooling towers) as well as for cooling condensers and as a heat sink at HP. Water temperatures and keeping the water body biologically clean are key factors.

	In addition to the pure use of water for heating or cooling purposes, the problem of keeping drinking and ground water clean due to foreseeable contamination from the breakdown products of refrigerants is becoming increasingly important (see section 2.3.2).
7 AFFORDABLE AND CLEAN ENERGY	Refrigeration technology (Organic Rankine Cycle-ORC) is increasingly being used to produce power. Heat pumps are considered a key technology in order to decarbonize heating demands in residential and industrial applications, by replacing fossil fuels. Renewable energies can also provide cooling such as solar cooling and evaporative cooling.
8 DECENT WORK AND ECONOMIC GROWTH	Air conditioning also affects the well-being and productiveness (Heal, 2014). Research suggests productivity decreases on hot and humid days. Higher temperatures decrease humans' physical and cognitive performance, making it harder for people to complete basic tasks. Evidence indicates that in countries with already high average temperatures, such as Thailand, India, or Nigeria, individual productivity reduces by as much as 4% for each one-degree Celsius increase in average temperature. Refrigeration is also increasingly used in surgery (cryosurgery), for diagnoses (scanners), for transplants and analyses (tissue, gametes banks, etc.).
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Research and development in the field of not-in-kind technologies is contributing to a refrigerant-free environment. Innovative technologies for ultra-low temperature refrigeration are enabling new applications including vaccine storage.
10 REDUCED INEQUALITIES	As at 2018, less than 3% of almost three billion people living in the hottest parts of the world own an air conditioner (IEA. 2018a). Advancement in technology and manufacturing processes can make cooling affordable to a larger percentage of people in the low-income bracket without compromising the efficiency of the units or the quality of performance.
11 SUSTAINABLE CITIES AND COMMUNITIES	Food and jobs are required for 80 million new people every year due to population growth (Nix. 2018). The population growth drives an increase in demand for food, housing, energy, and the associated waste products. Food security in cities is critical and relies on a functioning cold chain. Newly installed refrigerant-based products that support this demand provide improved energy efficiency, food storage efficiency and productivity.
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Food waste occurs in the lower levels of the food supply chain. It is estimated that a 1/3 of all food produced globally is lost or goes to waste (FAO. 2012). The importance of functioning cold chains has been further highlighted in the context of the COVID-19 pandemic. A functioning cold chain is essential for the distribution of most COVID-19 vaccines. Food and vaccine loss are reduced through proper access to refrigeration and cold chains.
13 CLIMATE ACTION	Buildings account for 17.5% of the global energy-related emissions from the generation of electricity used to run RACHP systems among others (Ritchie, et al. 2020). RACHP accounts for 7.8% of global greenhouse gas emissions (IEA. 2018b), of which 37% are due to direct emissions (leakage) of fluorocarbons (CFCs, HCFCs and HFCs) used as refrigerants, and 63% to the production of electrical energy required to operate the installations. Energy efficient products and use of ultralow-GWP refrigerants in the systems will further reduce the direct impact on global warming. The use of renewable energy (e.g., solar, wind, hydro, and geothermal) will reduce the

	indirect emissions. Heat pumps will also play an important role in replacing fossil fuels for heating purposes both residentially and in industry.
14 LIFE BELOW WATER	District cooling projects using deep sea cooling techniques reduce refrigerant emissions by 99% and GHG emissions by up to 40% compared to in-kind system (UNEP. 2022). The concept of using cold water to provide cooling for cities has taken root globally. For instance, in Canada's largest city, Toronto, the local government implemented the largest lake-source cooling system in the world. Commissioned in 2004, Enwave's Deep Lake Water Cooling system uses cold lake water as a renewable energy source. Similar large-scale projects have also been built in the United States and France (UNEP. 2022). The projects undergo strict analysis to reduce environmental impact on marine or aquatic life.
15 LIFE ON LAND	With less food loss, less land is needed to provide the amount of food that reaches the end consumer.
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Abundance of fresh food is a major factor in maintaining peaceful relations in developing countries. A reliable access to food that is supported by a cold chain prevents potential sources of conflict.
17 PARTNERSHIPS FOR THE GOALS	The Montreal Protocol is the most successful treaty encompassing all countries of the world and bringing benefits in terms of protecting humans and the earth from the effects of ozone depletion. The Kigali Amendment will add them to contribution of the Montreal Protocol in reducing GHG emissions through the phasing-down of HFCs. The programmes and activities funded by the MLF have enabled A5 countries to build their capacities and enhance the awareness about an efficient and performing RACHP. Harmonization of efforts with energy departments in introducing MEPS and labelling systems will further enhance the benefits of the programmes.

2.5 Concluding remarks

Over the last two decades, the scientific and technical communities have unearthed a wealth of information about the impact of refrigerants on the environment. This has resulted in the development of sustainability assessment tools (e.g., Table 2-1). It is considered important, e.g. by governments and standards bodies, to consider all major risks associated with refrigerant selection including: negative environmental impacts, scientific data , and scientific uncertainty/gaps. Based on that, standards have been developed as listed in Table 2-2.

The factors that affect business economics and thus sustainable refrigerant selection include: environmental legislation and laws, introduction of disruptive technologies, and investment funds targeted for converting to sustainable products or industries. There are global policy mechanisms such as: product bans, MEPS, and incentive programs to support the transition towards sustainable refrigerant selection.

CO_2 equivalents include direct and indirect emissions. There are policy measures for emission reduction both direct and indirect. Direct emissions reduction measures focus on leak minimisation and technician training while indirection emissions reduction measures focus on energy efficiency improvement and renewable energy integration.

Refrigerants sustainability assessment for RACHP applications is key to support the Montreal Protocol. The comparison between alternative and existing RACHP technologies should account for sustainability criteria over their lifetime. Tables 2-1 and 2-2 present a possible assessment framework for comparing refrigerant options, as an example.

A detailed review of RACHP sector supports 12 out of the 17 SDGs. RACHP sector will continue to play an important role into the sustainable future with a focus on efficient cold chains and comfort applications.

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ANNEX to Sustainability

This annex provides some examples for sustainability factors integrated with the assessment of refrigerant selection in RACHP applications.

Sustainable cold chains

A sustainable cold chain includes refrigeration from farm to fork, with the focus on the lowest consumption of natural resources and low refrigerant emissions, and therefore can provide minimum losses, high quality, and healthy food.

Agricultural food chain

The production, post-farm processes, and distribution of food require substantial amounts of energy and resources, making the food sector responsible for approximately 26 % of global anthropogenic greenhouse gas emissions, 18 % of this can be attributed to the supply chain[9]. Food waste emissions are large: one-quarter of emissions (3.3 billion tonnes of CO_2 equivalents) from food production ends up as wastage either from supply chain losses (Prevailing in article 5 countries) or consumers (typical for article 2 countries). A sustainable cold chain including refrigeration can help reducing these losses during processing, distribution, and storage in retail and at the consumers.

Nearly 60 % of the food consumed needs refrigeration at some point in the supply chain. An interrupted cold chain results in bacterial growth, especially in perishable foods such as fish and meat. It is important to distinguish between food loss and food waste. Food losses or post-harvest losses (PHL) occur along the value chain from harvest to delivery of the food to the consumer, whereas food waste refers to food wasted by the consumers themselves. While more developed countries struggle with the highest proportions of food waste, developing regions like Sub-Saharan Africa (SSA) face higher proportions of facing food losses. Deloitte reports that approximately 95% of losses in the SSA occur before the consumer purchases the crop, while more than half of losses in Europe and North America occur after the crop reaches the consumer. Therefore, optimizing the supply chains especially between small holder farmers (SHF) and the consumer is key to reducing losses in SSA (Deloitte 2015). In the EU alone, around 88 million tons of food are wasted every year, which corresponds to a savings potential of around 8% of the EU greenhouse gas emissions[10].

A continuous cold chain also combats malnutrition and hunger since food prices would be dropping due to the surplus of supply (Garnett 2011). Due to the globalization of the food market and climate change, it is expected that the energy consumption for the reliable cold chain will rise rapidly in the next century. The highest growth rate for refrigeration and cooling demand is expected in non-OECD countries, where environmental and occupational health and safety regulations are driven by the market economics of the technology.

It is necessary to improve the energy efficiency of the cold chain and decrease its direct and indirect emissions. Energy efficiency can be improved by at least 50 % if some of the following measures are taken (Kauffeld 2015):

1. Adjustments and optimization of control algorithms
2. Reduction of load and heat gains including proper insulation and limitation of waste air exchange in cold stores
3. Optimization of temperature difference in processes and equipment designs, for example decreasing the temperature lift by increasing the evaporator temperature and decreasing the condensing temperature

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[9] https://ourworldindata.org/food-ghg-emissions

[10] https://ec.europa.eu/food/safety/food_waste_en

4. Ensuring the rapid transfer of temperature-controlled food from one link of the cold chain to another
5. Reduction / control of fan power
6. Applying free cooling where- and whenever possible
7. Utilizing heat recovery
8. Incorporating cold energy storage to allow for the use of more renewable energy with its shifting supply
9. Use of renewable energy.

Fisheries

The fishing industry is an energy intensive industry throughout the whole value chain; however, many countries lack the infrastructure or the technology to maintain a sustainable cold chain which can lead to considerable wastage and the depletion of fish resources. Fish wastage is in some tropical countries as high as 80% due to the lack of continuous cooling.

As a highly perishable commodity, fish often needs rapid processing. However, fish post-harvest losses are high and seafood value chains' potential remains largely untapped due to limited cold chain infrastructure in most Article-5 countries. Current technologies used in these countries are often outdated, energy-intensive and have the potential to damage the environment. Furthermore, knowledge of cost-effective and ozone & climate-friendly cooling and refrigeration options that are readily available and accessible is lacking. Improvement in fisheries cold chain logistics efficiency will contribute to achieving climate change, SDGs, Montreal Protocol and Kigali HFC Phase Plan goals (FAO 2020).

Typical figures for the energy consumption per tons of fish intake are 65–87 kWh for filleting, 150–190 kWh for canning, and about 32 kWh for fishmeal and fish oil production, plus 32 litres of fuel oil. Substantial savings can be made in many cases with little or no capital investment, through simple housekeeping and through value recovery from process by-products. Typical figures for freshwater consumption per tons of fish intake are 5–11 m^3 for fish filleting, 15 m^3 for canning, and 0.5 m^3 for fishmeal and fish oil production. Fishmeal and fish oil production also consumes about 20 m^3 of seawater per tons of fish intake (FAO 2020).

Conclusions

The lack of infrastructure and technological options pose negative social, economic, and health impacts to the fish and farmers' communities and consumers, harm environment and likewise hinder the potential of the countries to scale-up sustainable activities in the fisheries and seafood sector. The current lack of sustainable cold chains means that in some countries, 30-50% of food produced is lost between harvest and market, hampering opportunities for raising farmers' incomes and economic development opportunities in many rural areas. Lack of proper cold chains is regarded as one of the barriers to developing the agriculture and food value chain. The implementation of eco-friendly alternatives would entail the need to build technical knowledge and capacity and reduce technology access costs in these countries.

Sustainable buildings

The technological development in building materials, energy sources, and controls and communication took the sustainability concept to new levels beyond the limits of the equipment. Equipment and systems now are smarter and can interact with surrounding environment and the application demands. Fluctuation of temperatures between day and night, summer and winter, and the cooling or heating demands can be utilized with the use of mixed technologies and solutions which offer an opportunity to achieve drastic reduction of energy consumption. For example, a potential of up to 40 % reduced energy demand was reported in Germany (FKT, 2012). This approach is trending now in buildings, including sustainability building concept. From there, the annualized energy use of an equipment or a system can be optimized or eliminated in some cases (Net (near) Zero Building Concept).

The sustainable building concept is looking at the building with its location, materials, systems, equipment, occupants, and controls as an integrated system designed for better environmental benefits. Measures (indicators) considered to evaluate the sustainability of a building are as follows:

- Lower CO_2 emissions
- Lower water consumption
- Lower waste, more recycling and reusing.
- More environmental quality

Demand based, or application-based concept in building design and development requires a proper framework of building energy models, regulations, and codes to implement. Several national, regional, and international codes have been developed and used globally for new buildings and for retrofitting existing buildings as well; yet more work is ongoing to support the growing interest in this concept globally. Reducing the cooling demand and heat load is an important consideration in the sustainable building design.

Furthermore, improving the indoor air quality (IAQ) has gained significant interest and supports sustainability. IAQ measures can vary from one application to another, and it can impact the sustainability and usability of buildings. IAQ measures includes:

- Higher efficiency filtration
- Demand controlled ventilation
- Higher fresh air rates
- UV treatment of (recirculated) air

Chapter 3

Refrigerants

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3 Refrigerants

3.1 Introduction

The first part of this chapter presents background information on refrigerants, including (1) the historic development of, (2) climate metrics for, and (3) the selection of refrigerants. Safety standards and their influence on the refrigerant selection are also discussed. Recent developments as to refrigerants are described, a list of new refrigerants is given with the refrigerants listed in ASHRAE Standard 34 and/or ISO 817 since the RTOC 2018 Assessment Report (UNEP, 2019), and selected topics relevant for new refrigerants are discussed, i.e., (1) the TFA atmospheric breakdown product, (2) developments related to FIC-13I1, and (3) the topic of thermal decomposition. It is followed by an assessment of current and future refrigerants and their GWPs.

The second part of the chapter deals with issues related to production and consumption reporting, followed by how the size of RACHP banks and emissions can be estimated and have been estimated in the recent past. In section 3.7, the modelling of consumption, inventories (i.e., banks) and emissions is elaborated upon. It describes the issues involved in bottom-up modelling and goes into the details of a number of modelling approaches.

The Annex to this chapter lists all refrigerants from ASHRAE Standard 34 and/or ISO 817. Table 3.I-1 covers single component refrigerants; Table 3.I-2 is the summary for zeotropic refrigerant blends, while Table 3.I-3 covers azeotropic refrigerant blends.

3.2 Background

3.2.1 Refrigerant development

The historic progression of refrigerants encompasses four phases based on their primary selection criteria (Calm and Didion, 1997; Calm, 2012):

- **1830-1930 – whatever worked (and was available):** primarily familiar solvents and other volatile fluids including ethers, ammonia (NH_3, R-717), carbon dioxide (CO_2, R-744), sulphur dioxide (SO_2, R-764), methyl formate ($HCOOCH_3$, R-611), hydrocarbons (HCs), water (H_2O, R-718), carbon tetrachloride (CCl_4, R-10), hydrochlorocarbons (HCCs), and others. Many of them are now defined as "natural refrigerants" (even when nearly all of them are synthesized, refined, or at least industrially purified to date).
- **1931-1990 – safety and durability:** primarily chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), ammonia, and water used in absorption cycles as a refrigerant or absorbent.
- **1989-2010 – avoidance of substances with high ozone-depleting potential (ODP)**, following the decrease and phaseout of consumption and production of ozone depleting substances for stratospheric ozone protection as regulated by the Montreal Protocol. Some ozone-depleting substances (ODSs) with low or very low ODP were allowed for interim use (e.g., HCFC-22) or substitute use (e.g., HCFC-123). The most widely adopted zero-ODP alternatives were high GWP HFCs such as R-404A, R-410A and HFC-134a. Interest in "natural" (non-fluorinated) refrigerants intensified, notably carbon dioxide (R-744) in large commercial refrigeration, HCs (mainly isobutane, HC-600a, and propane, HC-290, particularly in low-charge hermetically sealed applications such as refrigerators and small appliances), ammonia (R-717) and R-744 in industrial uses, and water in vapour-compression cycles for specialized applications such as desalination and deep-mine chillers, gradually also for smaller sized turbo-units for cooling (e.g., for data centres).
- **2010-onwards** – refrigerants with zero or near-zero ODP and very low global-warming potential (GWP), such as "natural refrigerants" and unsaturated synthetic chemicals.

Hence also significant pursuit of unsaturated halochemicals including hydrochloro-olefins (HCOs), hydrochlorofluoro-olefins (HCFOs), and hydrofluoro-olefins (HFOs). The olefinic double bond between two carbon atoms leads to atmospheric instability and, in turn, a very short atmospheric lifetime. The result is near-zero ODP predicated on the decomposition before rising to the stratosphere and likewise very low GWP again by atmospheric decomposition in the troposphere. Examples include HFO-1234yf for mobile air conditioner use, HFO-1234ze(E) and HCFO-1233zd(E) for (centrifugal) chillers, and HFO-1336mzz(Z) and HFO-1336mzz(E) gaining acceptance as blend components in addition to other refrigerants addressed below. The use of HCOs, HCFOs, and HFOs remains controversial as some parties deem them still of concern based on secondary chemistry of these chlorine- and fluorine-containing substances yielding longer-lived greenhouse gases (GHGs) or ozone-depleting substances. Likewise, there is potential to form such environmentally persistent chemicals as trifluoro-acetic acid (TFA). See further section 3.4.2. Another chemical group being pursued consists of the fluoro-iodocarbons, notably FIC-13I1 (CF3I). Proponents advocated their use in the late 1980s and 1990s, and FIC-13I1 is now being considered as a blend component. FIC-13I1 is addressed in more detail in section 3.4.3 below.

3.2.2 Global Warming impact metrics for refrigerants

The most commonly used metric for indicating the climate impact potential of a refrigerant emission is the GWP, which is the integrated radiative forcing of a pulse of refrigerant relative to a pulse of the same mass of carbon dioxide (CO_2) over a certain time period (the integration time horizon, ITH) when emitted to the atmosphere. In most cases, the 100-year GWP is taken. However, some experts advocate the use of GWP values with shorter integration time horizons, particularly in the case of HFCs which often have relatively short lifetimes. They also emphasise the use of various instantaneous or sustained metrics such as the global temperature potential (GTP) (Shine et al., 2005; Hodnebrog et al., 2013) See also section 8.7 of the IPCC (2013) AR5 WGI report for a detailed discussion of the pulse GTP and sustained GTP.

The GWP parameter is not directly related to sustainability. It is actually the policy choice of a certain GWP (with a certain ITH) that could lead to more or less sustainability in the operation of equipment with certain refrigerants. Although new concepts have recently been proposed (such as the GWP* which adds extra emissions in case of the consideration of short-lived compounds compared to CO_2), this has so far not been considered for refrigerants. There is also an effect on the GWP related to the carbon cycle feedback, i.e., the climate impact would change in a warming world; for this reason, GWPs including the carbon cycle feedback have been published in the IPCC AR6 (2021). This is a correction to the calculation of the GWP via the integration of the radiative forcing and does not change the GWP concept.

Where it relates to refrigerants (and particularly to blends of various refrigerants), the issue is how to best scale them via the use of a GWP with a certain ITH. Short-term climate impacts of short-lived chemicals (5-10 years) are underestimated in a 100-year GWP. They would contribute most to climate warming during a period of 20-30 years after their emission. Consideration of the 20-year GWP may not give an adequate picture as long-lived substances can be used in small amounts in blends with short-lived substances to create lower GWP blends, the use of the 20-year GWP may lead to decisions favouring the short-term climate impact neglecting longer-term impacts (i.e., up to 2050-2100).

In this chapter, both the 20-year GWP and 100-year GWP values are tabulated. An advantage of the 20-year GWP over the 100-year GWP is that a 20-year time horizon is more relevant when discussing climate change during the next few decades, where it may also be better in differentiating between substances with shorter lifetimes. The advantage of using the 100-year GWP is that this GWP is more commonly used — in scientific literature, standards, and regulations — which is important to an efficient discussion of the climate impact.

A classification of 100-year GWPs (which is identical to the classification in the previous RTOC reports ((UNEP, 2015) and (UNEP, 2019)) is given in Table 3-1. Table 3-1 categorizes using "less than" or "more than" and therefore a refrigerant such as HFO-1234yf is included in the ultra-low, very low, and low GWP groups. Likewise, HFC-23 is included in the ultra-high, very high, and high GWP groups.

The values in the table are not an attempt to match any "cut-off" values in legislation, which are often set based on the GWP of alternatives deemed viable at the time of writing of the specific legislation, and they are normally based on a specific publication that includes lists of GWP values, note that the GWPs from the IPCC AR4 report (IPCC, 2007) are used in the Kigali Amendment, however the Kigali Amendment covers a limited number of pure HFCs (18), HCFCs (8) and CFCs (5).

Table 3-1: Classification of 100-year GWP levels (UNEP, 2010)

100-year GWP	Classification
< 30	Ultralow
< 100	Very low
< 300	Low
300-1000	Medium
> 1000	High
> 3000	Very high
> 10000	Ultrahigh

For gases with lifetimes of 100-years or more the uncertainties in GWPs are of the order of ±20 % and ±30 % in case 20- and 100-year time horizons are applied, respectively. For shorter lived gases, which include nearly all the HCFCs and HFCs used as refrigerants, the uncertainties in GWPs will be larger (IPCC, 2013). This is one reason care must be taken when comparing the GWP values of refrigerants. For substances with a very low GWP, the picture becomes even more complicated since the GWP values do not include the radiative forcing of all breakdown products, including the longer-lived ones, such as CO_2.

Comparing carbon equivalent emissions associated with the use of refrigerants should be done with caution and include a comparison of the energy efficiency of a refrigerant in a given application. Emissions from energy production used to operate the equipment are normally having a greater climate impact than from direct refrigerant emissions, but this can vary significantly depending on the source of electricity. For a further discussion of these issues see Chapter 2.

3.2.3 Refrigerant selection

Many non-ODS low-GWP alternatives have additional environmental, safety and/or cost implications associated with them and therefore the selection of a refrigerant is seldom a straightforward one. Refrigerant selection may be done through several steps, considering environmental legal obligations, safety requirements, efficiency, material compatibility, availability of components and access to competent technicians. These steps filter out certain refrigerant options, leaving a smaller group to choose from. Thereafter, more subjective considerations may apply, such as customer preferences, commercial factors, in-house experiences, and so on.

Typically, for "off the shelf" RACHP systems, the manufacturer will have selected the refrigerant, whereas for bespoke systems, selections may be carried out by the designer, installer and/or service company. Industry organisations, such as AEM, SAE, AHRI, etc., conduct screening projects to understand how new refrigerants will meet user needs. Data are shared through industry consortiums to support users who are making refrigerant selections.

Environmental legal obligations

Legislation prohibits the use of certain refrigerants and in some cases the use for particular equipment and applications. This includes regulations covering fluids with an ozone depletion potential, but also GWPs above certain threshold values, although other environmental impacts may also apply in some countries.

Safety requirements

Typically, regulations impose safety requirements on the use of substances, covering pressure, machinery, toxicity, and flammability matters. In general, such regulations seldom prohibit the use of any substances (except the ones having certain toxicity), but mitigation requirements can result in systems using refrigerants with higher operating pressures, higher toxicity or flammability becoming more expensive. Safety standards tend to be more prescriptive and may not allow the use of certain refrigerants for particular installations. However, safety standards are often not mandatory provided alternative means can be used to satisfy the requirements of the regulations. See section 3.3 for an elaboration on safety standards.

Energy efficiency

For a cycle with a given temperature lift (the difference between the temperature at which heat is absorbed in the evaporator to the temperature at which it is rejected via the condenser), refrigerants have a theoretical efficiency that is only based on the refrigerant's thermodynamic properties. Among the refrigerants suitable for a given temperature lift, the cycle efficiency can vary by up to about ±10 %. However, the practical energy efficiency of the majority of refrigeration or air conditioning equipment is mainly determined by thermophysical and transport properties and other factors, including the efficiency of components such as the compressor and heat exchangers. Generally, the higher the refrigerant theoretical cycle efficiency, the higher will be the equipment's overall efficiency. Potential inconsistency between these two efficiencies may be caused by:

(1) Different refrigerants have different heat transfer and flow characteristics.
(2) The optimisation of components for various refrigerants is different. For instance, variable speed compressors for R-410A have been developed for decades and are well-optimised. That is, for the alternative refrigerants that have similar properties as R-410A it will be easier to utilize such variable speed compressors to achieve high efficiency sooner.
(3) Different system design requirements according to the standards or regulations. For example, where the maximum charge (mass) of refrigerants is limited.

For many types of equipment, there are regional or national minimum efficiency requirements (MEPS), so irrespective of the refrigerant used, the equipment operation has to achieve or exceed a certain efficiency threshold. Whilst most refrigerants will be able to meet such requirements, some may require greater investment in materials used in the system (e.g., greater heat exchanger size) than others.

Materials compatibility

Materials such as oils, elastomers, plastics, and metals. should both be compatible with and suitable for the refrigerant used in the system. Compatibility can refer to chemical stability (absence of strong chemical reactions), miscibility and solubility with oils, and structural stability (minimal changes in properties due to adsorption). Suitability includes function, thermal stability, and, in the case of lubricants, sufficient solubility, and fluid velocity to achieve a return to the compressor(s). These are usually handled at screening stages before commercialisation of the refrigerant.

Component availability

System components should be suitable where it concerns the refrigerant used. Sometimes components are unavailable for certain refrigerants and particular types of systems depending on capacity, temperature level, approvals, etc. This is often related to the above mentioned legal and safety requirements or that the refrigerant is in early stages of commercialisation. Using refrigerants with components that are not approved for their use can invalidate warranties and be counter to legal requirements.

Refrigerant availability

Amongst the numerous refrigerants listed in ASHRAE Standard 34 and/or ISO 817, many are not commercially available. Thus, local availability of refrigerants can also limit choice. With the phasedown introduced by the Kigali Amendment, certain high GWP HFC refrigerants may have limited availability in the future.

Technician competence

Given the wide variety of refrigerants' characteristics, technicians seldom have the competency to work on all refrigerants and any type of equipment. Therefore, it must be ensured that the technicians available to work on specific systems are suitably qualified. More details can be found in Chapter 13.

System architecture

Typically, users select refrigerants that are compatible with existing system requirements. Refrigerants that require new system design face other technical challenges but can still be successfully employed. One example of system architecture change is noted when going from R-404A to CO_2 (R-744) in large commercial refrigeration applications.

3.3 Refrigerants and safety standards

The framework of RACHP sector safety standards relies upon an alpha-numeric refrigerant safety classification (A1, B3, etc.) and safety limits (lower flammability limit (LFL), acute toxicity exposure limit (ATEL), etc.). Therefore, it is desirable that refrigerants be listed in the applicable classification and numbering standards, such as ISO 817 (ISO 817:2014) and ASHRAE Standard 34 (ASHRAE 34-2022), and amendments/addenda thereof.[11] Accordingly, refrigerant producers generally seek to add new refrigerants or refrigerant blends to these refrigerant standards.

In addition to assigning R-numbers, ISO 817 and ASHRAE Standard 34 assign the alpha-numeric classification of each refrigerant based on toxicity (A for lower toxicity and B for higher toxicity) and flammability (1 for no flame propagation, 2L for lower flammability, 2 for flammable, and 3 for higher flammability), see Table 3-2.

Table 3-2: Refrigerant safety classification ISO 817 (ISO 817:2014)

	Lower toxicity	Higher toxicity
No flame propagation	A1	B1
Lower flammability	A2L	B2L
Flammable	A2	B2
Higher flammability	A3	B3

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[11] Efforts are underway to align these two standards.

Application standards, such as those listed in Table 3-3, provide design, construction, installation, and service requirements according to the refrigerants' safety classification and safety limits (LFL, ATEL, etc.). Such standards may be categorised as:

a. "horizontal" or "group" standards (which cover all types and sizes of equipment and systems),
b. "vertical" or "product" standards (which are intended to cover particular applications) and
c. component standards (for elements of systems, such as valves, vessels, sensors, etc.).

Although safety standards are not mandatory in most countries, unless explicitly adopted by legislation, they are one important source through which the industry looks for guidance for handling flammability and toxicity, as well as other relevant hazards such as pressure, freeze-burn, oxygen deprivation, etc. For instance, most application standards in Table 3-3 specify limits for the amount of refrigerant that could be charged into a system, often depending on safety classification, system type, system location, and accessibility of people according to their knowledge of refrigeration systems (i.e., members of the public versus competent workers). In addition to those in Table 3-3, another standard, ISO/DIS 22712:2018, addresses the competence of workers involved in handling refrigerants and systems.

Historically, safety standards had been relatively prohibitive for flammable and higher toxicity refrigerants. However, as the application of such refrigerants is related to their lower environmental impact, safety standards are continually being revised. Revisions increasingly consider aspects that affect flammability and toxicity risks, such as leak tightness, dispersion of leaked refrigerant and mitigation measures including leak detection, airflow/ventilation, alarms, and system operation response. Refinements of requirements handle the trade-off between refrigerant hazards, the desire to use greater quantities of refrigerant, and technological advances in system design. The acceptance of flammable and higher toxicity refrigerants and the appropriate updates of standards is a contemporary challenge for the RACHP industry. CEN TR 17608:2022 (CEN, 2022) gives an overview of the state of the art of safety standards related to flammable refrigerants.

Further discussion can be found in the TEAP XXVIII/4 Task Force report (UNEP, 2017a) and an overview from this report concerning the scope of different international standards is provided in Table 3-3. However, many countries adopt international standards but add specific national deviations or publish their own standards equivalent to those in Table 3-3. Therefore, it is pertinent to refer to national standards as applicable. An overview of current safety standards is maintained by the Ozone Secretariat and can be accessed at: https://ozone.unep.org/system-safety-standards

Briefing notes have been provided by UNEP:

a) Safety standards relevant to Refrigeration, Air-Conditioning and Heat Pump equipment (UNEP, 2017b)
b) Updating the refrigeration, air-conditioning and heat pump (RACHP) safety standards (UNEP, 2017c)
c) Application of safety standards to Refrigeration, Air-Conditioning and Heat Pump equipment – a lifetime perspective (UNEP, 2017d)

Table 3-3: Scope of different international and regional safety standards for R/AC&HP systems from the TF XXVIII/4 report (UNEP, 2017a)

Sector	**Product safety standards**						**Group safety standard**
	IEC 60335 -2-11	IEC 60335 -2-24	IEC 60335 -2-40	IEC 60335 -2-89	ISO 13043[12]	ISO 20854[13]	ISO 5149
Domestic refrigeration		X					X
Commercial refrigeration				X			X
Industrial systems							X
Transport refrigeration							X
Air-to-air air conditioners & heat pumps			X				X
Water heating heat pumps			X				X
Heat pump tumble driers	X						X
Chillers			X				X
Vehicle air conditioning					X		X[14]
Refrigerated containers						X	X

3.4 Recent developments

3.4.1 New refrigerants since the RTOC AR2018 Report

Since the publication of the RTOC 2018 Assessment Report (UNEP, 2019), two new single-component refrigerants and 23 refrigerant blends have received designations and classifications from ASHRAE Standard 34 and/or from ISO 817. These 25 refrigerants are listed in tables 3-4, 3-5, and 3-6 below. GWP and ODP values have been taken from (WMO, 2022). The GWP 100-year values from the Montreal Protocol are also listed for blends. Most of these blends contain fluids that are not regulated under the Montreal Protocol and the contribution from these are not included. None of the new fluids have an ODP listed in the Montreal Protocol.

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[12] *ISO 13043 only covers HFC-134a, R-744 and HFO-1234yf, so all other alternative refrigerants are out of its scope.*

[13] *ISO 20854 Thermal containers — Safety standard for refrigerating systems using flammable refrigerants – Recommendations Requirements for design and operation is under preparation.*

[14] *ISO 5149-4 is relevant for servicing. ISO 5149-1 and ISO 5149-2 specifically exclude mobile air conditioning (MAC) systems from its scope, and ISO 5149-3 is not applicable to MAC.*

Table 3-4: Data summary for new single component refrigerants

Refrigerant Designation	Chemical Formula	Chemical Name	Molecular Weight (kg/kmol)	Boiling Point (°C)	Safety Class	Atmospheric Lifetime (Years)	Radiative Efficiency (W/m/ ppm)	GWP 100-year	GWP 20-year	ODP
FIC-13I1	CF_3I	trifluoroiodomethane	195.9	–21.9	A1	<5 days	0.067	<1	1	<0.09
HFO-1132(E)	CHF=CHF	trans-1,2-difluoroethene	64.0	–52,5	B2	1.3 days	2.46e-03	≪1	≪1	

Table 3-5: Data summary for new zeotropic refrigerant blends

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	Safety Class	GWP 100-year	GWP 20-year	ODP	GWP 100-year in Montreal Protocol
R-427B	R-32/125/143a/134a (20.6/25.6/19.0/34.8)	85	–46,2/–40,1	A1	2 765	5 192		2 382
R-427C	R-32/125/143a/134a (25.0/25.0/10.0/40.0)	83.3	–45.9/–39.4	A1	2 320	4 767		2 063
R-448B	R-32/125/1234yf/134a/1234ze(E) (21.0/21.0/20.0/31.0/7.0)	89.3	–44.1/–37.4	A1	1 415	3 235		1 320[a]
R-457B	R-32/1234yf/152a (35.0/55.0/10.0)	76.5	–46.4/–40.4	A2L	278	973		249[a]
R-457C	R-32/1234yf/152a (7.5/78.0/14.5)	95.5	–37,3/–32,1	A2L	79	278		69[a]
R-466A	R-32/125/13I1 (49.0/11.5/39.5)	80.7	–51.7/–51.0	A1	807	2 065	<0.04	733[a]
R-467A	R-32/125/134a/600a (22.0/5.0/72.4/0.6)	84.4	–40.5/–33.3	A2L	1 420	3 855		1 359[a]
R-468A	R-1132a/32/1234yf (3.5/21.5/75.0)	88.8	–51.3/–39.0	A2L	162	565		145[a]
R-468B	R-1132a/32/1234yf (6.0/13.0/81.0)	94.9	–52.4/–36.8	A2L	98	342		88[a]
R-468C	R-1132a/32/1234yf (6.0/42.0/52.0)	73.7	–56.6/–46.2	A2L	315	1 102		284[a]
R-469A	R-744/32/125 (35.0/32.5/32.5)	59.1	–78.5/–61.5	A1	1 485	3 059		1 357[a]
R-470A	R-744/32/125/134a/1234ze(E)/227ea (10.0/17.0/19.0/7.0/44.0/3.0)	84.4	–62.7/–35.6	A1	1 064	2 197		976[a]
R-470B	R-744/32/125/134a/1234ze(E)/227ea (10.0/11.5/11.5/3.0/57.0/7.0)	89.7	–61.7/–31.4	A1	821	1 615		748[a]
R-471A	R-1234ze(E)/227ea/1336mzz(E) (78.7/4.3/17.0)	122.1	–16.9/–13.8	A1	159	271		138[a]
R-472A	R-744/32/134a (69.0/12.0/19.0)	50.4	–84.3/–61.5	A1	370	1 086		353[a]
R-472B	R-744/32/134a (58.0/10.0/32.0)	54.8	–82.9/–54.8	A1	546	1 562		525[a]
R-473A	R-1132a/23/744/125 (20.0/10.0/60.0/10.0)	52.6	–87.6/–83.0	A1	1 853	1 920		1 830[a]
R-474A	R-1132(E)/1234yf (23.0/77.0)	96.7	–43,1/–36,4	A2L	1	1.8		[b]
R-475A	R-1234yf/134a/1234ze(E) (45.0/43.0/12.0)	108.5	–28.8/–28.3	A1	633	1 747		615[a]
R-476A	R-134a/1234ze(E)/1336mzz(E) (10.0/78.0/12.0)	116.9	–19,1/–16,1	A1	151	421		143[a]
R-477A	R-1270/600a (84.0/16.0)	44	–44.6/–37.2	A3	1	1		[b]
R-477B	R-1270/600a (38.0/62.0)	50.8	–31.5/–23.1	A3	1	1		[b]

[a] Blend containing one or more components which are not regulated under the Montreal Protocol, and the GWP of the blend does not include the contributions of these components.

[b] Blend containing no components which are regulated under the Montreal Protocol.

Table 3-6: Data summary for new azeotropic refrigerant blends

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Normal boiling point (°C)	Safety Class	GWP 100-year	GWP 20-year	ODP	GWP 100-year in Montreal Protocol
R-515B	R-1234ze(E)/227ea (91,1/8,9)	117.5	−19.0	A1	320	523		287[a]

[a] Blend containing R-1234ze(E) which is not regulated under the Montreal Protocol, and the GWP of the blend does not include the contributions of this component.

3.4.2 Trifluoro-acetic Acid, TFA

The topic of TFA is extensively covered in section 6.3 of the EEAP 2022 report and is briefly summarised below, because it is an aspect that is directly related to many refrigerant applications.

Certain refrigerant emissions into the atmosphere result in decomposition products which could be harmful to the Earth’s eco-system. Some of the current and alternative synthetic refrigerants (HCFCs, HFCs, HFOs) can produce significant amounts of trifluoroacetic acid (TFA, formula $C_2HF_3O_2$) during atmospheric decomposition (e.g., maximum one TFA molecule per refrigerant molecule, such as in the case of HFC-227ea or HFO-1234yf). Because of the shorter lifetime of HFOs, this TFA will be deposited nearer to the location of emissions; it will involve further analysis how these locations vs. TFA deposits are geographically distributed.

TFA is a persistent, long-lived chemical with potentially harmful (toxic) effects on animals, plants, and humans, the reason why it has been subject of debate for quite some time. TFA naturally occurs in oceans, but not in fresh water (Nielsen, 2001). TFA can be deposited in the environment by a number of anthropogenic sources (Solomon et al. 2016, Fitzgerald et al. 2018; Holland, 2021) i.e., next to refrigerant sources from sources such as (TFA) feedstock, the degradation of pesticides and pharmaceuticals (e.g., anaesthetics), the combustion of fluorinated products in waste incinerators, and from other sources (WMO, 2022; EEAP, 2022). Growing TFA concentrations are not expected to harm the environment over the next few decades, although some regional concerns are being raised. In view of changing and potential unknown sources, TFA concentrations and its deposition are expected to be monitored for changes in different parts of the environment and periodic re-evaluation is justified because of the persistence of TFA in the environment (WMO, 2022).

3.4.3 Fluoro-iodocarbon, FIC-13I1

As a substitute for ozone-depleting chemicals, CF_3I, designated as FIC-13I1 in ASHRAE Standard 34 and ISO 817, was introduced as early as 1995 as a total flooding fire suppressant (Federal Register, 1995; NIST, 2004), even though (JRAIA, 2011) suggests that CF_3I has some flammability at elevated temperatures. The NIST study reported a small amount of HFC-23 formed during the thermal decomposition of CF_3I. Use of CF_3I as a component of refrigerant blends was studied in the 1990s and some blends were listed as an acceptable substitute for CFC-12 in a variety of end-uses by the USEPA (Federal Register, 1999). These blends containing FIC-13I1 found little, if any, actual use. Renewed interest in this component as a low-GWP compound started in the 2010s, most prominently as one of the components of R-466A, which was added to ASHRAE Standard 34 in late 2019.

Further studies performed by Kujak and Sorenson (2021) presented accelerated lifetime materials compatibility tests with R-466A concluding that with “optimized materials and additives” the blend was viable for use. These conclusions were based on the estimated formation of HFC-23 during equipment operation. Hence the HFC-23 formation was negligible when CF_3I thermal decompositions were well-controlled.

Given the fact that R-466A is designed to replace the globally, widely used R-410A, should such use occur, the concern arises to better understand the possible environmental effects and the potential breakdown products particularly of the FIC-13I1 component. Some of these effects are highly dependent on the location and time of release (WMO, 2014; Zhang et al. 2020).

3.4.4 Thermal decomposition products

All fluorocarbon refrigerants will decompose at sufficiently high temperatures. Decomposition products can be formed when a fluorinated refrigerant comes into contact with a hot surface or naked flame. Fires or improper servicing (not fully evacuating and flushing before brazing) are the most common conditions where fluorinated refrigerants can decompose. The amount of decomposition products formed depends on the amount of fluorinated refrigerant that comes into contact with the hot surface or flame and the residence time in that location.

Decomposition products generated include carbon oxides and fluorinated species, carbonyl fluoride (COF_2), and hydrogen fluoride (HF). Studies sponsored by the US Federal Aviation Administration (FAA) found that carbonyl fluoride (COF_2) is a short-term intermediate (with a lifetime of milliseconds to one second, although larger volumes can be expected to persist for days) that is heterogeneously hydrolysed to HF in the presence of water (George, 1994, Zacharaiah, 1995). Acute (short-term) inhalation exposure to gaseous HF can cause severe respiratory damage in humans, including severe irritation and lung oedema. Severe eye irritation and skin burns may occur following eye or skin exposure. Chronic (long-term) exposure in workers has resulted in skeletal fluorosis, a bone disease (EPA, 2022).

HF can quickly combine with moisture to form hydrofluoric acid, which is extremely corrosive and can corrode metals, glass, and silicon-containing objects. Hydrofluoric acid and other decomposition products can damage equipment and cables. For example, during refrigerant ignition tests, it was found that video cameras needed frequent replacement due to the etching of lenses or corrosion of power and video cable connectors (AHRTI 9007-01, 2017).

AHRI (AHRI 8028, 2021) recently conducted research for firefighters and medical responders. The objective of the AHRI 8028 study was to compare the relative amount of heat and decomposition gases generated during a fire event for both A1 and A2L refrigerants. The AHRI study noted comparable amounts of heat generated ($< 5\ kW/m^2$) and HF gas was generated in the case of all fluorinated refrigerants applied. The study further noted that firefighters and medical first responders should always use the correct personal protective equipment (PPE), (i.e., safety equipment that protects responders from decomposition products during a fire situation). Although HF also applies to non-flammable fluorinated refrigerants that are involved in an external fire, flammable refrigerants can be ignited more easily than non-flammable ones. However, the RACHP safety standards consider only the flammability but not the toxicity of the decomposition products of ignited HFCs or HCFCs. The lower temperature limits of decomposition for some A1 and A2L refrigerants are listed in Table 3-7.

Table 3-7: Effects of temperature and humidity on decomposition temperature (JSRAE, 2016)

Refrigerant	**Lower temperature limit for refrigerant decomposition [°C]**	**Effect of humidity on refrigerant decomposition**
HFC-32	580-600	Very little
HFO-1234yf	560-580	Less decomposition in higher humidity
HFC-134a	610-640	Very little
HCFC-22	460-510	Very little
HFO-1123	400-420	Very little

3.5 Assessment of current and future refrigerants and their GWPs

Refrigerants that have been listed in ASHRAE Standard 34 and/or ISO 817 since 2010 are plotted in Figure 3-1 below. Each refrigerant is represented by a dot placed according to the normal boiling point and the 100-year GWP, and each refrigerant is labelled with its refrigerant number. For refrigerant blends that have a temperature glide, the glide at atmospheric pressure is given in brackets after the refrigerant number, and the normal boiling point is calculated as the average of the bubble and dew points. A few commonly used, older refrigerants are plotted as well, using white dots for ease of comparison. For the sake of creating an overview, new fluids with boiling points above 0 °C are not included in Figure 3-1.

From Figure 3-1, it can be seen that there is a trade-off between lowering GWP, having a low boiling point, and having a low temperature glide. R-466A is a notable exception amongst non-flammable refrigerants, with a GWP below 1,000 and a boiling point below -50 °C (see section 3.4.3 for a discussion of R-466A). It is also noted that non-flammable refrigerants generally have higher GWPs than flammable refrigerants.

These patterns arise because a low refrigerant boiling point, which is preferred in most applications, requires the use of relatively small molecules. McLinden (2017) screened more than 60 million chemical structures and found none to be ideal, hence in the refrigerant selection process, there is a need for trade-offs (Midgley 1937, Calm and Didion, 1997).

For a low boiling point, the required smaller size of the molecule leads to fewer molecules to choose from than for higher boiling points. A method to increase the number of options at lower boiling points, hence improving the chance of better matching the properties requested for a specific application, is to blend low boiling point fluids with higher boiling point fluids. However, blending a new refrigerant mixture from fluids with very different boiling points leads to a high temperature glide, which for most applications is not a desired property.

As no ideal refrigerant exists, it is expected that most future refrigerants will be mixtures of currently used refrigerant molecules in order to better match new and current applications while minimizing GWP. New molecules for application as refrigerants are likely to be proposed in the near future, but since none are ideal, each will come with pros and cons.

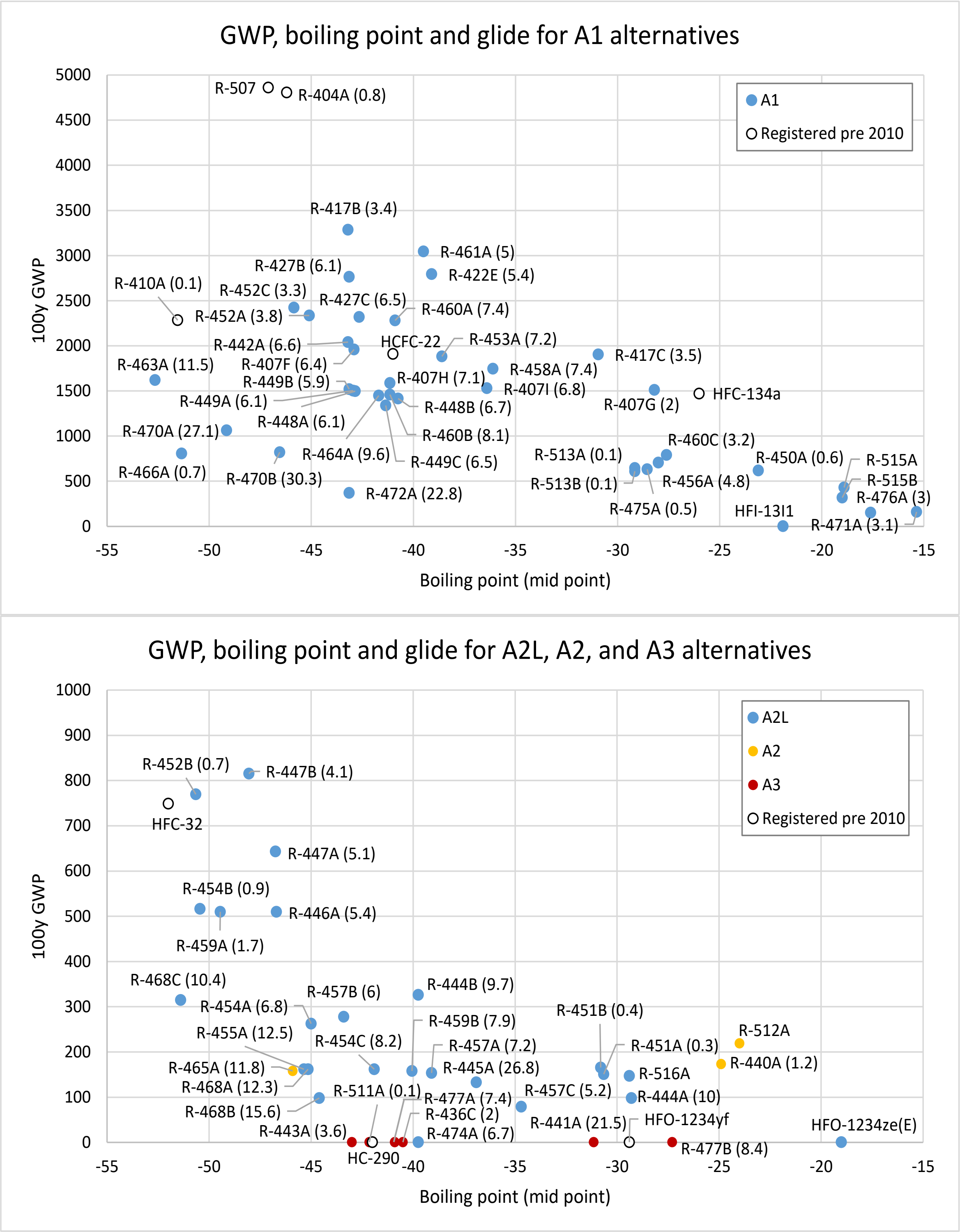

Figure 3-1: New refrigerants listed since 2010 according to flammability class, boiling point and 100y GWP. Glide is indicated in brackets where relevant. A few refrigerants listed prior to 2010 are shown as white dots for ease of comparison.

3.6 Background on refrigerant production, consumption, banks, emissions data

3.6.1 Availability of production and consumption data

CFC and HCFC (and some HFC) production and consumption data for dispersive uses are available from the UNEP Ozone Secretariat website, reported by countries that are parties to the Montreal Protocol under Article 7 of the Protocol. For most countries, HCFC data are available from 1995 to 2020. Under Article 7, HFC production, export, and import data are only available from parties that have ratified the Kigali Amendment, i.e., so far for the years 2019-2021 only. The data published by the Ozone Secretariat are aggregated into 3 groups (for CFCs, HCFCs, and HFCs) per country (or per region). The reported data by each country are for each individual fluorocarbon chemical, but these non-aggregated data are confidential.

Consumption data are not submitted by countries under Article 7. Consumption data are calculated via production, using the formula:

$$\text{consumption} = \text{production} - \text{exports} + \text{imports} - \text{destruction}$$

This even when reported destruction may lead to negative values since the amounts destroyed do not relate (there can be a significant delay in years) to the years for which the production, export, and import data are reported. This also implies that certain annual consumption data have uncertainties, e.g., imports may be stockpiled and not used in the same year as they are reported, etc.

Article 7 reported data do not give sector-specific consumption information. Some compounds are only used in specific applications and the Article 7 data can be mapped to them. For example, HCFC-142b is virtually only used for foam production and HFC-143a is only used as a blend component for the refrigerants R-404A and R-507A. However, other compounds are used in many applications and the Article 7 data are therefore harder to interpret. For example, HFC-134a is used in aerosols, foam production, and several different RACHP applications.

For all Article 5 parties, data on sector specific HCFC consumption are available from HCFC Phaseout Management Plan (HPMP) reports and other work carried out via the Multilateral Fund (MLF). Sector-specific HFC consumption data are now also available for some Article 5 parties from ODS alternative survey studies funded by the MLF, as well as from other surveys, such as the one done by the CCAC (Climate and Clean Air Coalition). Article 5 parties will soon begin planning for their HFC phasedown via MLF-funded Kigali Implementation Plan (KIP) studies. These should provide useful information on the sector-specific usage of HFCs.

Non-Article 5 parties cannot carry out funded HPMP or KIP studies, although some countries publish useful reports on HCFC and HFC consumption. For example, the EU publishes detailed HFC consumption data on an annual basis to monitor progress toward their HFC phasedown targets. These reports include estimates of sector specific HFC use. Certain data on HFC usage and HFC emissions from non-Article 5 parties is also available from annual reports on GHG use and emissions submitted to the UNFCCC.

3.6.2 Estimating refrigerant banks and emissions

To develop policies to phase down the use of HFCs it is important to understand the markets that use and emit HFCs and the options to switch to lower GWP alternative gases and to reduce leakage during operation as well as the end-of-life HFC emissions. Part of this has already been done during the last 5-10-years for HCFCs, in both non-Article 5 and Article 5 parties.

Given the lack of comprehensive and sector-specific HCFC and HFC consumption data, the best approach is the use of “bottom-up stock models”. This bottom-up approach to modelling is described in Section 3.7

3.7 Modelling consumption, inventories (banks) and emissions

3.7.1 General approach to bottom-up stock modelling

A number of bottom-up stock models (also referred to as “Vintaging Models”) have been used in the past or are in current use. These models all use a similar approach that includes the following elements:

1) The market being analysed is split into a suitable set of sectors and sub-sectors. For RACHP models, each sub-sector is represented by a nominal piece of equipment with a specified design and size; e.g., a sub-sector could be residential split air-conditioners, represented by one with a cooling capacity of 3.5 kW (or 1 TR in the USA). Given the complexity of the RACHP market, it is important that there are sufficient sub-sectors used to ensure that the bottom-up analysis is realistic.
2) Each market sub-sector is analysed at regular intervals – most models use annual analysis.
3) All models make a “historic analysis” (e.g., over the last 25 years), to create an inventory of the current stock of equipment in each sub-sector.
4) Some models provide a “forecast analysis” e.g., for the next 25 years, to evaluate future scenarios that can represent, for example, different pathways to an HFC phasedown.
5) The stock of equipment (i.e., number of items of equipment) is estimated each year. This is based on available market information which yields the number of new systems added each year and the number of old systems retiring.
6) Data are collected (or assumptions are made) about key factors in each sub-sector such as:
    - typical refrigerant charge per equipment item
    - refrigerant choices in new equipment (these change over time as new refrigerants become available in response to HCFC phaseout and HFC phasedown)
    - equipment life
    - average leakage rates during the operational life
    - end-of-life refrigerant emission rates.
7) These factors can be varied for each year in a modelling analysis. For example, the refrigerant choice for new car air-conditioners might have been CFC-12 until 1995, HFC-134a from 1996 to 2020 and then from 2017, there could have been started a transition to HFO-1234yf over a longer period until a complete HFO use in this equipment will have been reached.
8) This type of modelling can create many useful outputs such as:
    - estimates of refrigerant banks in each sub-sector, split by refrigerant type

- estimates of the total consumption of refrigerant in each sub-sector, split between requirements for installation of new equipment and servicing of existing equipment
- estimates of refrigerant emissions from each sub-sector, split between leaks during operation, emissions at end-of-life, and other emissions e.g., during equipment manufacture and installation.

The overall accuracy of bottom-up stock models can be confirmed by comparing the modelled estimates of refrigerant consumption with “top-down” data such as the Article 7 data reported to the Ozone Secretariat (as described in Section 3.6) and certain indications of emissions from atmospheric measurements of gas concentrations. However, confirming the accuracy of sector-specific estimates is more difficult as the top-down data and atmospheric concentrations give no indication of any sector-specific consumption or emissions.

In the following sections, a description is given of the RIEP, the EPA bottom-up, and the HFC model (all three models are proprietary). A description is also given of the Velders and the Lickley models, which use different modelling techniques.

3.7.2 The RIEP model

The Center of Energy Studies in Paris (under D. Clodic) developed a vintage model ‘RIEP’ (Refrigerant Inventory and Emissions Provision) in the 1990s. This model considered a number of regions (EU, North America, a number of developing countries and developing country regions), where the total of all countries and regions would yield the global consumption, as well as the global banks and emissions. The model included CFCs, HCFCs, HFCs, ammonia, and hydrocarbons. Palandre (2002) described the method of calculation and the approaches used for six important RACHP sub-sectors: domestic, commercial, industrial, transport, stationary AC, and mobile AC (MAC). The RIEP model does not use a refined subdivision of the six main sectors, but the overall estimates are reasonable, based on the fact that comparisons with top-down refrigerant data (i.e., from a comparison with AFEAS and the Ozone Secretariat Article 7 data) gave satisfactory results.

On the basis of what was described in 2002, calculations were made for the IPCC/TEAP report (IPCC/TEAP, 2005) for demand, inventories, and emissions. This concerned the years 2002, 2008 and 2015 for two scenarios (a business-as-usual and a mitigation scenario). Results for the RACHP sector have been given in the Supplement to the IPCC TEAP report (IPCC/TEAP, 2005a), and have been used in many reports after 2005, together with estimates of inventories and emissions for foams, aerosols, and fire suppressants.

In 2011, a study was done by Armines-CEP (Clodic, 2011) on “Previsions on banks and emissions from 2006 to 2030 for the European Union”, followed by studies for inventories and emissions for the countries Thailand and Mexico. In 2013, Barrault et al. (2013) published a summary of what an open RIEP model could accomplish, together with a description of the essential features of the model.

The RIEP program has been used to calculate various scenarios for HFC consumption, inventories, and emissions for non-Article 5 and Article 5 regions in the TEAP XXVII/4 report (UNEP, 2016b), which formed the basis for the TEAP ExIII.1 report (TEAP, 2016a) that was published before the Kigali negotiations in 2016 and dealt with various climate benefit scenarios.

The RIEP program has not been used for any major calculation efforts after 2016. The latest 2010 model version would have to be updated under the auspices of Armines, Paris (Zhoughaib, 2019), which does not seem likely.

3.7.3 The US EPA model

National model

The US EPA employs its "Vintaging Model" to estimate US emissions of HFCs and other alternatives to ozone-depleting substances (ODS) at the national level. The model basically conforms to the general structure of a "bottom-up" model described above in 3.7.1, including historical information and future projections. In addition to the refrigeration and air-conditioning sector, the model estimates emissions from the foams, aerosols, solvents, and fire-extinguishing sectors. Within these sectors, there are 78 independently modelled end-uses. As described above, such bottom-up models require myriad information, including:

a) Market size and growth for each of the end-uses
b) A history of the market transition from ODS to alternatives
c) Characteristics of each end-use such as charge sizes, emission profiles, etc.

In this way, the US EPA models the use of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of refrigerant required to manufacture and/or maintain the equipment. The US EPA Vintaging Model makes use of this market information to build an inventory of the in-use stocks of the equipment and ODS and HFC in each of the end-uses. The simulation is a "business-as-usual" baseline case and does not incorporate measures to reduce or eliminate the emissions of these gases other than those regulated by US law or otherwise common in the industry.

Comparisons to top-down analyses have been performed for several years. The model's estimate of annual HFC supply (across all sectors, not just RACHP) has been compared to information from US EPA's mandatory Greenhouse Gas Reporting Program (GHGRP). Total HFC supply in bulk (production plus import less export) as well as supply in pre-charged RACHP equipment and closed-cell foams from the GHGRP are each aggregated annually, and the total is compared to the Vintaging Model estimates. Beginning with the 2022 Inventory (covering 1990-2020 emissions), top-down atmospheric inversions of four HFCs are compared to the Vintaging Model (US EPA, 2022).

Global model

Rather than repeating a bottom-up analysis, the US EPA estimated consumption and emissions of HFCs in other countries by utilizing the US-based Vintaging Model and historical ODS consumption data reported to the Ozone Secretariat and HFC consumption data determined by the Multilateral Fund. This was done prior to the reporting of HFCs initiated as part of the requirements under the Kigali Amendment.

In developing these estimates for other countries, the US EPA initially assumed that the transition from ODSs to HFCs follows the same substitution patterns as the United States. The U.S.-based substitution scenarios were then customized to each region or country using adjustment factors that take into consideration differences in historical and projected economic growth, the timing of the ODS phaseout, the type of alternatives employed, the relative amount of recovery and re-use of refrigerants, and the distribution of ODSs across end uses in each region or country (US EPA, 2019).

3.7.4 The HFC model used by UNEP

A specific HFC model has been developed over the last 10 years on behalf of EPEE (an EU Trade Association that represents major RACHP) and UNEP. The model was originally developed for EPEE in 2012 to assess pathways to phasedown the HFC consumption in the EU. The model has since been further developed (HFC Outlook, 2021) with support from UNEP to:

a) Provide a platform for Article 5 parties to develop a country model to fully understand their HCFC phaseout and HFC phasedown options. By the end of 2021, models following this approach had been created for ten Article 5 parties[15].

b) To provide detailed estimates of the energy use and related emissions from RACHP sectors. This additional modelling capability provides a comparison of the direct refrigerant emissions with the indirect energy-related emissions from the RACHP sector.

This HFC model is a sophisticated bottom-up stock model using over 40 RACHP technology sectors to provide good granularity. The model also has sectors for non-RACHP applications including foams, aerosols, and MDIs. The model makes historic estimates over the 30 years period 1990-2020 and forecasts for the next 30 years, up to the year 2050. All relevant pure fluids and blends are modelled including CFCs, HCFCs, HFCs, HFOs, ammonia, CO_2, and hydrocarbons.

The bottom-up equipment stock model uses a single stock growth estimate for each technology sector between 1990 and 2020 and a set of 3 different growth forecasts for the 2020-2050 period. The same stock model is used for both refrigerant and energy consumption estimates.

This HFC bottom-up model (HFC Outlook, 2021) provides a wide range of outputs for individual technologies or for the whole market. These outputs include:

a) Refrigerant bank, consumption, demand[16], and direct GHG emissions, available for each refrigerant.

b) Energy use and indirect GHG emissions

c) Comparison of direct and indirect emissions

d) Estimates of fossil-fuel emission reductions created using heat pumps.

3.7.5 The Velders model

The Velders model (Velders et al., 2015) uses a different modelling approach to the bottom-up stock models described in sections 3.7.2 to 3.7.4.

The principal information sources are:

a) Historical HFC consumption data by sector for developed countries derived from their United Nations Framework Convention on Climate Change (UNFCCC) National Inventory Submissions

b) Historical HFC consumption data for China with some additional data for other developing countries

c) Data for historical HCFC consumption from Montreal Protocol Article 7 reports

d) Scenarios of Gross Domestic Product (GDP) and population from UNFCCC Shared Socioeconomic Pathway (SSP) projections

e) Observed atmospheric abundances of HFCs from 1990 to 2013 were used as constraints on the historical consumption data.

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[15] Article 5 parties for which HFC Outlook models have been made: Bahrain, Bosnia & Herzegovina, Dominican Republic, Gabon, Guatemala, Honduras, Kuwait, Mali, Senegal, Sri Lanka

[16] Refrigerant demand = consumption of bulk refrigerant (as defined in Montreal Protocol targets) plus the refrigerant contained in imported pre-charged RACHP equipment. Imported equipment usually is an important part of the bank of refrigerant in a country, hence it is essential to model this. So, the demand is not equal to consumption under the Montreal Protocol.

From these datasets HFC consumption is derived from 1990 to 2050 for 11 countries/regions, for 13 separate uses, and for 10 HFCs (-32, -125, -134a, -143a, -152a, -227ea, -236fa, -245fa, -365mfc, and -43-10mee).

The UNFCCC prescribes guidelines for reporting total greenhouse gas emissions. For the Velders model, the detailed underlying inventory information on stocks provides a consistent time series of HFC use by sector and a starting point for projections, especially when constrained by atmospheric measurements. Developed countries annually submit emissions and activity data to the UNFCCC as part of their National Inventory Submission, which can be used in the model. UNFCCC data are not available for developing countries, which historically have a much smaller HFC consumption than developed countries. However, in recent years HFC production and consumption have increased rapidly, particularly in China. Chinese HFC consumption is reported by several authors for 2005-2009 and for 2010-2012 showing increases of 20 to 40 % per year and is used for analysis in the Velders model. In other developing countries, the model only takes into account historical HFC consumption for mobile AC and for domestic refrigeration.

The HFC consumption in developed countries starts with the historical HFC consumption as derived from the UNFCCC data for each country from 1990 to 2011. In the model forecasts a replacement pattern is used. 50 % of HCFC-141b and -142b is replaced by HFCs and 50 % by low GWP alternatives. Also, 90 % of HCFC-22 is replaced by HFCs and 10 % by low GWP alternatives. This holds for the whole period to 2050.

Emissions are calculated for each sector and region from the HFC consumption data and for emission factors using a box model that can be constrained by observed atmospheric abundances of individual HFCs as well as HFC atmospheric lifetimes that account for the chemical removal of HFCs from the atmosphere. It will be clear that the emissions inferred from observed abundances and those derived from reported country data both have uncertainties.

Results of the 2015 Velders modelling approach have been published in the 2018 Science Assessment Report (WMO, 2018). The model and the input data have been updated as given in (Velders, 2022) and they are used to calculate results which are published in the 2022 Science Assessment Report.

3.7.6 The Lickley Bayesian-based model

Two recent publications describe a Bayesian analysis of banks (Lickley et al., 2020, Lickley et al., 2021). Banks are estimated by developing initial (prior) estimates where production is associated with the application and the product or equipment type using bottom-up reported data and scaled to match Montreal Protocol Article 7 reported data. Leakage rates from products and equipment follow previously published estimates, as e.g., in the 2006 IPCC guidelines and updates. Large uncertainties for production and release rates are accounted for. The above values and their uncertainties, along with time-varying atmospheric lifetime priors, are then used to simultaneously simulate initial distributions over time of banks, emissions, and atmospheric concentrations, which are then updated (conditioned) on observed atmospheric concentrations by applying Bayes' rule. The result is a final (posterior) distribution of banks by product and equipment type, along with an updated estimate of release rates and production for each product and equipment type that are statistically consistent with the observed concentrations. The Lickley method has so far been mainly applied for an analysis of the size of CFC and HCFC banks and emissions (CFC-11, HCFC-141b in foam, CFC-12, CFC-113 etc.).

3.7.7 Comparison of the RIEP, HFC Outlook, US EPA and Velders and Lickley models

It is clear that the bottom-up models given above have many common ways of looking at consumption and emissions. However, the Velders model is mainly based on historical consumption data, GDP data, plus China consumption data and atmospheric abundances; it has therefore a set of input data that cannot be compared to the usual bottom-up data based on equipment data, exports, imports, etc. The Lickley model uses a different mix of data. On the basis of atmospheric data and specific overall information usage patterns, it matches data to come to banks and emission estimates (where these can only be global, of course).

Where there have been requests to compare the outcome of all these models, it is definitely possible to do so. However, the analysis of the differences in banks and emissions values (related to different time frames) would require major efforts. The conclusion now is that this cannot be addressed in an RTOC assessment report, and it should be left to separate studies, which are assumed to give new useful input over the next four years.

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ANNEX I to Refrigerants

This annex lists all refrigerants from ASHRAE Standard 34 and/or ISO 817. Table 3.I-1 covers single component refrigerants, while Table 3.I-2 covers refrigerant blends, and Table 3.I-3 azeotropic refrigerant blends.

GWP and ODP values according to (WMO, 2022), which the exception of data for HE-E170, which is taken from (UNEP, 2019) (originally based on (IPCC, 2007)). The GWP 100-year and ODP values from the Montreal Protocol are also listed where available.

Table 3.I-1: Data summary for single component refrigerants

Refrigerant Designation	Chemical Formula	Chemical Name	Molecular Weight (kg/kmol)	Boiling Point (°C)	Safety Class	Atmospheric Lifetime (Years)	Radiative Efficiency (W/m/ppm)	GWP 100-year	GWP 20-year	ODP	GWP 100-yr in Montreal Protocol[a]	ODP in Montreal Protocol
Methane Series												
CFC-11	CCl_3F	trichlorofluoromethane	137,4	24	A1	52	0.299	6 410	8 560	1	4 750	1
CFC-12	CCl_2F_2	dichlorodifluoromethane	120,9	–30	A1	102	0.358	12 500	12 700	0.75	10 900	1
BCFC-12B1	$CBrClF_2$	bromochlorodifluoromethane	165,4	–4		16	0.31	1 990	5 080	7.1		3
CFC-13	$CClF_3$	chlorotrifluoromethane	104,5	–81	A1	640	0.279	16 300	12 400	0.3		1
BFC-13B1	$CBrF_3$	bromotrifluoromethane	148,9	–58	A1	72	0.309	7 430	8 580	17		10
IFC-13I1	CF_3I	trifluoroiodomethane	195,9	–21.9	A1	<5 days	0.067	<1	1	<0.09		
PFC-14	CF_4	tetrafluoromethane (carbon tetrafluoride)	88	–128	A1	50	0.1	7 490	5 380			
HCFC-21	$CHCl_2F$	dichlorofluoromethane	102,9	9	B1	1.71	0.145	161	578	0.036	151	0.04
HCFC-22	$CHClF_2$	chlorodifluoromethane	86,5	–41	A1	11.6	0.214	1 910	5 610	0.038	1 810	0.055
HFC-23	CHF_3	trifluoromethane	70	–82	A1	228	0.192	14 700	12 400		14 800	
HCC-30	CH_2Cl_2	dichloromethane (methylene chloride)	84,9	40	B1	176 days	0.0287	11	39			
HCFC-31	CH_2ClF	chlorofluoromethane	68,5	–9		1.29	0.068	85	307	0.019		0.02
HFC-32	CH_2F_2	difluoromethane (methylene fluoride)	52	–52	A2L	5.27	0.111	749	2 620		675	
HCC-40	CH_3Cl	chloromethane (methyl chloride)	50,5	–24	B2	0.9	4.66E-03	6	20	0.015		
HFC-41	CH_3F	fluoromethane (methyl fluoride)	34	–78		2.8	0.025	137	492		92	

Refrigerant Designation	Chemical Formula	Chemical Name	Molecular Weight (kg/kmol)	Boiling Point (°C)	Safety Class	Atmospheric Lifetime (Years)	Radiative Efficiency (W/m/ppm)	GWP 100-year	GWP 20-year	ODP	GWP 100-yr in Montreal Protocol[a]	ODP in Montreal Protocol
HC-50	CH_4	methane	16	–161	A3	11.8	3.89E-04	29.8	82.5			
Ethane Series												
CFC-113	CCl_2FCClF_2	1,1,2-trichloro-1,2,2-trifluoroethane	187,4	48	A1	93	0.302	6 530	6 870	0.82	6 130	0.8
CFC-114	$CClF_2CClF_2$	1,2-dichloro-1,1,2,2-tetrafluoromethane	170,9	4	A1	189	0.315	9 450	8 280	0.53	10 000	1
CFC-115	$CClF_2CF_3$	Chloropentafluoroethane	154,5	–39	A1	540	0.247	9 630	7 430	0.45	7 370	0.6
PFC-116	CF_3CF_3	hexafluoroethane	138	–78	A1	10	0.264	12 600	9 040			
HCFC-123	$CHCl_2CF_3$	2,2-dichloro-1,1,1-trifluoroethane	152,9	27	B1	1.31	0.16	91	329	0.02	77	0.02
HCFC-124	$CHClFCF_3$	2-chloro-1,1,1,2-tetrafluoroethane	136,5	–12	A1	5.9	0.207	596	2 060	0.022	609	0.022
HFC-125	CHF_2CF_3	pentafluoroethane	120	–49	A1	30.7	0.234	3 820	6 790		3 500	
HFC-134a	CH_2FCF_3	1,1,1,2-tetrafluoroethane	102	–26	A1	13.5	0.167	1 470	4 060		1 430	
HCFC-141b	CH_3CCl_2F	1,1-dichloro-1-fluoroethane	116,9	32		8.81	0.161	808	2 590	0.102	725	0.11
HCFC-142b	CH_3CClF_2	1-chloro-1,1-difluoroethane	100,5	–10	A2	17.1	0.194	2 190	5 400	0.057	2 310	0.065
HFC-143a	CH_3CF_3	1,1,1-trifluoroethane	84	–47	A2L	51.8	0.169	5 900	7 900		4 470	
HFC-152a	CH_3CHF_2	1,1-difluoroethane	66,1	–24	A2	1.5	0.101	153	550		124	
HFC-161[b]	CH_3CH_2F	fluoroethane	48,1	–38	A2	0.217	0.016	5	17			
HC-170	CH_3CH_3	ethane	30,1	–89	A3	76 days	1.61E-03	<1	3			
Ethers												
HE-E170	CH_3OCH_3	dimethyl Ether	46,1	–25	A3	0.015	0.02	1	1			
Propane Series												
PFC-218	$CF_3CF_2CF_3$	octafluoropropane	188	–37	A1	2.6	0.276	9 500	6 920			
HFC-227ea	CF_3CHFCF_3	1,1,1,2,3,3,3-heptafluoropropane	170	–15.6	A1	35.8	0.273	3 580	5 830		3 220	
HFC-236fa	$CF_3CH_2CF_3$	1,1,1,3,3,3-hexafluoropropane	152	–1	A1	213	0.263	9 120	7 820		9 810	
HFC-245fa	$CHF_2CH_2CF_3$	1,1,1,3,3-pentafluoropropane	134	15	B1	7.74	0.251	966	3 190		1 030	
HC-290	$CH_3CH_2CH_3$	propane	44,1	–42	A3	15 days	3.96E-04	<<1	<<1			
Cyclic Organic Compounds												

Refrigerant Designation	Chemical Formula	Chemical Name	Molecular Weight (kg/kmol)	Boiling Point (°C)	Safety Class	Atmospheric Lifetime (Years)	Radiative Efficiency (W/m/ppm)	GWP 100-year	GWP 20-year	ODP	GWP 100-yr in Montreal Protocol[a]	ODP in Montreal Protocol
PFC-C318	$-(CF_2)_4-$	octafluorocyclobutane	200	–6	A1	3.2	0.328	10 600	7 740			
Hydrocarbons												
HC-600	$CH_3CH_2CH_2CH_3$	butane	58,1	0	A3	6.5 days	2.60E-04	<<1	<<1			
HC-600a	$CH(CH_3)_2CH_3$	isobutane	58,1	–12	A3	7.0 days	2.87E-04	<<1	<<1			
HC-601	$CH_3CH_2CH_2CH_2CH_3$	pentane	72,2	36.1	A3	4.0 days	2.11E-04	<<1	<<1			
HC-601a	$CH(CH_3)_2CH_2CH_3$	isopentane	72,2		A3	3.9 days	2.57E-04	<<1	<<1			
Oxygen compounds												
HE-610	$CH_3CH_2OCH_2CH_3$	ethyl ether	74,1	35								
R-611	$HCOOCH_3$	methyl formate	60,1	32	B2	86 days	4.90E-02	13	46			
Nitrogen Compounds												
R-630	CH_3NH_2		31,1	–7								
R-631	$CH_3CH_2(NH_2)$		45,1	17								
Inorganic Compounds												
R-702	H_2	hydrogen	2	–253	A3							
R-704	He	helium	4	–269	A1							
R-717	NH_3	ammonia	17	–33	B2L	days	0.0014	<<1	<1			
R-718	H_2O	water	18	100	A1							
R-720	Ne	neon	20,2	–246	A1							
R-728	N_2	nitrogen	28	–196	A1							
R-732	O_2	oxygen	32	–183								
R-740	Ar	argon	39,9	–186	A1							
R-744	CO_2	carbon dioxide	44	–78[c]	A1			1	1			
R-744A	N_2O	nitrous oxide	44	–90		109	3.20E-03	273	273	0.017		
R-764	SO_2	sulphur dioxide	64,1	–10	B1							
Unsaturated Organic Compounds												

Refrigerant Designation	Chemical Formula	Chemical Name	Molecular Weight (kg/kmol)	Boiling Point (°C)	Safety Class	Atmospheric Lifetime (Years)	Radiative Efficiency (W/m/ppm)	GWP 100-year	GWP 20-year	ODP	GWP 100-yr in Montreal Protocol[a]	ODP in Montreal Protocol
HCC-1130(E)	$CHCl=CHCl$	trans-1,2-dichloroethene	96,9	47.7	B1	5.5 days	5.15E-03	<<1	<1	<0.0003		
HFO-1132(E)	$CHF=CHF$	trans-1,2-difluoroethene	64	–52.5	B2	1.3 days	2.46E-03	<<1	<<1			
HFO-1132a	$CF_2=CH_2$	1,1-difluoroethylene	64	–83	A2	4.6 days	4.32E-03	<<1	<1			
HC-1150	$CH_2=CH_2$	ethene (ethylene)	28,1	–104	A3	1.7 days	7.75E-04	<<1	<<1			
HCFO-1224yd(Z)	$CF_3CF=CHCl$	(Z)-1-chloro-2,3,3,3-tetrafluoropropene	148,5	14.5	A1	12 days	0.0335	<1	2			
HCFO-1233zd(E)	$CF_3CH=CHCl$	trans-1-chloro-3,3,3-trifluoro-1-propene	130,5	18.1	A1	41.9 days	0.0651	4	14	<0.0004		
HFO-1234yf	$CF_3CF=CH_2$	2,3,3,3-tetrafluoro-1-propene	114	–29.4	A2L	12 days	0.0268	<1	2			
HFO-1234ze(E)	$CF_3CH=CHF$	trans-1,3,3,3-tetrafluoro-1-propene	114	–19.0	A2L	19 days	0.0459	1	5			
HC-1270	$CH_3CH=CH_2$	propene (propylene)	42,1	–48	A3	0.4 days	1.65E-04	<<1	<<1			
HFO-1336mzz(E)	$CF_3CH=CHCF_3$	trans-1,1,1,4,4,4-hexafluoro-2-butene	164,1	7.4	A1	121 days	0.193	26	94			
HFO-1336mzz(Z)	$CF_3CH=CHCF_3$	cis-1,1,1,4,4,4-hexafluoro-2-butene	164,1	33.4	A1	27 days	0.0809	2	9			

[a] The annexes of the Montreal Protocol contains values for ODP and 100-year GWP for the regulated substances only.
[b] HFC-161 is discussed in this report, but not listed in ASHRAE Standard 34 nor in ISO 817.
[c] R-744 sublimates at -78 °C and does not have a boiling point at 1 atm.

Table 3.I-2: Data summary for zeotropic refrigerant blends

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	Safety Class	GWP 100-year	GWP 20-year	ODP	GWP 100-year in Montreal Protocol	ODP in Montreal Protocol
R-400	R-12/114 (50.0/50.0)	141.6		A1	10 975	10 490	0.64	10 450	1
R-400	R-12/114 (60.0/40.0)	136.9		A1	11 280	10 932	0.66	10 540	1
R-401A	R-22/152a/124 (53.0/13.0/34.0)	94.4	–34.4/–28.8	A1	1 235	3 745	0.028	1 182	0.037
R-401B	R-22/152a/124 (61.0/11.0/28.0)	92.8	–35.7/–30.8	A1	1 349	4 059	0.029	1 288	0.040
R-401C	R-22/152a/124 (33.0/15.0/52.0)	101	–30.5/–23.8	A1	963	3 005	0.024	933	0.030
R-402A	R-125/290/22 (60.0/2.0/38.0)	101.5	–49.2/–47.0	A1	3 018	6 206	0.014	2 788[a]	0.021
R-402B	R-125/290/22 (38.0/2.0/60.0)	94.7	–47.2/–44.9	A1	2 598	5 946	0.023	2 416[a]	0.033
R-403A	R-290/22/218 (5.0/75.0/20.0)	92	–44.0/–42.3	A2	3 333	5 592	0.029	1 358[a]	0.041
R-403B	R-290/22/218 (5.0/56.0/39.0)	103.3	–43.8/–42.3	A1	4 775	5 840	0.021	1 014[a]	0.031
R-404A	R-125/143a/134a (44.0/52.0/4.0)	97.6	–46.6/–45.8	A1	4 808	7 258		3 922	
R-405A	R-22/152a/142b/C318 (45.0/7.0/5.5/42.5)	111.9	–32.9/–24.5	ND	5 496	6 150	0.02	950[a]	0.028
R-406A	R-22/600a/142b (55.0/4.0/41.0)	89.9	–32.7/–23.5	A2	1 948	5 300	0.044	1 943[a]	0.057
R-407A	R-32/125/134a (20.0/40.0/40.0)	90.1	–45.2/–38.7	A1	2 266	4 864		2 107	
R-407B	R-32/125/134a (10.0/70.0/20.0)	102.9	–46.8/–42.4	A1	3 043	5 827		2 804	
R-407C	R-32/125/134a (23.0/25.0/52.0)	86.2	–43.8/–36.7	A1	1 892	4 411		1 774	
R-407D	R-32/125/134a (15.0/15.0/70.0)	91	–39.4/–32.7	A1	1 714	4 254		1 627	
R-407E	R-32/125/134a (25.0/15.0/60.0)	83.8	–42.8/–35.6	A1	1 642	4 110		1 552	
R-407F	R-32/125/134a (30.0/30.0/40.0)	82.1	–46.1/–39.7	A1	1 959	4 447		1 825	
R-407G	R-32/125/134a (2.5/2.5/95.0)	100	–29.2/–27.2	A1	1 511	4 092		1 463	
R-407H	R-32/125/134a (32.5/15.0/52.5)	79.1	–44.7/–37.6	A1	1 588	4 002		1 495	
R-407I	R-32/125/134a (19.5/8.5/72.0)	86.9	–39.8/–33.0	A1	1 529	4 011		1 459	
R-408A	R-125/143a/22 (7.0/46.0/47.0)	87	–45.5/–45.0	A1	3 879	6 746	0.018	3 152	0.026
R-409A	R-22/124/142b (60.0/25.0/15.0)	97.4	–35.4/–27.5	A1	1 624	4 691	0.037	1 585	0.048

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	Safety Class	GWP 100-year	GWP 20-year	ODP	GWP 100-year in Montreal Protocol	ODP in Montreal Protocol
R-409B	R-22/124/142b (65.0/25.0/10.0)	96.7	–36.5/–29.7	A1	1 610	4 702	0.036	1 560	0.048
R-410A	R-32/125 (50.0/50.0)	72.6	–51.6/–51.5	A1	2 285	4 705		2 088	
R-410B	R-32/125 (45.0/55.0)	75.6	–51.5/–51.4	A1	2 438	4 914		2 229	
R-411A	R-1270/22/152a (1.5/87.5/11.0)	82.4	–39.7/–37.2	A2	1 688	4 969	0.033	1 597[a]	0.048
R-411B	R-1270/22/152a (3.0/94.0/3.0)	83.1	–41.6/–41.3	A2	1 800	5 290	0.036	1 705[a]	0.052
R-412A	R-22/218/142b (70.0/5.0/25.0)	92.2	–36.4/–28.8	A2	2 360	5 623	0.041	1 845[a]	0.055
R-413A	R-218/134a/600a (9.0/88.0/3.0)	104	–29.3/–27.6	A2	2 149	4 196		1 258[a]	
R-414A	R-22/124/600a/142b (51.0/28.5/4.0/16.5)	96.9	–34.0/–25.8	A1	1 505	4 339	0.035	1 478[a]	0.045
R-414B	R-22/124/600a/142b (50.0/39.0/1.5/9.5)	101.6	–34.4/–26.1	A1	1 396	4 121	0.033	1 362[a]	0.042
R-415A	R-22/152a (82.0/18.0)	81.9	–37.5/–34.7	A2	1 594	4 699	0.031	1 507	0.045
R-415B	R-22/152a (25.0/75.0)	70.2	–27.7/–26.2	A2	592	1 815	0.0095	546	0.014
R-416A	R-134a/124/600 (59.0/39.5/1.5)	111.9	–23.4/–21.8	A1	1 103	3 209	0.0087	1 084[a]	0.009
R-417A	R-125/134a/600 (46.6/50.0/3.4)	106.7	–38.0/–32.9	A1	2 515	5 194		2 346[a]	
R-417B	R-125/134a/600 (79.0/18.3/2.7)	113.1	–44.9/–41.5	A1	3 287	6 107		3 027[a]	
R-417C	R-125/134a/600 (19.5/78.8/1.7)	103.7	–32.7/–29.2	A1	1 903	4 523		1 809[a]	
R-418A	R-290/22/152a (1.5/96.0/2.5)	84.6	–41.2/–40.1	A2	1 837	5 399	0.036	1 741[a]	0.053
R-419A	R-125/134a/E170 (77.0/19.0/4.0)	109.3	–42.6/–36.0	A2	3 221	6 000		2 967[a]	
R-419B	R-125/134a/E170 (48.5/48.0/3.5)	105.2	–37.4/–31.5	A2	2 558	5 242		2 384[a]	
R-420A	R-134a/142b (88.0/12.0)	101.8	–25.0/–24.2	A1	1 556	4 221	0.0068	1 536	0.008
R-421A	R-125/134a (58.0/42.0)	111.7	–40.8/–35.5	A1	2 833	5 643		2 631	
R-421B	R-125/134a (85.0/15.0)	116.9	–45.7/–42.6	A1	3 468	6 381		3 190	
R-422A	R-125/134a/600a (85.1/11.5/3.4)	113.6	–46.5/–44.1	A1	3 420	6 245		3 143[a]	
R-422B	R-125/134a/600a (55.0/42.0/3.0)	108.5	–40.5/–35.6	A1	2 718	5 440		2 526[a]	
R-422C	R-125/134a/600a (82.0/15.0/3.0)	113.4	–45.3/–42.3	A1	3 353	6 177		3 085[a]	

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	Safety Class	GWP 100-year	GWP 20-year	ODP	GWP 100-year in Montreal Protocol	ODP in Montreal Protocol
R-422D	R-125/134a/600a (65.1/31.5/3.4)	109.9	–43.2/–38.4	A1	2 950	5 699		2 729[a]	
R-422E	R-125/134a/600a (58.0/39.3/2.7)	109.3	–41.8/–36.4	A1	2 793	5 534		2 592[a]	
R-423A	R-134a/227ea (52.5/47.5)	126	–24.2/–23.5	A1	2 472	4 901		2 280	
R-424A	R-125/134a/600a/600/601a (50.5/47.0/0.9/1.0/0.6)	108.4	–39.1/–33.3	A1	2 620	5 337		2 440[a]	
R-425A	R-32/134a/227ea (18.5/69.5/12)	90.3	–38.1/31.3	A1	1 590	4 006		1 505	
R-426A	R-125/134a/600/601a (5.1/93.0/1.3/0.6)	101.6	–28.5/–26.7	A1	1 562	4 122		1 508[a]	
R-427A	R-32/125/143a/134a (15.0/25.0/10.0/50.0)	90.4	–43.0/–36.3	A1	2 392	4 911		2 138	
R-427B	R-32/125/143a/134a (20.6/25.6/19.0/34.8)	85	–46.2/–40.1	A1	2 765	5 192		2 382	
R-427C	R-32/125/143a/134a (25.0/25.0/10.0/40.0)	83.3	–45.9/–39.4	A1	2 320	4 767		2 063	
R-428A	R-125/143a/290/600a (77.5/20.0/0.6/1.9)	107.5	–48.3/–47.5	A1	4 141	6 842		3 607[a]	
R-429A	R-E170/152a/600a (60.0/10.0/30.0)	50.8	–26.0/–25.6	A3	16	56		12[a]	
R-430A	R-152a/600a (76.0/24.0)	64	–27.6/–27.4	A3	117	418		94[a]	
R-431A	R-290/152a (71.0/29.0)	48.8	–43.1/–43.1	A3	45	160		36[a]	
R-432A	R-1270/E170 (80.0/20.0)	42.8	–46.6/–45.6	A3	1	1		[b]	
R-433A	R-1270/290 (30.0/70.0)	43.5	–44.6/–44.2	A3	1	1		[b]	
R-433B	R-1270/290 (5.0/95.0)	44	–42.7/–42.5	A3	1	1		[b]	
R-433C	R-1270/290 (25.0/75.0)	43.6	–44.3/–43.9	A3	1	1		[b]	
R-434A	R-125/143a/134a/600a (63.2/18.0/16.0/2.8)	105.7	–45.0/–42.3	A1	3 711	6 363		3 245[a]	
R-435A	R-E170/152a (80.0/20.0)	49	–26.1/–25.9	A3	31	111		25[a]	
R-436A	R-290/600a (56.0/44.0)	49.3	–34.3/–26.2	A3	1	1		[b]	
R-436B	R-290/600a (52.0/48.0)	49.9	–33.4/–25.0	A3	1	1		[b]	
R-436C	R-290/600a (95.0/5.0)	44.6	–41.5/–39.5	A3	1	1		[b]	
R-437A	R-125/134a/600/601 (19.5/78.5/1.4/0.6)	103.7	–32.9/–29.2	A1	1 899	4 511		1 805[a]	
R-438A	R-32/125/134a/600/601a (8.5/45.0/44.2/1.7/0.6)	99.1	–43.0/–36.4	A1	2 432	5 073		2 264[a]	

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	Safety Class	GWP 100-year	GWP 20-year	ODP	GWP 100-year in Montreal Protocol	ODP in Montreal Protocol
R-439A	R-32/125/600a (50.0/47.0/3.0)	71.2	–52.0/–51.8	A2	2 170	4 501		1 983[a]	
R-440A	R-290/134a/152a (0.6/1.6/97.8)	66.2	–25.5/–24.3	A2	173	603		144[a]	
R-441A	R-170/290/600a/600 (3.1/54.8/6.0/36.1)	48.3	–41.9/–20.4	A3	1	1.1		[b]	
R-442A	R-32/125/134a/152a/227ea (31.0/31.0/30.0/3.0/5.0)	81.8	–46.5/–39.9	A1	2 041	4 443		1 888	
R-443A	R-1270/290/600a (55.0/40.0/5.0)	43.5	–44.8/–41.2	A3	1	1		[b]	
R-444A	R-32/152a/1234ze(E) (12.0/5.0/83.0)	96.7	–34.3/–24.3	A2L	98	346		87[a]	
R-444B	R-32/1234ze(E)/152a (41.5/48.5/10)	72.8	–44.6/–34.9	A2L	327	1 145		293[a]	
R-445A	R-744/134a/1234ze(E) (6.0/9.0/85.0)	103.1	–50.3/–23.5	A2L	133	370		129[a]	
R-446A	R-32/1234ze(E)/600 (68.0/29.0/3.0)	62	–49.4/–44.0	A2L	510	1 783		459[a]	
R-447A	R-32/125/1234ze(E) (68.0/3.5/28.5)	63	–49.3/–44.2	A2L	643	2 021		582[a]	
R-447B	R-32/125/1234ze(E) (68.0/8.0/24.0)	63.1	–50.1/–46.0	A2L	815	2 326		739[a]	
R-448A	R-32/125/1234yf/134a/1234ze(E) (26.0/26.0/20.0/21.0/7.0)	86.3	–45.9/–39.8	A1	1 497	3 300		1 386[a]	
R-448B	R-32/125/1234yf/134a/1234ze(E) (21.0/21.0/20.0/31.0/7.0)	89.3	–44.1/–37.4	A1	1 415	3 235		1 320[a]	
R-449A	R-32/125/1234yf/134a (24.3/24.7/25.3/25.7)	87.2	–46.0/–39.9	A1	1 504	3 358		1 396[a]	
R-449B	R-32/125/1234yf/134a (25.2/24.3/23.2/27.3)	86.4	–46.1/–40.2	A1	1 519	3 419		1 411[a]	
R-449C	R-32/125/1234yf/134a (20.0/20.0/31.0/29.0)	90.3	–36.6/–44.6	A1	1 340	3 060		1 250[a]	
R-450A	R-1234ze(E)/134a (58/42)	108.7	–23.4/–22.8	A1	618	1 708		601[a]	
R-451A	R-1234yf/134a (89.8/10.2)	112.7	–30.8/–30.5	A2L	151	416		146[a]	
R-451B	R-1234yf/134a (88.8/11.2)	112.6	–31.0/–30.6	A2L	166	456		160[a]	
R-452A	R-1234yf/32/125 (30/11/59)	103.5	–47.0/–43.2	A1	2 336	4 295		2 139[a]	
R-452B	R-32/125/1234yf (67.0/7.0/26.0)	63.5	–51.0/–50.3	A2L	769	2 231		697[a]	
R-452C	R-32/125/1234yf (12.5/61.0/26.5)	101.9	–47.5/–44.2	A1	2 424	4 470		2 219[a]	
R-453A	R-32/125/134a/227ea/600/601a (20.0/20.0/53.8/5.0/0.6/0.6)	88.8	–42.2/–35.0	A1	1 884	4 358		1 765[a]	
R-454A	R-32/1234yf (35.0/65.0)	80.5	–48.4/–41.6	A2L	263	918		236[a]	

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	Safety Class	GWP 100-year	GWP 20-year	ODP	GWP 100-year in Montreal Protocol	ODP in Montreal Protocol
R-454B	R-32/1234yf (68.9/31.1)	62.6	–50.9/–50.0	A2L	516	1 806		465[a]	
R-454C	R-32/1234yf (21.5/78.5)	90.8	–46.0/–37.8	A2L	162	565		145[a]	
R-455A	R-744/32/1234yf (3.0/21.5/75.5)	87.5	–51.6/–39.1	A2L	162	565		145[a]	
R-456A	R-32/134a/1234ze(E) (6.0/45.0/49.0)	101.4	–30.4/–25.6	A1/ A1	707	1 987		684[a]	
R-457A	R-32/1234yf/152a (18.0/70.0/12.0)	87.6	–42.7/–35.5	A2L	154	539		136[a]	
R-457B	R-32/1234yf/152a (35.0/55.0/10.0)	76.5	–46.4/–40.4	A2L	278	973		249[a]	
R-457C	R-32/1234yf/152a (7.5/78.0/14.5)	95.5	–37.3/–32.1	A2L	79	278		69[a]	
R-458A	R-32/125/134a/227ea/236fa (20.5/4.0/61.4/13.5/0.6)	89.9	–39.8/–32.4	A1	1 747	4 136		1 650	
R-459A	R-32/1234yf/1234ze(E) (68.0/26.0/6.0)	63	–50.3/–48.6	A2L	510	1 782		459[a]	
R-459B	R-32/1234yf/1234ze(E) (21.0/69.0/10.0)	91.2	–44.0/–36.1	A2L	158	552		142[a]	
R-460A	R-32/125/134a/1234ze(E) (12.0/52.0/14.0/22.0)	100.6	–44.6/–37.2	A1	2 282	4 415		2 101[a]	
R-460B	R-32/125/134a/1234ze(E) (28.0/25.0/20.0/27.0)	84.8	–45.2/–37.1	A1	1 459	3 244		1 350[a]	
R-460C	R-32/125/134a/1234ze(E) (2.5/2.5/ 46.0/49.0)	105.3	–29.2/–26.0	A1	791	2 105		762[a]	
R-461A	R-125/143a/134a/227ea/600a (55.0/5.0/32.0/5.0/3.0)	109.6	–42.0/–37.0	A1	3 045	5 720		2 767[a]	
R-462A	R-32/125/143a/134a/600 (9.0/42.0/2.0/44.0/3.0)	97.1	–42.6/–36.6	A2	2 437	5 032		2 249[a]	
R-463A	R-744/32/125/1234yf/134a (6.0/36.0/30.0/14.0/14.0)	74.7	–58.4/–46.9	A1	1 622	3 549		1 493[a]	
R-464A	R-32/125/1234ze(E)/227ea (27.0/ 27.0/40.0/6.0)	88.5	–46.5/–36.9	A1	1 449	2 893		1 320[a]	
R-465A	R-32/290/1234yf (21.0/7.9/71.1)	82.9	–51.8/–40.0	A2	158	552		142[a]	
R-466A	R-32/125/13I1 (49.0/11.5/39.5)	80.7	–51.7/–51.0	A1	807	2 065	0.036	733[a]	
R-467A	R-32/125/134a/600a (22.0/5.0/72.4/0.6)	84.4	–40.5/–33.3	A2L	1 420	3 855		1 359[a]	
R-468A	R-1132a/32/1234yf (3.5/21.5/75.0)	88.8	–51.3/–39.0	A2L	162	565		145[a]	
R-468B	R-1132a/32/1234yf (6.0/13.0/81.0)	94.9	–52.4/–36.8	A2L	98	342		88[a]	
R-468C	R-1132a/32/1234yf (6.0/42.0/52.0)	73.7	–56.6/–46.2	A2L	315	1 102		284[a]	
R-469A	R-744/32/125 (35.0/32.5/32.5)	59.1	–78.5/–61.5	A1	1 485	3 059		1 357[a]	

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	Safety Class	GWP 100-year	GWP 20-year	ODP	GWP 100-year in Montreal Protocol	ODP in Montreal Protocol
R-470A	R-744/32/125/134a/1234ze(E)/227ea (10.0/17.0/19.0/7.0/44.0/3.0)	84.4	–62.7/–35.6	A1	1 064	2 197		976[a]	
R-470B	R-744/32/125/134a/1234ze(E)/227ea (10.0/11.5/11.5/3.0/57.0/7.0)	89.7	–61.7/–31.4	A1	821	1 615		748[a]	
R-471A	R-1234ze(E)/227ea/1336mzz(E) (78.7/4.3/17.0)	122.1	–16.9/–13.8	A1	159	271		138[a]	
R-472A	R-744/32/134a (69.0/12.0/19.0)	50.4	–84.3/–61.5	A1	370	1 086		353[a]	
R-472B	R-744/32/134a (58.0/10.0/32.0)	54.8	–82.9/–54.8	A1	546	1 562		525[a]	
R-473A	R-1132a/23/744/125 (20.0/10.0/60.0/10.0)	52.6	–87.6/–83.0	A1	1 853	1 920		1 830[a]	
R-474A	R-1132(E)/1234yf (23.0/77.0)	96.7	–43.1/–36.4	A2L	1	1.8		[b]	
R-475A	R-1234yf/134a/1234ze(E) (45.0/43.0/12.0)	108.5	–28.8/–28.3	A1	633	1 747		615[a]	
R-476A	R-134a/1234ze(E)/1336mzz(E) (10.0/78.0/12.0)	116.9	–19.1/–16.1	A1	151	421		143[a]	
R-477A	R-1270/600a (84.0/16.0)	44	–44.6/–37.2	A3	1	1		[b]	
R-477B	R-1270/600a (38.0/62.0)	50.8	–31.5/–23.1	A3	1	1		[b]	

[a] Blend containing one or more components which are not regulated under the Montreal Protocol, and the GWP of the blend does not include the contributions of these components.

[b] Blend containing no components which are regulated under the Montreal Protocol.

Table 3.I-3: Data summary for azeotropic refrigerant blends

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Normal boiling point (°C)	Safety Class	GWP 100-year	GWP 20-year	ODP	GWP 100-year in Montreal Protocol	ODP in Montreal Protocol
R-500	R-12/152a (73.8/26.2)	99.3	–33	A1	9 265	9 517	0.55	8 077	0.738
R-501	R-22/12 (75.0/25.0)	93.1	–41	A1	4 558	7 383	0.22	4 083	0.291
R-502	R-22/115 (48.8/51.2)	111.6	–45	A1	5 863	6 542	0.25	4 657	0.334
R-503	R-23/13 (40.1/59.9)	87.2	–88	A1	15 658	12 400	0.18	5 935[a]	0.599
R-504	R-32/115 (48.2/51.8)	79.2	–57	A1	5 349	5 112	0.23	4 143	0.311
R-505	R-12/31 (78.0/22.0)	103.5	–30		9 769	9 974	0.59	8 502[a]	0.784
R-506	R-31/114 (55.1/44.9)	93.7	–12		4 290	3 887	0.25	4 490[a]	0.460
R-507A	R-125/143a (50.0/50.0)	98.9	–46.7	A1	4 860	7 345		3 985	
R-508A	R-23/116 (39.0/61.0)	100.1	–86	A1	13 419	10 350		5 772[a]	
R-508B	R-23/116 (46.0/54.0)	95.4	–88.3	A1	13 566	10 586		6 808[a]	
R-509A	R-22/218 (44.0/56.0)	124	–47	A1	6 160	6 344	0.017	796[a]	0.024
R-510A	R-E170/600a (88.0/12.0)	47.2	–25.2	A3	1	1		[b]	
R-511A	R-290/E170 (95.0/5.0)	44.2	–42.1	A3	1	1		[b]	
R-512A	R-134a/152a (5.0/95.0)	67.2	–24.0	A2	219	726		189	
R-513A	R-1234yf/134a (56/44)	108.4	–29.2	A1	647	1 788		629[a]	
R-513B	R-1234yf/134a (58.5/41.5)	108.7	–29.2	A1	611	1 686		593[a]	
R-514A	R-1336mzz(Z)/1130(E) (74.7/25.3)	139.6	29.0	B1	1.7	7	0.000076	[b]	
R-515A	R-1234ze(E)/227ea (88.0/12.0)	118.7	–18.9	A1	430	704		386[a]	
R-515B	R-1234ze(E)/227ea (91.1/8.9)	117.5	–19.0	A1	320	523		287[a]	
R-516A	R-1234yf/134a/152a (77.5/8.5/14.0)	102.6	–29.4	A2L	147	424		139[a]	

[a] Blend containing one or more components which are not regulated under the Montreal Protocol, and the GWP of the blend does not include the contributions of these components.

[b] Blend containing no components which are regulated under the Montreal Protocol.

Chapter 4

Sealed Domestic and Commercial Refrigeration Appliances and Heat Pump Tumble Dryers

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4 Sealed Domestic and Commercial Refrigeration Appliances and Heat Pump Tumble Dryers

4.1 Introduction

Under factory sealed domestic and commercial appliances category, domestic refrigeration is a major component and comprises appliances that are broadly used for household purposes, such as refrigerators, freezers, and combined refrigerator/freezers. In the RTOC 2018 Assessment Report – AR 2018 (UNEP, 2019), domestic appliances were covered under Chapter 3. The other domestic appliance covered in that chapter was the heat pump clothes (laundry or tumble) dryers (HPTDs). In this 2022 Assessment Report – AR 2022, besides domestic appliances, the commercial factory sealed appliances, which were originally covered in Chapter 4 of the AR 2018 Report, have been included in this chapter. These appliances are also referred to as plug-in or factory sealed appliances.

4.2 Types of equipment and applications

This chapter includes a variety of systems used in different application areas, but which are all characterized by a compact, factory sealed refrigeration system. Units are self-contained and can be used in a stand-alone mode.

Domestic refrigerators (Figure 4-1) are predominantly used for food storage in residential dwellings, with a significant minority used in offices and small businesses for commercial use. Typical storage volumes range from 20 to 850 litres. Typical products employ compressors within a capacity range from 50 to 250 W. Domestic refrigerator productions are also typically large-scale.

Figure 4-1: Domestic refrigerator (source: Topten.eu)

Domestic refrigeration appliances are typically small refrigeration systems containing between 20 and 150 g of refrigerant, currently using HC-600a (most predominantly) or HFC-134a. The growth rates in US, Japan and Mexico are lower than the global average (which is approximately 2.5 %) while the developing countries have much higher growth rates (IIR, 2015).

Approximately 200 million domestic refrigerators and freezers were sold with a market value of about US$ 35-50 billion annually. The global installed inventory of domestic refrigerators in the field was estimated to be 2.0 billion and consuming almost 4 % of global electricity (IIR, 2019). Energy efficiencies of refrigerators have been constantly increasing, including in many Article 5 parties, mainly due to Minimum Energy Performance Standards (MEPS) and increased consumers' awareness. The energy consumption of typical household refrigerators has dropped significantly in the last 15 years as shown in Decision XXIX/10 TEAP EETF Report (UNEP, 2018b).

With the development of smart homes and cities and advances in Internet of Things (IOT) and smart controls, some of the developed countries have started introducing smart refrigerators with many advanced features coupled with other features unrelated to refrigeration. Such smart refrigerators are generally much more expensive initially as well as for their servicing thus limiting their market share. Smart refrigerators are still emerging and are not covered in this report.

Stand-alone commercial refrigeration appliances are self-contained refrigeration systems and comprising a wide variety of appliances e.g., ice-cream freezers, ice machines, beverage vending machines, and display cases. These systems are found not only in large commercial stores (hypermarkets, supermarkets, etc.) but also in restaurants, convenience stores, mini supermarkets, and gas stations. Stand-alone equipment is increasingly used in both developed and developing countries. Typical refrigerants used in these applications include HFC-134a, R-404A and HCs. For HCs, safety standards were restricting their use in larger units. With the revision of safety standards in 2019, this is likely to change the scenarios in the future.

According to IIR (IIR, 2019), the current global installed inventory of Commercial refrigeration equipment (including condensing units, stand-alone equipment, and supermarket systems) in the field is estimated to be 120 million. The growth rates of stand-alone commercial refrigeration appliance in US, Japan, and Mexico are higher than the global average (estimated at 2.8 %). In developing countries, where the growth rate is expected to be higher from much lower penetration, it is still lagging behind (IIR, 2015).

Some topics discussed below have been covered in earlier reports of this committee. These are briefly included here to provide a more comprehensive perspective

Beverage coolers (Figure 4-2) are typically glass-door coolers which can be found in nearly every supermarket, gas station, and convenience store. The most common type is the one door 400-litre type.

Ice cream freezers (cabinets) (Figure 4-3) can have a glass or solid lid and can be found in similar locations as the beverage coolers. A typical volume is 300 litres. Many of the beverage coolers and ice cream freezers are owned and installed by food and beverage companies. The refrigerant choice and energy efficiency of the products depend on the environmental policy of those companies.

Beverage coolers and ice cream freezers are produced at large scale though the average annual production figures are significantly below the level of domestic refrigerators.

Figure 4-2: Beverage cooler (source: Topten.eu)

Figure 4-3: Ice cream freezer (source: Topten.eu)

Vending machines (Figure 4-4) can be of the refrigerated type and used in locations such as offices, hotels, etc. Vending machines, as well as beverage coolers, typically have a high cooling capacity in order to cool products quickly to the sales temperature. In some markets (e.g., Japan) combined “hot and cold” vending machines are popular, allowing in principle also to use the rejected heat.

Water coolers (dispensers) can be found in many locations, such as offices and hotels. Specific systems are available for bottled water and for tap water, in the latter case it often includes a water filtering system. Depending on the dispensing capacity required, the cooling capacity typically ranges from the capacity of domestic refrigerators up to beverage coolers. Water coolers for bottled water are often serviced by the water supplier.

Ice machines (Figure 4-5) are installed in restaurants, bars, and hotels, and are very common all over the world. Many different refrigeration capacities prevail depending on the size of the machine, as well as different technologies depending on the shapes of the ice: cubes, pellets, flakes etc.

Figure 4-4: Vending machine (source: Topten.eu)

Figure 4-5: Ice machine (source: Topten.eu)

Professional refrigerated under counter storage cabinets are typically refrigerators (Figure 4-6) or freezers (upright or chest) e.g., Figure 4-7, with an insulated door and are used in restaurants, professional kitchens, etc. The products share a large similarity with domestic appliances but often use specific materials for the environment being placed (e.g., stainless steel). Volumes vary from 200 to over 1000 litres. They can also maintain the required internal temperature despite the high number of door openings.

Figure 4-6: Under counter storage refrigerator (source: Topten.eu)

Figure 4-7: Double door storage refrigerator (source: Topten.eu)

Stand-alone plug-in display cases can be found in supermarkets, gas stations etc. Frozen food as well as refrigerated food versions are available, both in horizontal (Figure 4-8) and vertical (Figure 4-9) format. Many display cases are open for easy access, though the use of glass doors or lids has become very common to reduce energy consumption. Plug-in display cases can be found especially in small- and medium-sized supermarkets instead of the cabinets cooled by a remote refrigeration system, which are discussed in Chapter 5. The plug-in cabinets have lower installed cost, are more flexible and require less system maintenance. However, the cabinets are typically less energy efficient compared to display cases cooled by condensing units or compressor racks, as small compressors typically have lower energy efficiency than larger ones. However, small commercial compressors continue to improve in efficiency. A drawback for plug-ins is that the condenser heat is released into the sales area where the display cases are installed, possibly adding load to the air conditioning systems. As a solution, stand-alone display cases are designed with water cooled condensers allowing the release of heat outdoor or heat recovery in other periods of the year. Increasingly, this version is becoming popular.

Figure 4-8: Horizontal plug-in display unit (source: Topten.eu)

Figure 4-9: Vertical plug-in display unit (source: Topten.eu)

Factory sealed systems similar to the ones described above can also be found outside of the food and beverage applications. Examples are medicine or drug coolers including vaccine coolers (Figure 4-10). Temperature levels range from around +5 °C down to -120 °C for ultra-low freezers. Specific temperature stability and spread requirements may apply as well as off-grid operational requirements. Refrigerants of choice are similar to the previous applications, meaning HFC as well as HC based solutions. For ultra-low freezers, cascade systems are applied with two compressors or auto-cascade systems with a single compressor. Also, Stirling cycles are employed, in a lesser extent, in a single stage operation.

Figure 4-10: Refrigerated drug cabinet (source: Topten.eu)

Figure 4-11: Heat pump tumble dryer (source: Topten.eu)

Domestic heat pump tumble (clothes or laundry) dryers (HPTDs) shown in Figure 4-11, an energy efficient alternative to the conventional electric heater dryer, have entered the market and are characterised by a compact heat pump system integrated tumble dryer. It can be seen in Figure 4-12 that HPTDs contain an evaporator to condense the water vapour from the circulating wet air stream and the dehumidified air is reheated by a condenser, before the hot and dry air returns to the tumble, in a closed air loop. The refrigeration circuit in HPTDs differs from other refrigeration appliances by its very high evaporation temperature (typical 10 to 30 °C) and high condensation temperature (up to 70 °C). Most systems use rotary compressors.

The system is significantly more efficient than conventional direct electrically heated dryers. Typically, HFC-134a is currently applied with some transition to HC-290.

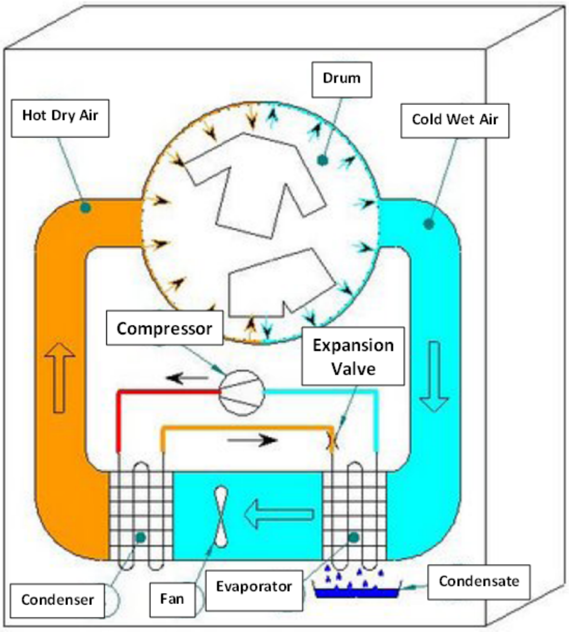

Figure 4-12: Schematic of heat pump clothes dryer cycle (Gluesenkamp, 2017)

HPTDs have become dominant on the EU market and have been introduced in the US and other parts of the world. There are major manufacturers from EU, Japan, and Australia and production is also typically large scale. HPTDs use about 40 to 50 % of the energy of conventional tumble dryers. Therefore, some EU manufacturers have ceased production of conventional electrical dryers

In North America, over six million clothes dryers are sold each year; with close to 100 million clothes dryers in operation and has reached 80 % market saturation. These dryers are predominantly vented conventional tumble dryers. A typical electric conventional dryer consumes about 600-1,000 kWh per year and is one of the largest power-consuming domestic appliances in North America.

In the EU, the 2018 penetration rate of household tumble dryer was estimated to be 24.7 % in a total number of households of about 217 million (EC, 2019a). It was projected that the penetration rate in 2030 will likely be 28 %. It is estimated that the market share for heat pump tumble dryer has increased in EU from 9 % in 2010 to 57 % in 2016 (EC, 2019a). It is projected that HPTDs will continue to gain market share in the next few years. Concurrently, costs of heat pump dryers have also reduced substantially. Switzerland already banned the sale of tumbler dryers without an integrated heat pump in 2012.

HPTDs have yet to make any significant penetration in the North American market. The current market share in Article 5 parties for this product is almost negligible.

4.3 Refrigerant options for new equipment

Refrigerant choices are driven by market considerations as well as regional regulations. Globally, there is a shift to ultralow-GWP refrigerants.

4.3.1 Domestic refrigerators

Currently, the entire global new production is based on non-ODS refrigerants, predominantly HC-600a and to some extent HFC-134a. Refrigerant migration from HFC-134a to HC-600a is expected to continue, driven by the Kigali Amendment schedule and/or local regulations. It was estimated that in 2020, about 75 % of new refrigerator production were using HC-600a and the rest with HFC-134a.

HC-600a: HC-600a was originally the standard refrigerant for European domestic refrigerators and freezers as a CFC-12 alternative (with HFC-134a as an interim choice for a short period) and proliferated into other regions, including Article 5 parties. Worldwide about 100 million appliances are produced annually with HC-600a. Concerns with the high flammability, which existed at the introduction of the refrigerant in 1994 in Europe, were addressed with improvements in the safety standards e.g., IEC 60335-2-24.

There are no significant technical barriers to the use of HC-600a, illustrated by the probable estimate of over 800 million domestic fridges in the field to date. In the USA, a substantial progress has been made to convert from HFC-134a to HC-600a and is expected to be complete by 2023. The UL Standard for safety of household refrigerators has been harmonized with IEC 60335-2-24 as UL 60335-2-24 in 2018, which includes new safety requirements for HC-600a. This has reduced the product cost differential between manufacturers by imposing common safety requirements for HC-600a.

HC-600: The application of HC-600 (n-butane) is being explored and can potentially reduce energy consumption compared to HC-600a due to its higher boiling point and critical temperature (Bjerre and Larsen, 2006; Yaru and Igbogbo, 2021). However, its application would require increase in compressor swept volume to compensate for its lower volumetric capacity.

HFC-134a: HFC-134a was originally the predominant refrigerant for domestic refrigeration for the phaseout of CFC-12. After Kigali Amendment, many non-Article 5 parties and a few Article 5 parties including China, India, and a few others have migrated to HC-600a.

HFO-1234yf: HFC-1234yf is similar in thermophysical properties to HFC-134a with slightly lower pressure and capacity. It was originally thought that the lower flammability of HFO-1234yf (classified as A2L) might make its application easier for countries that are concerned about the liability associated with the use of HC-600a. HFC-1234yf is not likely to displace HC-600a or HFC-134a given additional conversion costs and the proven satisfactory operation (both performance and safety) of HC-600a. More details on academic studies on HFOs and their blends with HFCs were presented in UNEP 2018 Report of this committee (UNEP, 2018).

HFO-1234ze: This refrigerant, also classified as A2L, has been selected for some commercial applications. For domestic refrigerators, compressor adaptations are required to match the reduced volumetric capacity compared to HFC-134a. Therefore, this refrigerant also is not likely to displace HC-600a or HFC-134a in the near future.

R-744: Currently, experience on the use of R-744 is available from a number of commercial beverage coolers. This application implies additional costs due to greater mass of materials necessary to achieve protection against the high-pressure level, in particular for the compressor. Manufacturing compressors with very small swept volumes at the required efficiency levels poses a significant challenge. Altogether this makes the application of R-744 for this application very unlikely.

4.3.1.1 Conversion of HFC-134a domestic refrigerators to low-GWP alternatives

Current industry dynamics include increasing migration from HFC-134a to HC-600a. European production of No-frost side by side refrigerators began their conversion from HFC-134a to HC-600a in the early 2000’s. Conversions of automatic defrost refrigerators in Japan from HFC-134a to HC-600a were discussed in the 2006 report of this committee (UNEP, 2006). This conversion had progressed to include more than 90 % of refrigerator production in Japan.

Significant progress has been made in the USA. Conversion from HFC-134a to HC-600a is complete for household refrigerators and freezers with the exception of built-in residential consumer refrigeration products that will be completed in January of 2023 driven by regulatory requirements.

A major U.S. manufacturer introduced auto-defrost refrigerators using HC-600a refrigerant to the U.S. market as early as 2010. US EPA had approved 150 g of HC-600a as acceptable alternative under their Significant New Alternatives Policy Program (SNAP) for household and small commercial refrigerators and freezers.

Many Article 5 parties, including China, India and few others are rapidly phasing-out HFC-134a using HC-600a. Concurrently, HC-based refrigerator models in other parts of the world, including Central and South America are rising as well.

In many non-Article 5 parties, it is mandatory for service technicians to undergo training with certification for both good service practices and safety. Such trainings are also being imparted in many Article 5 parties by Montreal Protocol implementing agencies and supported by funding from the Montreal Protocol Multilateral Fund.

4.3.2 Commercial plug-in appliances

Several trends for refrigerant choices depending on the cooling capacity are described in this section, including the refrigerant charge, and the refrigerant circuit design. Many of such equipment types are owned and installed by food and beverage multi-national companies. These companies develop their own environmental policies to choose low-GWP refrigerants as well as energy-efficient systems as a part of their environmental policies (“green positioning”). The latter has been an important factor in improving efficiency levels of these systems and have driven component manufacturers, in particular compressor manufacturers, to improve their efficiency levels.

Beverage coolers have predominantly been produced with HFC-134a. Migration has taken place to HC-290 with energy efficiency improvements in several European and US companies. This trend is spreading to some of the Article 5 parties too. Also, HC-600a is being employed where availability of compressors with sufficient capacity may be a limitation. The application of R-744 gained a lot of interest initially but has not been continued.

In ice-cream cabinets, R-404A and HFC-134a are progressively being replaced by HC-290 by large food companies.

Vending machines typically use HFC-134a and is currently migrating to R-744 (e.g., high-efficiency R-744 cassettes have been developed by a Japanese company) and HCs. HC-290 vending machines have also been developed with comparable energy efficiencies. The choice between R-744 and HCs is made based on risk assessments. Vending machines differ from beverage coolers as often a larger refrigeration system is employed, and the interior of the machines includes various parts such as actuators which need safety considerations. In the “hot and cold” vending machines, R-744 is well suited due to its heat rejection characteristics, but other high-pressure refrigerants could also be applied.

Water coolers typically have a small refrigeration system similar to domestic refrigeration systems. Many companies have switched from HFC-134a to HC-600a.

Ice machines are using R-404A with a charge varying from 500 g to 2 kg. In Europe, and in other regions, small ice machines now use HC-600a and HC-290 and are sold as a standard option. A few European manufacturers are manufacturing ice machines using R-744 as the refrigerant.

Supermarket plug-in display cases often use R-404A or HFC-134a. As early as 2000, HC-290 based display cases were introduced as an option in Europe with an energy efficiency gain of 10 to 15 % compared to R-404A or R-744 systems.

In the stand-alone equipment, HFC-134a and R-404A are being phased down progressively in developed countries. Multi-national companies are also driving this phasedown in many Article 5 parties. There are several low-GWP refrigerant options, such as, HCs, R-744 and new low-GWP HFC-based blends that can be used depending on commercial availability.

Regulations limiting the use of HFCs for certain applications have been introduced in a number of countries and regions e.g., EU and California in the US. Due to production rationalisation, it is often most beneficial for manufacturers to align with the most stringent regulations, resulting in an increased use of low-GWP solutions, even in countries where the use is not yet restricted.

Recently, the US EPA (2022) proposed new rules to phase down the production and consumption of HFCs by 85 % by 2036. If approved, this would restrict the use of HFCs in specific sectors or subsectors and would prohibit manufacture and import of products containing restricted HFCs by 1st January 2025, in most cases, and would prohibit the sale, distribution, and export of products containing restricted HFCs a year later i.e., 1st January 2026. For the sub-sectors considered in this chapter, the GWP limit is likely to be 150.

4.3.3 Heat pump tumble dryers

The most commonly used refrigerants in HPTDs are HFC-134a, R-407C, and R-410A. HPTDs do not have any significant historical use of CFCs or HCFCs. HFC-134a is probably the most common refrigerant used, with the refrigerant charges varying from 200 to 400 g; the continued use of HFC-134a is under discussion in several global regions. HPTDs with HC-290 have emerged on the market a few years ago (EC, 2019a) and in the meantime several European manufacturers, motivated by the reduction of refrigerant quotas under the F-Gas regulation as well as for improved efficiency, have already switched to HC-290 and use less than 150g of refrigerant to comply with the safety norms. The main disadvantage of HC-290 is the relatively higher pressure for a condensing temperature of 70 °C. The additional safety features to use HC-290 also add to the overall cost.

Low-GWP refrigerants currently explored are:

- R-744 (CO_2): The high temperature glide at the gas cooler side can effectively result in an efficient drying process and possibly higher air exit temperatures than possible with subcritical refrigerants. High costs of some components and the probable need of an effective intercooler in order to reduce gas exit temperatures are the challenges currently faced.
- Hydrocarbons: HC-290 is already being applied as mentioned. Safety hazards due to the refrigerant flammability need careful evaluation, as discussed in 4.4.3. It has been reported that performance tests on a HPTD, using HC-290, showed that performances are very close to HFC-134a and that an energy saving around 5 % could be obtained.
- Low-GWP HFC/HFO blends: With similar characteristics to HFC-134a, these blends may offer potential candidates. However, their flammability poses similar safety hazards as listed for HCs, though some of these hazards may be easier to deal with due to the reduced flammability characteristics of HFCs /HFOs and their blends.

4.3.4 Other heat pump appliances

Washing machines and dishwashers with an integrated heat pump have been introduced into the market. In a washing machine, approximately 80 % of the energy consumption is used to heat the water. The heat pump is used to heat the water during the wash process. These products still represent a very small share of the market, but it is possible that it will grow as the energy efficiency regulations become more stringent. So far, the products with this technology use HFC-134a. Similar to HPTD, these products may also shift to HC-290.

4.4 Safety aspects of using flammable refrigerants

Generic safety standards exist for refrigeration systems or heat pumps, such as EN 378, which specify design rules and related safety features. However, for most appliances and components used in appliances, particular safety standards are available within the IEC 60335 framework. Part 1 sets the generic rules and Part 2 contains numerous versions for specific systems. Applicable standards from the 60335-2 series (Household and similar electrical appliances):

- 60335-2-11 Tumble dryers
- 60335-2-24 Refrigerating appliances, ice-cream appliances and ice makers
- 60335-2-75 Commercial dispensing appliances and vending machines
- 60335-2-89 Commercial refrigerating appliances and icemakers with an incorporated or remote refrigerant unit or motor-compressor
- 60335-2-118 Professional ice-cream makers

4.4.1 Domestic refrigerators

Beasley et al. (2017) examined the generic reasons for the cause and spread of domestic refrigeration fires using information obtained from London Fire Brigade investigations over the past decade. It was found that fires caused by fridge/freezers exhibited a higher degree of fire spread than other types of appliances (e.g., washing machine, dishwasher, or tumble dryer). There are different reasons for these causes (a main one is electrical short circuit problems) and only a few may relate to the use of a flammable refrigerants. A number of common failure modes for ignition in domestic refrigeration fires identified were: (i) starter relays; (ii) PTC switches; (iii) mechanical defrost switches; and (iv) capacitor failures.

Additional failure modes related to insulation break down due to corrosion may exist. Following design measures can be used to reduce the likelihood of fridge/freezer fires and some of these are addressed in the new harmonized standard of IEC 60335-2-24:

- Limiting the refrigerant charge to 25 % Lower Flammability Limit (LFL) in the occupied space
- Prevent contact between single insulated electrical components and refrigerant tubing
- Apply fuses to both sides of defrost heaters in proximity to refrigerant tubing to limit energy release during heater failure
- Limiting energy available for spark generation
- Use explosion rated components that meet requirements for spark generation
    - IEC 60079-11, Non-Sparking
    - IEC 60079-15, Sealed
- Limit and provide margin between the maximum surface temperatures and the worst-case ignition temperature of the refrigerants
- Contain potential ignition sources in sealed boxes
- Use metal drip trays
- Use fire retardant added to insulation foam or applied to insulation surfaces
- Fit a non-combustible or fire-resistant covering at the back of the appliances

4.4.2 Commercial plug-in appliances

Commercial refrigeration plug-in appliances also followed the process of domestic refrigeration, leading to the revision of IEC 60335-2-89: 2019. Design measures are similar to the points listed for domestic refrigerators.

Products initially converted to HC refrigerants (ice cream freezers and smaller bottle coolers) could be managed within the prescribed charge limit, while it was more restrictive for larger sized commercial applications. In response to this, the maximum charge limit has been increased in the updated version of this standard (IEC 60335-2-89:2019) with some additional conditions. The limit (in kg) is then defined as 13 times the Lower Flammability Limit (in kg/m^3), subject to a maximum of 1.2 kg. For higher charge systems, this equates to 494 g of HC-290, when compared with 1.2 kg of HFC-32 or HFO-1234yf.

If charges above 150 g are used, the IEC 60335-2-89: 2019 standard requires more stringent safety measures compared to systems with a charge below 150 g. Amongst others these contain:

- Restrictions on the room size, where the appliance is installed
- Limitations to the vibration level, which must be assessed at different operating frequencies at the piping with the largest vibration amplitude.

Further, it must be noted that these increased charges do not apply to all commercial appliances discussed in this chapter, as water and ice cream dispensers and vending machines are excluded in IEC 60335-2-89 and are dealt with in IEC 60335-2-75.

4.4.3 Heat pump tumble dryer

The safety aspects of tumble dryers are prescribed in IEC60335-2-11 (2019). This standard includes tumble dryers that use a refrigerating system, incorporating a sealed motor-compressors, and such system may use flammable refrigerants. Some safety considerations for these types of appliances are:

- The charge for flammable refrigerant is limited to 150 g.
- HPTDs pose additional risks compared to domestic refrigerators due to the high temperatures involved, the presence of dry textile materials and particles, mechanically moving objects (drum, motor etc.) and the presence of static charges. Many of these risks are also present for conventional laundry driers

4.5 Refrigerant options for existing units

In general, it is not recommended to retrofit with another refrigerant, especially any flammable refrigerant, as it may impact the safety of the system. Nevertheless, for completeness, some retrofit options are discussed in the following sections

4.5.1 Domestic refrigerators

Most products containing CFC-12 were either disposed or are reaching the end of their life cycle and are being disposed. Similar situation may follow with the phased down of HFC-134a. More details on academic studies on HFOs and their blends with HFCs as retrofit alternatives to HFC-134a were presented in UNEP 2018 Report of this committee (UNEP, 2018). There are some safety issues with respect to flammability, even when using A2L refrigerants and these fluids are probably no more under consideration in systems covered in this chapter.

4.5.2 Commercial plug-in appliances

Many of the new lower GWP refrigerant options may have some issues, including, higher pressure, higher flammability/toxicity, and temperature glides for blends and as such, cannot be used to replace high GWP refrigerants in existing equipment. Therefore, one should be cautious about any retrofit option. Recovery and recycling of existing refrigerants represent a strong option in order to smooth the transition from present day refrigerants to a series of lower GWP options.

4.5.3 Heat pump tumble dryers

Heat pump variants of tumble dryers have been put on the market only in recent years, with most of the installed units using HFC-134a. There is no immediate incentive for refrigerant replacement.

Gataric and Lorbek (2021) have experimentally evaluated R-450A (GWP of 604) as a possible drop-in to HFC-134a in a HPTD. The energy consumption as per IEC 61121 (2012) was first evaluated using HFC-134a. After retrofitting with optimal charge R-450A, the energy consumption of HPTD decreased by 3.7 % and the refrigerant charge in CO_2 equivalent was reduced by more than 50 %. However, the duration of the drying cycle increased by 4.2 %, due to a slightly lower condensing temperature in the heat pump.

4.6 Not-in-kind alternative technologies

Not-in-kind technologies are discussed in Chapter 12 of this report. Only brief discussion on applications relevant to this chapter is presented here.

Alternative refrigeration technologies for domestic refrigeration continue to be pursued for applications with unique drivers such as very low noise, portability, or no access to the electrical energy distribution network. Technologies of interest include Stirling cycle, absorption, and adsorption cycles, thermoelectric, and magnetic. In the absence of unique drivers such as the examples cited above, no identified technology is yet cost or efficiency competitive with conventional vapour-compression technology for mass-produced domestic refrigerators. For more details, readers may refer to 2018 Report of this committee.

Existing heat pump dryers need to significantly cool the air to achieve dehumidification and then reheat the dehumidified air. A sorption-based dehydration system decoupling latent and sensible loads has been proposed by Ahmadi et al., (2021) using a liquid-desiccant solution for gas-based laundry dryers. The proposed system directly captures the latent heat of the moisture in the wet air exiting the dryer and reuses it to improve energy efficiency.

4.7 Energy Consumption Considerations

Energy efficiency has become a global strategy to combat climate change and is an integral part of the Kigali Amendment which stipulates that HFC phasedown should not come at the expense of energy efficiency improvements in appliances. At the UNFCCC COP 26, 14 countries came together and signed the largest global commitment to CO_2 reduction through appliance energy efficiency policy COP 26 (2021). Each Party has pledged to focus improving the energy efficiency of at least one of four products (industrial motor systems, air conditioners, refrigerators, and lighting) that contribute to 40 % of global electricity consumption as way to tackling their climate goals.

A recent study by IEA (2021) showed the positive impact of energy efficiency standards, and also highlighted that such improvements did not increase the cost of products and in some cases resulted in some marginal reduction in costs. It is now established that the long running energy labelling programmes in some countries like US and EU have been resulting in annual reductions of around 15 % of their total current electricity consumption. This percentage also is increasing each year as older and less-efficient inventories are replaced with new units having higher efficiencies. These regulatory schemes drive manufacturers to innovate for better energy efficiency at lower costs. In many cases, the manufacturers overestimated the costs necessary to comply with the newer regulations. Still many countries are yet to initiate MEPS as it is likely to lead to increased cost in low market volume situations owing to costs related to establishing the test facilities and running these tests regularly. Some indicative range of capital and operating costs of test facilities for energy labelling programmes are provided by SEAD (2019).

4.7.1 Domestic refrigerators

Domestic refrigeration consumes a significant percentage of the global energy production. The largest part of this consumption is due to high number of inexpensive, small to medium size refrigerators that are sold in emerging markets. This growth in the emerging markets makes it difficult for any reductions in consumption. However, reductions in the rate of growth of energy consumption are possible when the refrigeration and insulating technologies that are currently in use in the higher end efficient products (sophisticated but expensive), are also directed to the lower end products (more in market demand with lower costs).

In EU, the electricity consumption of the gross installed stock of household refrigeration appliances in 2014 was estimated to be 87 TWh/year, which was more than 3 % of the EU's total electricity consumption (European Commission, 2016). This makes domestic refrigeration appliances as one of the most important targets in terms of climate impact. With a total expenditure over 17.1 billion EUR on energy consumption for a stock of 303 million appliances, there is an urgent need for improving the energy efficiency not only for environmental considerations but also for consumer cost savings. Newly revised Ecodesign and Energy Labelling regulations have entered into force in March 2021 (European Commission, 2019a; 2019b and 2019c).

In the USA, the electricity consumption of the gross installed stock of household refrigeration appliances in 2015 was estimated to be 7 % of the total residential electricity consumption or 3 % of the total energy consumption (Figure 4-15). The overall annual electricity consumption is slightly less than 100 million MWh and is the lowest for household refrigeration in the previous 15 years (IEA, 2015).

Factors influencing refrigerant selection and product energy efficiency include local, regional, and national regulations, Eco-labelling, and third-party standards. Globally labelling requirements and minimum standards are reviewed and upgraded on a regular basis. Such standards provide transparency and credibility in the labelling of product impact on the environment, thus driving a more informed decision for the consumer. EIA (2021) reported that owing to the implementation of energy labelling programmes, the energy reduction in new refrigerators was up to 8 % while the global average was about 2.2 %.

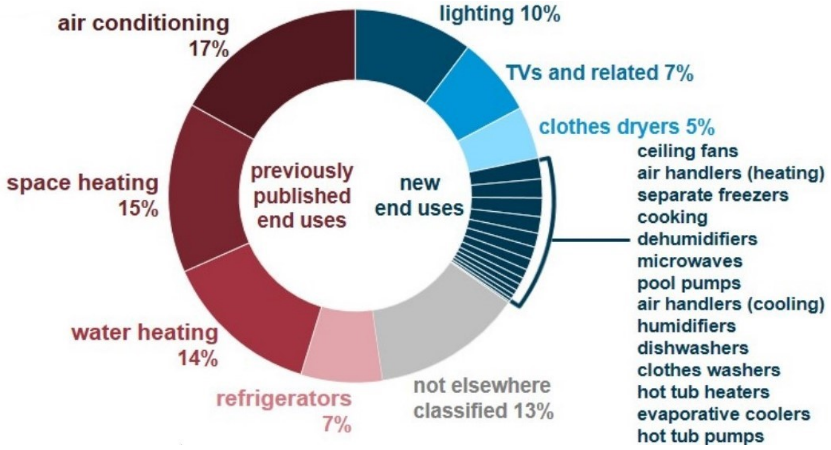

Figure 4-15: US residential energy consumption survey (IEA, 2015)

A universal energy test protocol has been standardised by IEC (IEC 62552-1, 2 and 3:2015 with amendments in 2020) and this was the basis of energy legislation in many countries including Article 5 parties. For other countries, test procedures are unique and the results from one should never be directly compared to results from another procedure. Several regions are already committed to apply the IEC test protocol in energy regulations updates.

A number of improved energy efficiency design options are fully mature, and future improvements of these options are expected to be evolutionary. Extension of these options to all global domestic refrigeration would yield significant benefit but is generally constrained by availability of capital funds and related product cost implications.

An option for energy improvement is the application of variable capacity compressors (VCC, either variable speed or variable displacement). With a VCC, the capacity is adjusted to the heat load hereby reducing on/off cycling losses and it operates at more favourable temperature levels. Energy efficiency gains of 10 to 25 % are found, compared to fixed capacity compressors. As costs of VCCs have reduced, their applications are progressing in domestic and commercial refrigeration as well. More details on energy efficiency aspects of domestic refrigerators may be found in the RTOC assessment reports (2006 - 2018) as well as in the TEAP energy efficiency reports (see chapter 1).

4.7.2 Commercial plug-in appliances

Although most of the features for improvements in energy efficiencies for domestic refrigerators are also applicable to sealed commercial plug-in appliances, the standards are much less common as there are too many product variations and standards become complicated. However, there are MEPS for selected popular commercial refrigeration appliances in both Article 5 and non-Article 5 parties. This has created competition between manufacturers to reach higher energy efficiencies.

When a beverage cooler was tested and compared with a household refrigerator, under different testing EN standards, the results showed that the beverage coolers consumed much more power than refrigerators and considerable technological development is possible that would reduce the energy consumption by half using cost-effective non-proprietary technologies (topten.eu, 2018). It was also found that the relative energy efficiency between the appliances remained constant independent of the test standards.

- Solid door beverage cooler consumed 3.5 times as much energy as household refrigerator with the same internal volume
- Glass door beverage cooler consumed 5 times as much energy as household refrigerator
- Solid door cooler versus a glass door equivalent cooler showed an improvement in energy consumption of more than 40 %.

Additions of glass doors, LED lighting and electronically commutated motor (ECM) fans to display cases, not only reduce the refrigeration load but indirectly also the refrigerant charge in general. Besides refrigeration system design changes (layout, volumes of heat exchangers etc.), this enables the use of flammable refrigerants for these display cabinets within the allowable charge limits.

In EU, it was estimated that in hypermarkets, the refrigeration systems account for between 30 and 60 % of the electric power used. A regulation for these products (refrigerating appliances with direct sales function) has entered into force in March 2021, subjecting them to Ecodesign MEPS and an energy label. It is expected that the regulations for these appliances will lead to an estimated annual energy savings of 48 TWh by 2030 (EC, 2019b). Professional storage refrigerators that are mainly used in the restaurant industry were already regulated since 2015

4.7.3 Heat pump tumble dryers

In HPTDs, the inclusion of a heat pump in itself is a major energy saving technology compared to conventional laundry dryers. Current energy saving option is predominantly related to optimisation of the heat pump system in combination with the air circulation system. An efficient HPTD consumes up to 50 % less energy than a simple clothes dryer.

Other savings can be realised by integrating sensors assessing the remaining humidity of the load and shorten programme times.

TeGrotenhuis (2016), developed a prototype system by modifying a commercial electric tumble dryer with readily available affordable components and demonstrated 50 % energy savings. The modifications included the following:

1. An electric heater in combination with a heat pump was used as a trade-off between energy efficiency and drying time, to use the heater, during the initial warm-up phase to heat the incoming fresh air.
2. Incorporate a recuperative heat exchanger to recover heat from the exhaust hot air to preheat the inlet cold air. This was particularly effective at the end of the cycle when the load is mostly dry and enabled the heater and heat pump to be turned off earlier.
3. Use of standard fin-tube technology for heat exchangers.

The energy efficiency was 30 % better than the newly introduced commercial HPTDs.

In the US (Energy Star, 2021), the efficiency of HPTDs is assessed by Combined Energy Factor (CEF), which is a measure of energy efficiency of a dryer. For typical HPTDs capacity range 0.113 -0.139 m^3, with Energy Star rating in US, the CEF is in the range 5.7 -9.75, with the estimated energy consumption in the range 125-263 kWh/year, while for a vented electric dryer with capacity range 0.127–0.130 m^3, the CEF is in the range 9.75-10.14 with the estimated energy consumption in the range 236-245 kWh/year. Consumers with high clothes dryer usage and high electricity rates have the potential for large energy and cost savings.

4.7.4 The effect of high ambient temperatures on energy consumption

High ambient temperature conditions beyond test conditions have several effects on product design including reliability, higher operating pressure, reduced stability, and lower efficiency.

Most consumer products are designed to operate reliably at ambient temperature conditions below 43 °C, corresponding to the maximum temperature of the tropical rating of IEC 62552-1 for household refrigerating appliances. However, ambient temperature conditions higher than 43 °C may require design (larger condenser, appropriate compressor) and material (lubricating oil, motor winding insulation) changes to ensure that the appliance reliabilities and efficiencies are unaffected.

Refrigerant selection is affected by the maximum temperature and pressure. HFC-134a, HC-600a, HC-290 all operate well in high ambient environments. However, if R-744 is used e.g., commercial plug-in systems, relatively high operating pressure (130 bars) and low critical point make it a challenge at high ambient conditions.

4.8 End-of-life disposal

The small unit charge and the geographically dispersed location of the units treated in this chapter complicate commercial opportunities to promote recovery and recycling initiatives to manage emissions from disposed units. Regulations for mandatory end-of-life refrigerant handling have existed in many developed countries for several years and are being introduced in Article 5 parties. Interest in conservation programmes is leveraged by the 1 to 2 kg of foam blowing agents typically present in refrigeration appliances.

For HPTDs, similar recovery and recycling technologies apply for refrigerant and lubricant as for domestic refrigeration systems, although there is no adequate experience in this emerging segment.

A brief overview of the current global regulations, containing only a few selected countries with geographical distribution, on the end of life of appliances is presented in Table 4-1. In most cases, the existing regulations have been amended to include appliances containing refrigerants.

Table 4-1: End-of-life regulations for appliances containing refrigerants

Country	Regulations	Short Description
China	GB/T 38099.2-2019 Requirements of treatment for waste electrical and electronic product—Part 2: Electrical appliances containing refrigerants	Special materials and special parts such as insulation materials, compressors and related refrigerants in the products are uniformly specified from the aspects of identification, disassembly, collection, storage, handling, recycling, and reuse, as well as the treatment technology, environmental pollution prevention and control, and labour health and safety requirements of relevant personnel engaged in treatment.
European Union	Waste from Electrical and Electronic Equipment (WEEE Directive) – August 2012 (with subsequent amendments)	The objective of the Directive is the efficient use of resources and the retrieval of secondary raw materials through reuse, recycling, and other forms of recovery. The Directive requires the separate collection and proper treatment of WEEE and sets targets for their collection as well as for their recovery and recycling. The regulation harmonizes the national EEE waste registers and reporting. The regulation covers large household appliances (refrigerators, freezers, and air conditioners). Commercial appliances are not mentioned.
Japan	Japanese Home Appliance Recycling Law, April 2001(with subsequent amendments)	With the enactment of the Home Appliance Recycling Law in April 2001, a system was established to properly dispose of home appliances at their EoL and efficiently recycle them so that they can be reused as raw materials. Products that are covered by this regulation are air conditioners, refrigerators, televisions, washing machines and tumble driers.
Switzerland	Swiss Ordinance on the Return, Taking Back and Disposal of Electrical and Electronic Equipment (ORDEE) – July 1998 (with subsequent amendments)	The ORDEE governs the handling of old electrical and electronic appliances. Retailers are obligated to take back used appliances from their product range free of charge and have these professionally recycled. All products at sale are subject to an advance recycling fee (ARF). This allows for the financing of Recycling program in Switzerland. The fee covers household appliances and professional appliances.
United States	Title 40 of the Code of Federal Regulations (40 CFR Part 82 Subpart F) and (40 CFR Parts 273, 279, 761) – 2017 (with subsequent amendments)	When household appliances are taken out of service, federal law requires that: (1) all refrigerants be recovered prior to dismantling or disposal; and (2) universal waste (e.g., mercury), used oil, and PCBs be properly managed and stored. At the State level, more stringent regulations may apply.

The UNEP TEAP Destruction Task Force Report (2018a) describes all the approved refrigerants destruction technologies and related issues. Some of the Article 5 parties have only considered the destruction of ODSs and contaminated refrigerants, which are normally classified as hazardous materials. However, it should be mentioned that recovery of refrigerants from appliances with relatively low charge pose many operational and economic challenges for Article 5 parties and even for some non-Article 5 parties. Refrigerant destructions in Article 5 parties are implemented through co-processing in cement kilns and incinerators. However, safe dismantling of appliance and recycling the materials following the local regulations can be found only in country specific regulations and the details are likely to vary significantly. Most of the Article 5 parties are yet to address the end-of-life disposal in a holistic manner.

4.9 Concluding remarks

In domestic refrigeration sector, migration from HFC-134a to HC-600a is continuing. In the USA, migration to HC-600a is expected to be complete by 2023. Many Article 5 parties, including China, India and few others have migrated to HC-600a.

With the revision of safety standards in 2019, migration to HC-290, with better energy efficiencies, in stand-alone commercial refrigeration appliances is taking place. This trend is spreading to some of the Article 5 parties too. In larger charge systems, migration from R-404A to R-744 is happening. Some migration to HCs is also likely to happen in this sub-sector. With the proposed regulations by US EPA (2022), migration to refrigerants with GWP less than 150 is expected to happen soon.

HPTDs continue to gain market share and concurrently costs have also reduced substantially. Some transition to HC-290 has happened in European countries. HPTDs have yet to make any significant penetration into the North American market. The current market share in Article 5 parties for this product is almost negligible.

Globally, there is a considerable improvement in the energy efficiency of appliances. MEPS drive manufacturers to innovate for better energy efficiency at lower costs.

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Chapter 5

Food retail and food service refrigeration

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5 Food retail and food service refrigeration

5.1 Introduction

Food retail and food service refrigeration is characterized by storing and displaying food and beverages at different levels of temperature within retail stores (supermarkets, grocery stores, etc.) and food service outlets (restaurants, cafes, hotels, etc.) with sales areas varying in size from approximately 10 to 20,000 m^2. The refrigerating capacities of equipment vary from hundreds of Watts to around 1.5 MW. Two main levels of temperatures are generated by refrigeration systems, one from around 0 to 8 °C for the conservation of fresh food and beverages, commonly referred to as medium temperature and the second, around -25 to -18 °C for frozen food and ice cream, commonly referred to as low temperature.

In Article 5 parties, HCFC-22 continues to represent a large refrigerant bank within food retail and food service refrigeration and is used at all temperature levels. The most used HFCs are HFC-134a predominantly for medium temperature and R-404A for all temperature levels. Historically, larger sizes of food retail and food service refrigeration applications are prone to significant refrigerant leakage because most of the large systems are field installed with many joints and fittings. In recent years, progress has been made to improve leak tightness, especially for centralized systems, and the effort continues for better refrigerant management during the life of the equipment.

The progressing phaseout of HCFC-22 in Article 5 parties, and the phasedown of high-GWP HFCs in many countries, requires making informed choices on the best replacement options. To facilitate this, many industry organizations have conducted and published research into alternative refrigerants that can meet the needs of these applications in a safe and reliable manner.

There has been significant development of technology and concepts for using low-GWP R-744 (CO_2) as refrigerant, especially for larger capacity systems (Hafner, 2018), and low-GWP HC-290 (Propane), especially for smaller capacity systems. Both R-744 and HC-290 continue to grow not just in Europe, but also in Canada, United States and in many countries in Asia and South America.

AHRI launched a low-GWP Alternative Refrigerant Evaluation Program (AREP) in 2010 (AHRI, 2013). Several new blends based on HFO-1234yf and HFO-1234ze(E) as well as HFC-32 have been formulated to replace HFC-134a, HCFC-22, and R-404A. So, for the different groups of food retail and food service refrigeration equipment, comparisons were made to select amongst the most energy efficient options with the smallest environmental impact due to refrigerant emissions. Additional studies have also been carried out or are ongoing, with cooperation between AHRI, ASHRAE and the U.S. Department of Energy to study the effects of flammable (A2L, A2 and A3) refrigerants in various applications (ASHRAE, 2016).

In food retail and food service refrigeration, as in air-conditioning, high ambient temperature applications require special consideration in selecting and designing components and equipment. However, designers of food retail and food service refrigeration equipment choose components to design systems based on delivering the cooling required at the highest ambient condition to preserve the quality and safety of food. The accelerating global warming makes more areas high ambient temperature areas, e.g., Germany has encountered more than 40 °C over several days during recent years posing new requirements on refrigeration systems.

The refrigeration equipment operates throughout the year and for this reason, energy efficiency of the equipment is a very important consideration. For moderate and cold climate regions recovering heat from the refrigeration system for heating purposes in the cold season can increase system efficiency. Considering the supermarket as a single energy system, (including the building HVAC, water use, lighting and the food retail and food service refrigeration) for which energy use should be minimized, may give considerable total energy savings.

5.2 Types of equipment and applications

There are 3 basic types of refrigeration equipment used in food retail and food service applications as discussed below.

5.2.1 Stand-alone equipment

Stand-alone equipment is also called plug-in or self-contained equipment. This type of equipment is widely used in food retail and food service refrigeration (e.g., in small retail stores, restaurants, convenience stores, mini supermarkets, and gas stations). This type of equipment is dealt with in Chapter 4 but is also mentioned here since these systems are used alongside of, or instead of the larger equipment covered in this chapter. Stand-alone equipment is factory-built and comprises of a wide variety of appliances: e.g., ice-cream freezers, ice machines, vending machines, and display cases. Most stand-alone equipment has a refrigerant charge in the range 0.1 to 1 kg. In some Article 5 parties, domestic refrigerators and freezers can also be found in small shops and are being used for commercial purposes. Stand-alone equipment is increasingly used also in developed countries in medium-size supermarkets because of the ease of maintenance of the factory-sealed circuit.

5.2.2 Condensing units

Condensing units are “split systems” with the cooling evaporator connected by site installed pipework to a compressor and condenser situated away from the retail space. This configuration ensures that the heat rejected from the refrigeration system is rejected to ambient air (unlike stand-alone units where condenser heat is rejected inside the retail space). Condensing units exhibit refrigerating capacities ranging typically from 1 to 20 kW. They are composed of one (or two) compressor(s), one condenser, and one receiver assembled into a so-called “condensing unit”, which is located external to the sales area (often called remote condensing units). The condensing unit is connected to one or more display case(s) in the sales area and/or to a small cold room. The condensing units and display cases are factory built but require on-site installation of refrigerant pipework to connect them together. Most condensing unit systems have a refrigerant charge in the range 2 to 15 kg. Condensing units are typically installed in specialty shops such as bakeries, butcher shops, and convenience stores. In some supermarkets, one can find many condensing units (sometimes up to 20) installed side-by-side in a small machinery room. In most of the Article 5 parties, the use of systems based on condensing units is quite common. The global market of condensing units has a strong consequence in terms of refrigerant choices; they are traditionally developed based on the most used refrigerants: HCFC-22, R-404A, and HFC-134a. These systems will be addressed in Section 5.3.

5.2.3 Centralized and distributed systems

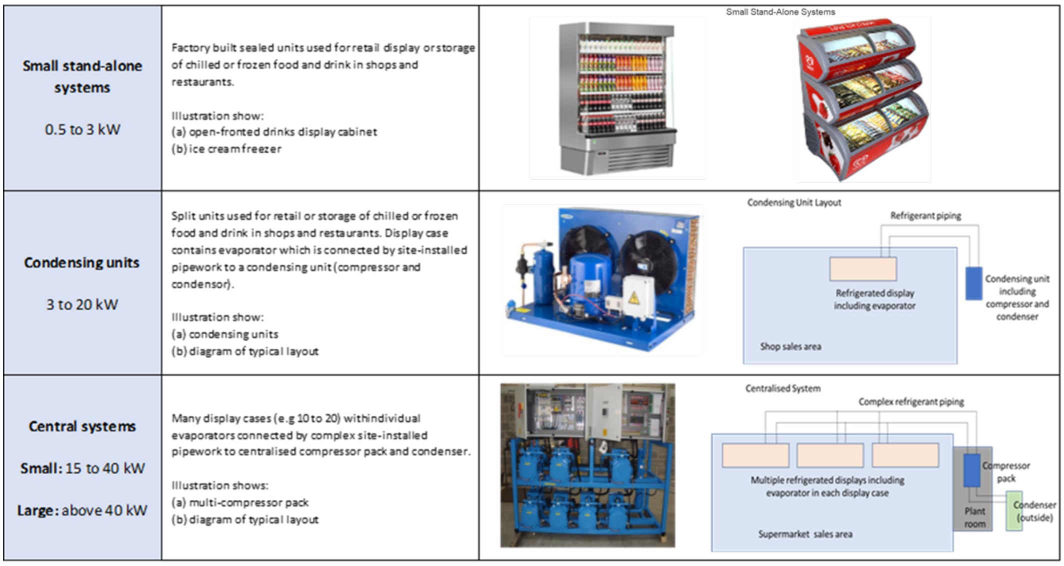
Centralized and distributed systems are the preferred options in large supermarkets. They operate with racks of compressors installed in a machinery room (as in the case of a centralized system) or on the rooftop (for distributed systems) while cooling coils are in the display cabinets or cold rooms. Distributed systems may be thought of as smaller centralized systems which have lower refrigerant charge levels (and therefore, less leak impact and better energy efficiency due to closer matching of the system to the refrigeration load). Several possible designs exist and will be addressed in greater detail in Section 5.4. Two main design options are: direct and indirect systems.

5.2.3.1 Direct systems

Direct systems are the most widespread. The refrigerant circulates from the machinery room to the sales area or cold rooms, where it evaporates in heat exchangers, and then returns in vapour phase to the suction headers of the compressor racks. In the machinery room, racks of multiple compressors are installed; these utilize common discharge lines to the air- or water-cooled condenser(s) (located outside the store or on the roof) and common suction and liquid lines to the refrigerated fixtures. Specific compressor racks are dedicated to low temperature and others to medium temperature. The refrigerant circuit of each rack can be independent or coupled, as in a booster system. Supermarket centralized systems with long piping circuits have led to large refrigerant charges (100 to 3,000 kg depending on the size of the supermarket) and consequently to large refrigerant losses if ruptures occur. Average leak rates are historically around 15 to 25 % of refrigerant charge per year. Data from supermarkets that have made efforts to reduce leakage through improved design and maintenance measures show that it is possible to reduce leak rates from large direct systems to under 5 % (EPA, 2022). Use of flammable refrigerants combined with leak detectors and isolating valves could lead to a reduction in leaks for these types of systems.

5.2.3.2 Indirect systems

Indirect systems are composed of primary heat exchangers where a heat transfer fluid (HTF), also called secondary refrigerant, is cooled, and pumped to the display cases where it absorbs heat, and then returned to the primary heat exchanger. The primary refrigeration system could be in a machinery room or on the roof, away from the display cases and refrigerated spaces. HTFs have been receiving interest because indirect systems allow for lower primary refrigerant charge and facilitate the use of flammable or toxic refrigerants when isolated from the sales area. Indirect systems also offer a greater level of flexibility in the display of food products in a retail environment. However, indirect systems are usually less energy efficient than direct systems due to the transfer of heat from the air to the refrigerant through an intermediary fluid and because of the pumping power required to circulate the secondary refrigerant.



Small stand-alone systems 0.5 to 3 kW	Factory built sealed units used for retail display or storage of chilled or frozen food and drink in shops and restaurants. Illustration show: (a) open-fronted drinks display cabinet (b) ice cream freezer
Condensing units 3 to 20 kW	Split units used for retail or storage of chilled or frozen food and drink in shops and restaurants. Display case contains evaporator which is connected by site-installed pipework to a condensing unit (compressor and condensor). Illustration show: (a) condensing units (b) diagram of typical layout
Central systems **Small:** 15 to 40 kW **Large:** above 40 kW	Many display cases (e.g 10 to 20) withindividual evaporators connected by complex site-installed pipework to centralised compressor pack and condenser. Illustration shows: (a) multi-compressor pack (b) diagram of typical layout

Figure 5-1: Types of equipment and applications in food retail and food service

5.3 Refrigerant options for new remote condensing unit systems

In this section, the different types of refrigeration equipment and the lower GWP refrigerant options for use in new remote condensing units are presented. The shift to non-ODS refrigerants has been completed in non-Article 5 parties, but HCFC-22 is still used in new equipment in some Article 5 parties. Globally, high-GWP HFC refrigerants are still widely used for new equipment, but it is expected that the phasedown according to the Kigali amendment will rapidly advance the use of low- and ultra-low GWP alternatives.

Refrigerant options for new remote condensing units can employ direct expansion (DX) with the exception of the Ultralow-GWP HCs that may require indirect (using a heat transfer fluid, or HTF). Flammability and toxicity are often the reasons why a refrigerant is used in an indirect system instead of a direct.

5.3.1 System configurations

Condensing units comprise of one or two compressors, an air- or water-cooled condenser (air-cooled is most common) and a refrigerant liquid receiver tank, assembled on a base plate, to be connected to the evaporator coil section of a refrigeration circuit. Condensing units are designed for different capacities and are standardized equipment. They are commonly used in food retail and food service refrigeration worldwide, especially in developing countries. The design is usually a basic vapour compression cycle and the usual refrigerants used in Article 5 parties are HCFC-22 and more recently HFC-134a and R-404A. In all non-Article 5 parties HCFC-22 is no longer used in new condensing units and the use of HFC-134a and R-404A is rapidly declining. Instead, several lower GWP alternatives are used as described in Section 5.3.4.

Figure 5-2: A Condensing unit with a condenser and one compressor

5.3.2 Important Parameters Influencing Refrigerants' Choice

Availability of refrigerant, including regulatory restrictions and the total cost of ownership. The local regulations often dictate the types of refrigerants that are commonly used as regulations lead to availability of refrigerants for charging new equipment and servicing when the need arises. Total cost of ownership is the first cost of the equipment, including the refrigerant cost, as well as the operating cost, which will include energy input and service over the life of the equipment.

Performance – capacity under all ambient and use conditions. Most refrigeration systems are selected to operate at around two-thirds to three quarters of their full rated capacity, which gives the system that extra refrigeration capacity that is needed for unforeseen extreme thermal load conditions. It is not uncommon for condensing unit systems to require very low capacities, especially during those times when the door openings are few and at large intervals (e.g., night-time). It is important therefore for the system to perform efficiently at all these different load conditions. For these reasons, variable capacity condensing units are used if the total cost of ownership can be justified. The refrigerant that is chosen must be able to operate efficiently at different evaporating and condensing temperature conditions.

Energy efficiency is one of the performance characteristics that is important in the choice of the refrigerant. When choosing based on energy efficiency, the tendency is to select best efficiency for the peak load condition; however, systems operate at maximum peak load only for a few hours. It is important to perform a whole year analysis based on the location's weather data if the condensing unit is to be located outdoors. If the condensing unit is located in an indoor conditioned space, of course, the annual performance is not likely to vary significantly. While the whole year performance affects the total energy demand, in some areas, the peak power consumed could dictate how the utility bill is calculated and will be important to reduce operating costs.

Safety considerations are important since low- and ultralow-GWP refrigerants are often toxic, flammable, or with high operating pressures which need special design and installation procedures to be followed. The choice of the refrigerant becomes important to where and how the equipment will be used including what is permitted as per local codes and standards. Of course, this could also increase the first cost and the installation cost of the equipment. Global, regional, and national standards exist that detail all the requirements for safe design, installation, operation, and maintenance of systems that contain flammable refrigerants. The two standards that are relevant for food retail and food service refrigeration condensing unit equipment safety are the IEC 60335-2-89 or the corresponding local and regional standards. In addition, ASHRAE Standard 15 and ISO 5149 are also important for the installation of these types of equipment. Chapter 3 of this report covers safety considerations in refrigerant selection.

5.3.3 Refrigerant Options

5.3.3.1 High- and medium-GWP non-flammable HFC and HFC/HFO blends

For HCFC-22 and R-404A replacement, several refrigerant blends such as R-448A, R-449A, R-449B, R-452A including some that have not yet received their ASHRAE-34/ISO-817 designations are being made available that serve as "transition" options. Their GWPs range from about 1000 to 2100 and are considered high-GWP refrigerants. However, as alternatives to R-404A these refrigerants can still offer a significant reduction in GWP. They are all non-flammable (A1) and are designed to replace HCFC-22 or R-404A, used either as retrofit refrigerants or in new equipment. Many of them exhibit temperature glide from 4 to 7 K which requires special attention for the selection and operation of components. R-450A and R-513A are considered as medium-GWP refrigerants and are non-flammable alternatives for HFC-134a in this type of equipment.

Wherever safety standards are not yet adopted for the use of flammable refrigerants, and wherever it is not possible to design and install R-744 condensing units for cost or building code reasons, choosing a lower GWP A1 refrigerant in place of R-404A or HFC-134a, is always recommended.

5.3.3.2 Low-GWP and lower flammability (A2L) HFC/HFO blends

A new set of low-GWP alternative refrigerant blends for HFC-134a, R-404A and HCFC-22 replacement is also being introduced with GWPs ranging from less than 150 to 300, such as R-454A, R-454C, R-455A and R-457A. These are all lower flammability (A2L) refrigerants. Many low-GWP HFC/HFO blends contain HFC-32 and HFO-1234yf and/or HFO-1234ze(E). Tests on these alternative blends reported by Schultz, 2013 show a volumetric capacity either identical or varying in the range of ±5 %, with an efficiency 2 to 7 % lower compared to HCFC-22. The results indicate that "soft optimization" (no major component changes in equipment) could lead to performances on the level of the baseline refrigerants. Nevertheless, equipment manufacturers must consider in the new equipment design that all these refrigerant blends have temperature glide varying from 4 to 7 K. Many HFO refrigerants are A2L and do not exhibit glide and are used in larger medium temperature condensing unit applications where the size of the system is acceptable. Equipment using A2L class of refrigerants have to meet safety standards and local codes for installation and use.

5.3.3.3 Ultralow-GWP R-744 (CO_2)

R-744 condensing units are commercially available in Europe and Asia. R-744 condensing units may require a two-stage design if high ambient temperatures occur frequently. Cost remains the main barrier for R-744 condensing units in certain regions, but with increasing production capacity and financial incentives, this barrier may be overcome in the future. In a pilot program using R-744 condensing units in 12 Indonesian pilot stores, energy savings of 20 % compared to the existing older design HCFC-22 system was observed which can also be attributed to the age of the equipment and the technology advances in components such as compressors and controls (Santoso, 2016). Other references to this type of development are also found in open literature (Karve, 2022 and Dickes, 2022).

5.3.3.4 Ultralow-GWP Hydrocarbons

Direct expansion condensing units using HC-600a, HC-290 or HC-1270 for capacities ranging from 0.1 to 10 kW (up to 1.4 kg charge) are commercially available from major manufacturers for service temperatures ranging from -40 to 0 °C. Costs for these HC-based systems can be up to 15 % higher than HFC systems due to safety measures required for risks' mitigation, but life-time operating cost may be lower due to their higher energy efficiency. Due to flammability concerns (Hydrocarbons are A3 flammable), indirect condensing units using HC-290 or HC-1270 with typical refrigerant charges varying from 1 to 20 kg, are emerging in several regions.

5.3.4 Summary for Remote Condensing Unit Systems

The replacements of HCFC-22 and R-404A with low-GWP HFC/HFO blends are underway and very low-GWP alternatives such as R-744 and HCs are also available. Many of the newer low-GWP replacement refrigerants for R-404A tend to be classified as lower flammability A2L refrigerants. The use of these refrigerants can be expected to grow as standards get developed and the refrigerants become more readily available. The use of HC-290 is also growing in this application as safety standards get updated. R-744, the only ultralow-GWP refrigerant classified as an A1 alternative, is also increasing in use, especially in Europe and more recently, Asia. Many Article 5 parties are still using HCFC-22 and may wish to take steps to avoid introduction of R-404A and to leapfrog to low-GWP solutions.

5.4 Refrigerant options for new centralized and distributed systems

In this section, different types of refrigeration equipment and lower GWP refrigerant options for use in new centralized systems are presented. Transfer to non-ODS refrigerants has been completed in non-Article 5 parties, but HCFC-22 is still in use in Article 5 parties. High-GWP refrigerants like R-404A are used for new equipment, but it is expected that phasing down according to the Kigali amendment will advance the use of low-GWP alternatives.

Table 5-1 indicates how current high-GWP and replacement lower GWP refrigerants are used in the direct expansion (DX) or indirect (with a heat transfer fluid, or HTF) configurations. Flammability and toxicity are often the reasons why a refrigerant is used in an indirect system instead of a direct.

***Table 5-1**: Refrigerant options for new centralized and distributed systems.*

	System Configuration	
High-GWP HFC (current)	DX and indirect	
Medium-GWP HFC/HFO	DX and indirect	
Low-GWP HFC/HFO	DX and indirect	
Ultralow-GWP HFC/HFO	DX and indirect	
Ultralow-GWP HCs	Indirect	
Ultralow-GWP R-744	DX	
Ultralow-GWP R-717	Indirect	

5.4.1 System Configurations

Centralized systems are the preferred option in medium to large supermarkets, because they usually achieve better energy efficiency than stand-alone cabinets and condensing units. This is mainly due to compressor isentropic efficiencies being higher for larger compressors (in the range of 60 to 70 %) compared to smaller compressors (in the range of 40 to 50 %) used in stand-alone cabinets. Having multiple compressors also enables modulation that reduces the system cycling losses. The sales area of supermarkets with centralized refrigeration systems varies from 400 up to 20,000 m^2.

Generally, for large supermarkets, the reference design is a direct-expansion centralized system with several racks of compressors operating at the two evaporation temperature levels (-10 ± 4 °C and -32 ± 4 °C for example). Several refrigeration system designs exist for medium to large supermarkets; these designs have an impact on refrigerant choices, refrigerant inventories, and energy efficiency. Conventionally, they operate with racks of parallel piped compressors installed in a machinery room, typically in the past using HCFC or HFC in direct expansion refrigeration systems. Usually, the multi-compressor racks operate with a common condenser which provides several different evaporators with liquid refrigerant.

The different central multi-compressor refrigeration systems offered on the market can be categorized according to:

- The choice of refrigerant(s),
  - HCFC, HFC or HFC/HFO blends
  - Carbon dioxide (R-744)
  - Hydrocarbon (HC, e.g., HC-290, HC-1270)
  - Ammonia (R-717)
- The type of refrigerant distribution
  - Direct expansion or
  - Indirect via a heat transfer fluid (HTF) – the HTF can be single phase liquid (mainly used for MT), melting ice slurry (only MT) or evaporating R-744 (MT and LT)
- The method of cooling of the condenser/gas cooler
  - Air cooled, with or without heat recovery from outgoing hot air
  - Water cooled, with or without heat recovery from outgoing hot water

Typical refrigeration systems have separate MT and LT circuits, but systems working with R-744 often combine MT and LT in one compound system. Due to safety and technology reasons, not all combinations are acceptable in practice. For example, R-717 by reason of its higher toxicity is excluded from the sales area and it will therefore never be used in direct expansion systems in the sales area of a supermarket; but R-717 can be and is being used safely as a refrigerant in an indirect supermarket refrigeration system.

The evaporator of a direct expansion systems is in the cooled space (i.e., within refrigerated cases and cold rooms). Condensers can be arranged in air-cooled machine rooms in the building or outside of the building. Heat recovered from the condenser can be used for room air or water heating. DX systems are common worldwide and is the dominant technology for supermarkets. The direct expansion centralized system is therefore often used as the reference for comparisons of energy performances and refrigerant charges.

Direct expansion systems will always have refrigerant-carrying pipes and components inside the sales area where the public may enter. Therefore, the refrigerant will be restricted to lower toxicity, non-flammable safety classification (i.e., class A1 as per ASHRAE 34 and safety standards such as ISO 5149 and EN 378) or the charge will be limited if the refrigerant is flammable.

For cost reasons and for technical simplicity, food retail and food service centralized systems have usually been designed with a single compression stage even for deep freezing levels down to -38 °C. Two design options, cascade, and booster systems, which are common in industrial refrigeration, have been introduced in food retail and food service refrigeration to improve energy efficiency (see Figures 5-3 and 5-4). They can be used for all refrigerants, but the development has been especially made for R-744.

5.4.1.1 Cascade systems

The cascade system, as shown in Figure 5-3, connects the low-temperature compressor rack to the medium-temperature level, via an evaporator-condenser where the heat released by the low-temperature rack is absorbed by the evaporation of the medium-temperature refrigerant. The refrigerants at the two levels of temperature can be either different or identical. However, typically different refrigerants that are energy efficient in the respective temperature range are selected. Two-stage cascade systems can be more efficient than single-stage ones depending on the choice of refrigerant and the geographic or climate location. This could be a cascade system – e.g., by using HFC-134a or R-513A at the medium-temperature level and R-744 in the low temperature – in large supermarkets.

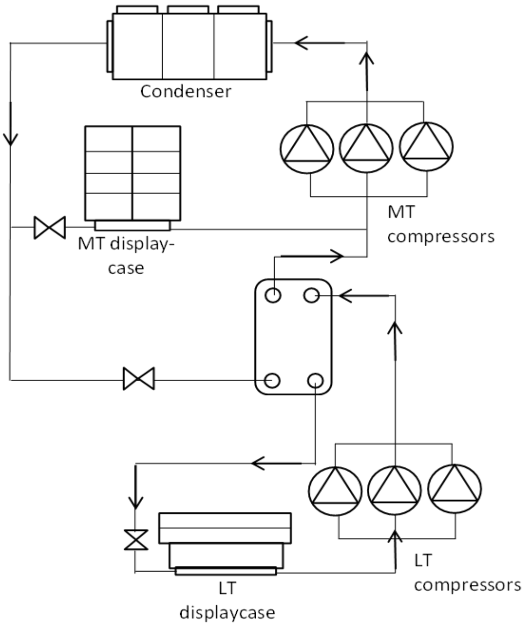


Figure 5-3: Cascade system.

5.4.1.2 Booster systems

Another design, which is simpler and less costly, is also developed and now installed frequently for centralized systems in food retail and food service refrigeration. Figure 5-4 depicts a typical booster system. The low-temperature compressor rack discharges its vapour directly in the suction line of the medium-temperature rack where it is mixed with the medium-temperature vapour. In this design, the refrigerant is the same for the low- and medium-temperature levels. The booster system offers several levels of pressure by using a flash tank and several expansion valves. A first expansion valve EV1 expands the refrigerant exiting the gas cooler/condenser into the flash tank at a first intermediate pressure; the vapour generated by this first expansion is either expanded by EV2 to the suction of the medium-temperature compressor rack, or it can be directly compressed back to the high-pressure level in a parallel compressor, improving the overall efficiency (not shown in the figure). The intermediate pressure level can also be used for comfort cooling purposes.

These two designs are now installed in thousands of stores: booster systems – with an all R-744 systems - both for larger and smaller stores, as well as for large hypermarkets. These stores are currently mostly found in Europe, North America, and Australia, but are gaining adoption in the rest of the world.

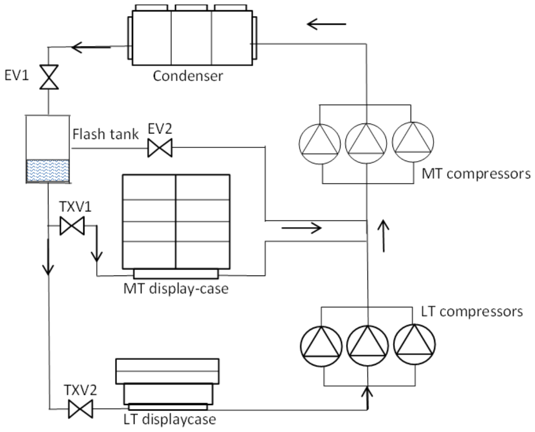


Figure 5-4: Booster system

5.4.1.3 Distributed systems

Distributed systems (Figure 5-5) consist of several compact compressor systems with air or water-cooled condensers. The compressor systems are located in sound-proof boxes, which can be installed in the sales area or close to it. The design is compact, and the refrigerant lines are short, which improves reliability and limits the pressure-drop losses in the refrigerant lines. The refrigerant inventory of a distributed system could be smaller by as much as 50 % or more, compared to a DX centralized system, while the energy efficiency can be in the same range or higher. The lower refrigerant charge in the various distributed system designs leads to less impact of accidental leaks and therefore, a lower Life Cycle Climate Performance (LCCP) for these systems compared to a single large system with HFC as refrigerant. With the new refrigerants being A2L, limits on maximum refrigerant charge make the distributed system well suited for accommodating A2L flammable refrigerants.

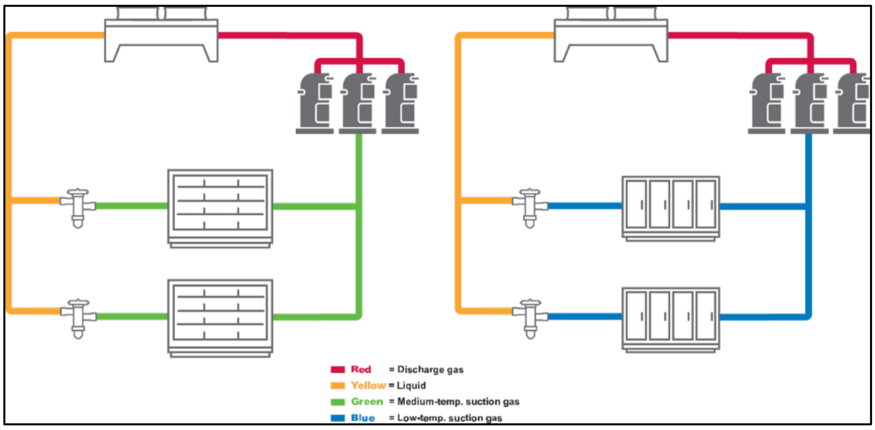


Figure 5-5: Distributed refrigeration system

A version of a distributed system with low refrigerant charge uses the booster architecture that was reviewed in section 5.4.1.2, except that the refrigerant is a low pressure, medium or low-GWP refrigerants like R-513A, HFO-1234ze or HFO-1234yf and is shown in Figure 5-6. The booster architecture, with the low temperature units placed close to the refrigeration load, allows for minimal pressure drop losses thus enabling the use of low-pressure refrigerants in a central architecture (Patenaude, 2021).

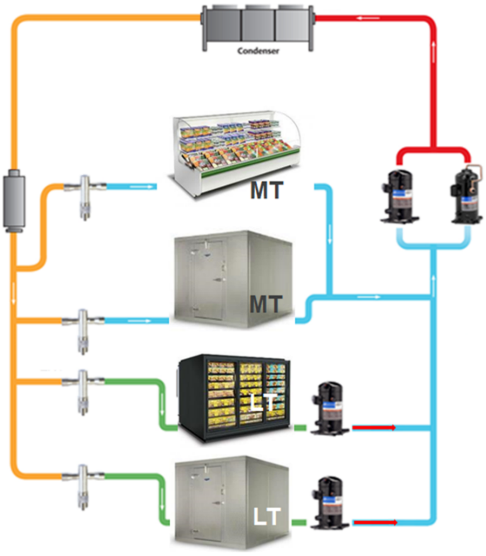


Figure 5-6: Low temperature booster compressors in a distributed MT system

Another version of this uses the cascade arrangement discussed above. The claimed advantage with this architecture is that the medium temperature could use a low-pressure A1 refrigerant like R-471A, and the low temperature freezer cases could be low-charge stand-alone systems with an A3 or A2L refrigerant in it and rejecting the condenser heat to the medium temperature system. This is shown in Figure 5-7 below (Gao, 2022).

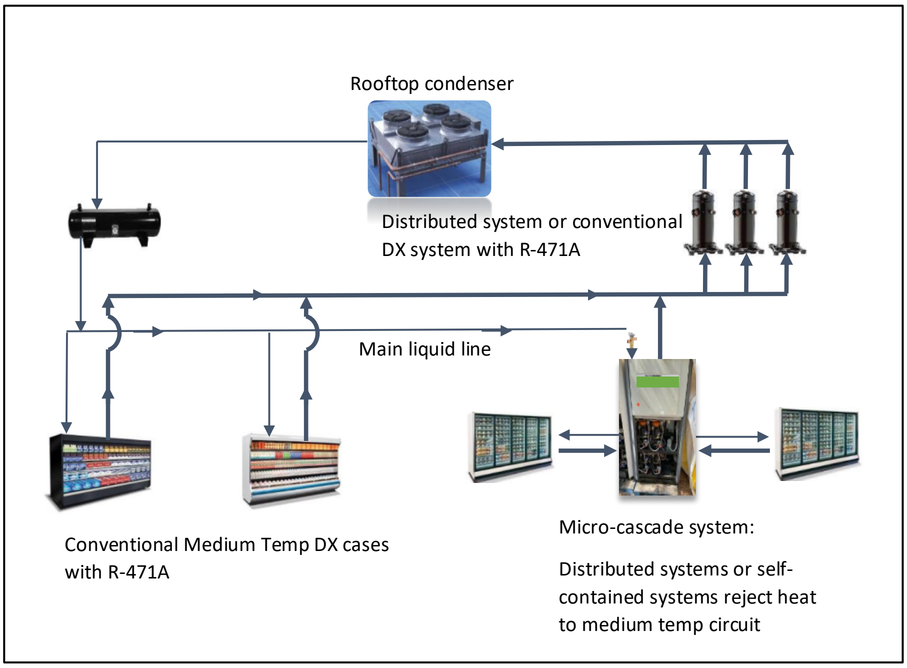


Figure 5-7: Self-contained low temperature freezers cascaded to the central medium temperature refrigeration system

5.4.1.4 Indirect Systems

Indirect systems include primary refrigeration circuits, heat exchangers and secondary refrigeration circuits, in which the secondary refrigeration cycle transports the heat by means of a HTF from the refrigerated cases or cold rooms to the evaporator of the primary refrigeration system, which can be located in a secured machine room or in the open air, i.e., isolated with no public access, see Figure 5-

8. During the last few decades, indirect systems have been developed mostly for the medium temperature level, enabling a reduction of the refrigerant charge by at least 50 %.

One configuration is shown in

8, where the low-temperature direct expansion system releases the condensation heat to the HTF secondary loop, leading to better energy efficiency of the low-temperature system and also allowing the use of R-744 in subcritical operation at the low-temperature level. Some other designs are also possible where the condensation heat of the low-temperature system is directly released to the atmosphere.

The use of a HTF with phase change offers an energy saving potential: ice slurry for medium temperature or R-744 for medium and low temperatures (Møller, 2003). Through the selection of the correct additive, ice slurry can also outperform a single-phase HTF (Hägg, 2005; Lagrabette, 2005). Combining thermal storage and HTF can be beneficial but has to be balanced with the increased cost and complexity of these systems.

Indirect systems make the primary refrigeration system design very compact. This enables the use of A2L and A3 refrigerants since the primary refrigerant is restricted to a machine room. One can use prefabricated units and the assembly of systems can be simplified on site. Indirect systems allow also for providing more stable temperatures and increased humidity at the points of refrigeration (Rhiemeier et al., 2009). The pumping energy of heat transfer fluid, which can be significant, in combination with the increased temperature differential due to the additional heat exchanger, must be compared with the additional energy consumption due to pressure losses of the long suction lines of direct expansion systems. In order to prevent the energy consumption increase, it is also important to select the appropriate HTF based on liquid viscosity and heat capacity (Eckert et al., 2022).

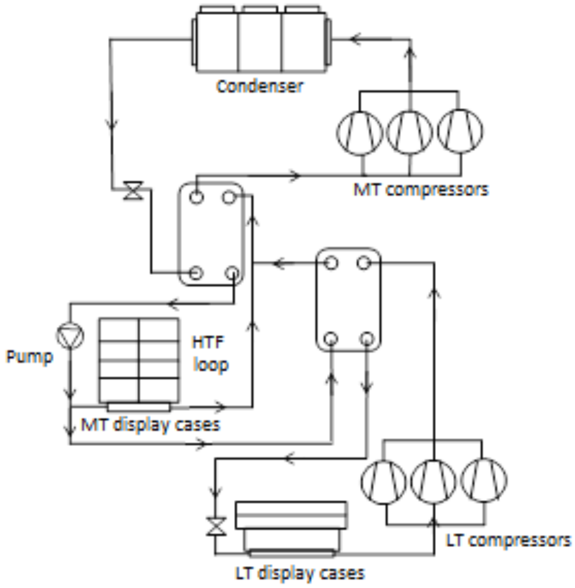


Figure 5-8: Indirect system at the medium-temperature level and direct expansion at the low-temperature level

5.4.2 Important Parameters Influencing Choice of Refrigerants

The parameters that are considered when the choice of refrigerants is being made for a new central or distributed system, are similar to those for a remote condensing unit system discussed in section 5.3.2 and safety considerations discussed in section 5.3.3.

5.4.3 Refrigerant Options

5.4.3.1 High- and medium-GWP HCFCs, HFCs and HFC/HFO blends

The dominant refrigerants for centralized systems in Article 5 parties are still HCFC-22 and, in newer systems R-404A and HFC-134a. There are various non-flammable lower GWP alternatives to R-404A including R-407A, R-407F, R-448A, R-449A, and R-452A. Non-flammable HFC-134a alternatives include medium-GWP blends like R-450A and R-513A and are becoming common in non-Article 5 parties. In Japan R-407C is also used, and some stores using R-404A have switched to R-410A in the recent past. HFC-32 is beginning to be used at the medium-temperature level and is under evaluation for the low-temperature level in Japan.

5.4.3.2 Low-GWP HFCs and HFC/HFO blends

The AHRI/AREP Report # 21 (AHRI, 2013) presents several low-GWP A2L HFC/HFO blends proposed to replace R-404A in condensing units (that are the same as those proposed for centralized systems). Compared to R-404A, these blends have slightly lower refrigeration capacities, slightly higher energy efficiency, and temperature glides in the range of 4 to 7 K as against 0.7 K for R-404A. For the blends exhibiting temperature glide it is important to follow manufacturer recommendations for installing, commissioning, and servicing systems.

For some of the low-GWP HFC/HFO blends that are formulated to replace HCFC-22, tests show that the cooling capacity is 2 to 7 % lower, and the efficiency varies from -5 to +10 % (AHRI, 2013 and AHRI, 2014). Some of the blends formulated to replace R-404A can also replace HCFC-22.

The results of the AHRI/AREP reports show that soft optimization of refrigeration systems using those blends have shown similar levels of performance. Three issues on zeotropic blends are still on top of the industry list: (1) safety rules for flammable refrigerants, (2) servicing of leaked systems (operating with blends since the individual refrigerant components may leak at individual rates), and (3) commercial availability of the refrigerants (often due to pending adoption of safety standards in local codes in a region). A new set of ultralow- and low-GWP HFC/HFO refrigerant blends is also being introduced with GWP around 150 or less. In general, these new refrigerants are A2L rated and could only be used in charge-limited systems such as stand-alone, condensing units, distributed, and secondary equipment indirect systems (de Larminat, 2018). In Europe, R-454A and R-454C are being used by several retailers in supermarket settings with good results (Emerson, 2021).

5.4.3.3 Ultralow-GWP HC-290 and HC-1270

Refrigerant changes to A3 HC refrigerants began in the early 2000s in Europe, especially in Germany, where propylene (HC-1270) was introduced in supermarkets, using a secondary loop indirect system, HC-290 is now the preferred option due to better refrigerant stability at high compression discharge temperatures. For all HCs, due to the A3 rating of the refrigerant, the machinery room is located outside of the store or well ventilated. The number of these HC-systems is limited; however, charge reduction strategies can help in increasing the number of systems with these flammable refrigerants.

5.4.3.4 Ultralow-GWP R-717

Due to its toxicity, R-717 is confined in a ventilated machinery room and R-717 systems are always designed with secondary loops, indirect systems, at each temperature level. Several large supermarkets operate with R-717 especially in Luxembourg and Switzerland. R-717 can be used in indirect systems at the medium-temperature level, and also cascaded together with R-744 at the low-temperature level. Research into low-charge R-717 systems are also underway in Europe and North America.

5.4.3.5 Ultralow-GWP R-744

The real breakthrough in using R-744 as a refrigerant began around 2005 with two major new options: R-744 as the only refrigerant in booster systems and R-744 in cascade systems along with HFCs or other refrigerants.

For using R-744 as the only refrigerant in small, medium, and large size supermarkets, R-744 has been introduced in transcritical booster systems (Figure 5-4). In 2021, more than 40,000 transcritical R-744 systems of different sizes have been installed, mainly in Europe (85 %) (Koegelenberg, 2021)). Due to the widespread use of R-744 in Europe and growing use in North America, the cost of systems has been significantly reduced and now compete with HFC systems. These systems are often made as integrated systems, serving all refrigeration, air-conditioning, and heating loads in a building.

In cascade systems, R-744 operates only at the low-temperature level. The medium-temperature compressor rack works with HFC-134a or R-717. Level of training and preferences of the contractor may influence the choice between transcritical R-744 and cascade system.

Basic R-744 transcritical booster systems without design enhancements to improve performance are less efficient than HFC systems at ambient temperatures above 26 °C, but methods such as mechanical subcooling, ejectors, vapour injection, adiabatic condenser, and parallel compression, for example, are being used to improve performance. These concepts enable energy efficient operation also at higher ambient temperature conditions, and numerous systems have been implemented lately in hot climates (Hafner, 2018).

5.4.4 Summary for Centralized Systems

For centralized systems several options are available and proven; some of them require a higher technical training for contractors, especially for R-744 systems.

The replacement of R-404A is underway and will lead to several technical options with either R-744 at all temperature levels or low-GWP HFC/HFO blends at the medium temperature operating in cascade with R-744 at the low temperature. R-404A replacements that are non-flammable and lower than 1500 GWP will grow in use in existing R-404A systems. Low-GWP and A2L flammable HFC/HFO blends at all temperature levels will also increase in use, largely in Europe, followed by the United States and other countries. The change to flammable lower GWP alternatives is giving rise to innovations in system architecture with a focus on charge reduction strategies, with fewer or better joints, variable speed technology, and better control, leak detection and isolation valves, all with the goal of reducing risk, cost, and complexity.

Regardless of the refrigerant chosen for a food retail and food service refrigeration system, it is important that a whole system approach be taken to the design, selection, installation, and commissioning of the equipment. Load reduction, through better insulation, or location of refrigerated cases, use of doors for retail cabinets and shelves whenever possible, etc., can help reduce the size of the equipment and the refrigerant charge. An integrated approach to system design should account for the presence of and interaction with other equipment in the space, such as the space heating/cooling, air conditioning, dehumidifying, and even the heating of water, to name a few. This approach may lead to new system designs that minimize the amount of refrigerant used, reduce the potential for leaks, and improve the life cycle climate performance of the food retail and food service refrigeration system in the context of the use of the equipment.

5.5 Refrigerant options for existing equipment

This section covers the retrofit options for the installed base of equipment. Many of the new lower GWP refrigerant options have higher pressures, higher flammability, and as such, cannot be used to replace high-GWP HFCs in existing equipment. When retrofitting refrigerants in existing equipment, it is recommended to consult with the refrigerant and equipment manufacturers as well as appropriate safety standards and building codes. The newer lower GWP HFC/HFO blends also exhibit “temperature glide.” Therefore, it is important to make sure that the system design can accommodate this glide, such as design and selection of heat exchangers, expansion devices, etc. It is also important to follow manufacturer recommended guidelines to adjust superheat and subcooling setpoints for optimum performance.

For stand-alone equipment, there is no real incentive to change the refrigerant because the refrigeration circuit is totally brazed and hermetic, and this type of equipment will be changed based on its current lifetime if no heavy leaks occur. However, options for stand-alone equipment include R-448A, R-449A, or R-452A as replacements for R-404A and R-450A or R-513A as replacements for HFC-134a. These replacement refrigerants are classified as A1 and can be used for retrofitting. This list can be expected to grow as more manufacturers release alternatives for existing refrigerants and equipment.

The R-407 series of refrigerants like R-407A, R-407F, and R-407H are now used in many countries as retrofit refrigerants for R-404A depending on individual manufacturers’ approvals. These refrigerants, including R-407C, are commercially available and are also formulated to replace HCFC-22. Newer HFC/HFO blends with GWP close to or lower than 2000, such as R-448A, R-449A, R-452A, etc., are also commercially available and are candidates to replace HCFC-22 and R-404A. In fact, the most important issue for the replacement of HCFC-22 in Article 5 parties will be to find replacement options at acceptable costs; given the fact that low-income countries will lag behind non-Article 5 parties in adopting these changes, the cost of these changes can be expected to be better when Article 5 parties are ready to make the change.

Depending on the lifetime of refrigeration systems, the retrofit option is part of the refrigerant management plan required to follow the phasedown schedule. Recovery and recycling of existing refrigerants represent a strong option in order to smoothen the transition from present day refrigerants to a series of lower GWP options.

In Europe, particularly in the UK, one large retailer has embarked on a conversion and retrofit program (Emerson, 2021) to transition from R-407A to R-448A and eventually to the low-GWP R-454A (an A2L), thus bringing the store down to a GWP of around 250 from close to 2000. Changing classes from A1 to A2L in an existing store requires careful planning to first convert all the equipment over to A2L compliance and then change the refrigerant, if the local and regional regulation will allow it. More common is the transition to around 1400 GWP, by retrofitting R-404A and R-407A systems with R-448A or R-449A. The fact that all these refrigerants use the same lubricant family has helped the retrofit process to a great extent. In some regions, as in the state of California, owners of large fleet of equipment are required to reduce the fleet wide average GWP by significant amounts in order to stay compliant with the local regulations.

5.6 Energy Efficiency in Food Retail and Food Service Equipment

5.6.1 New equipment

Energy efficiency of food retail and food service refrigeration equipment is often prescribed by national and regional mandated minimums and defined or measured using standards and test methods defined by organizations such as ISO, ASHRAE and AHRI. A few additional points are made here which are particularly relevant for new equipment but could have relevance to existing equipment as well. As is common practice, the term “energy efficiency” is used in these sections, but what is more relevant for any refrigeration system is the energy consumed. Reductions in electricity consumption can come from reduction in cooling load, component, and refrigeration system design improvements as well as optimum control, operation, and maintenance of the system. The first measure often yields better results, e.g., the addition of doors to retail display cabinets can reduce cooling load by as much as two-thirds, thus leading to significant electrical energy consumption reduction. This is shown in Figure 5-9, i.e., a comparison of the individual electrical energy saving measures in percent of aggregate energy consumption of the refrigeration system. The savings illustrated cannot be added together, but they illustrate the excellent potential to reduce energy consumption in food retail and food service refrigeration (Kauffeld, 2015).

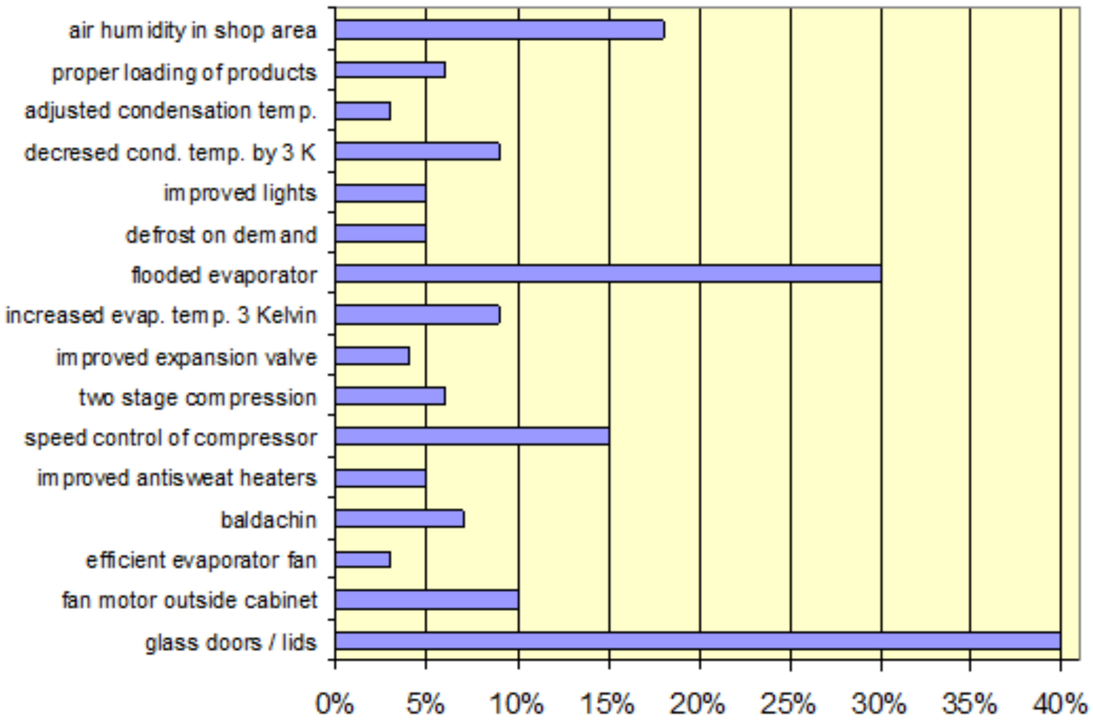


Figure 5-9: Comparison of individual energy saving measures as a percent of total electrical energy consumption of the refrigeration systems (Kauffeld, 2015)

According to the study (Kauffeld, 2015), the following opportunities for energy savings are possible for retail refrigeration systems:

- Refrigeration cabinets/rooms cooling load reduction
  - Glass door or lid
  - Improved insulation
  - Infrared reflecting shades or baldachins
  - Improved air flow in open multideck (e.g., using aerofoil shelf edges)
  - Improved antisweat heaters, edge/rim heating, dew point control
  - Syphon in defrost drain
  - Improved lighting (e.g., high efficiency LED lights)
- Component design
  - Compressor
    - high efficiency compressor
    - two-stage compression with interstage cooling
    - speed control of compressor
    - drive (partially) by expansion machine
  - Expansion valve
    - improved expansion valve (e.g., electronic expansion valve)
    - expansion machine
    - ejector
  - Evaporator/condenser
    - high effectiveness evaporator/condenser
    - flooded evaporator
    - defrost on demand

        - hot gas defrost
        - high efficiency fan and/or fan motor
        - speed control of fan
        - fan motor outside cabinet
        - reduced condensation temperature
            - floating condensing pressure
            - evaporative cooling of the condenser
            - condenser heat to soil
            - separate subcooler
        - free ambient cooling
- Refrigeration system design
    - Heat recovery
    - Peak load shaving through cold thermal energy storage (CTES) intelligent controls
    - Cycle modification
        - parallel compression
        - suction line heat exchanger/internal heat exchanger
        - vapour injection
        - economizer
- Operation and maintenance
    - Correct product loading of the refrigerator/freezer units
    - Reduced air humidity in sales area
    - Cleaning of evaporator and condenser
- Integrated system designs, considering the supermarket as an energy system serving all duties required, RACHP, which may significantly improve the overall energy efficiency.

Since equipment design changes are commonly done when there is a change of refrigerant, this might be a good opportunity to use one or more of the following methods to improve the new system's performance (Kauffeld, 2015). The methods to improve energy efficiency listed below are not meant to be a complete and exhaustive list and as a general rule, could all be used in centralized systems and condensing units. Component level efficiency improvement such as variable capacity or variable speed compression to match load, electronically commutated motors (ECM) for fans etc., are all well established and important and are not discussed here.

5.6.1.1 Glass doors/glass lids

The use of glass doors on multideck cabinets and chest freezers can reduce the energy consumption by up to 65 % and 40 % respectively. Further reduction in energy consumption may be expected if the glass doors or lids are coated with thin metal layer capable of effectively reflecting infrared radiation. Besides the reduced cooling load via glass doors or lids the energy consumption for defrosting will be reduced by as much as 35 % (AIRAH, 2015).

5.6.1.2 System vs component efficiency

In food retail and food service refrigeration, more than in most other types of applications, it is important to take a holistic system approach to define energy efficiency. For condensing units, there are some countries that have established a whole system efficiency measure (AHRI 1250, 2014). However, for centralized systems in supermarkets, system efficiency measures are rare. Because of this, performance of components such as compressors are used to define the whole system efficiency. Taking a component or a sub-system approach to efficiency improvement, when other factors like the outdoor ambient, the cooling load, and all components of a system also influence the performance, it leaves many energy savings opportunities unaddressed (Minetto, 2018). Some of these measures, that can only be realized through a whole system approach, are described below.

5.6.1.3 Floating head pressure or low condensing operation

When air cooled condensers are used, the condensing temperature or pressure of a system tracks the ambient air temperature. It is common practice to restrict the condensing temperature from going too low in order to allow the expansion devices and compressors to work optimally. With improvements in these component technologies and the widespread use of electronics, it is possible to allow this minimum condensing temperature to be much lower. The advantage of doing this is that as the condensing temperature decreases, power consumption decreases about 3 % for every degree lower condensing temperature (Kauffeld, 2015), other studies suggest even higher impact, thus increasing the energy efficiency. By calculating the system efficiency for a whole year of operation, as opposed to just one “standard” condition, the value of this “floating head pressure” operation can be measured and accounted for.

5.6.1.4 Adiabatic condensing/Evaporative condensing

This is a method to lower the temperature of the air cooling in the condenser coil by adding moisture to the (dry) air stream. This type of condenser has been shown to be quite effective in dry warm climates for improving the efficiency of R-744 centralized systems, though this method of efficiency improvement is applicable to all refrigerants. Availability and treatment of water may however be a challenge in some areas.

5.6.1.5 Heat recovery and system integration

This has always been one of the more popular forms of system efficiency improvement and has found an increasing number of applications with the growth of R-744 as a refrigerant. The heat from the condenser/gas-cooler of the refrigeration system – especially in a centralized system – can be recovered and used to heat or preheat water, indoor air heating in the winter, and even snow melting systems buried in sidewalks at the entrance to buildings. Utilisation of heat recovery can contribute to improve the overall efficiency of the entire refrigeration system beyond what is found by the traditional method of calculating performance. When describing R-744 Booster systems, the possibility of combining comfort cooling and providing refrigeration for food was mentioned. Such a system integration may contribute to reduce the overall power consumption and also the overall cost of the supermarket energy system.

5.6.1.6 Mechanical subcooling

Mechanical subcooling is the process of cooling the refrigerant liquid out of the condenser or flash tank in order to increase the realized cooling capacity in the evaporator coil by reducing the dryness fraction of the refrigerant coming out of the expansion device and entering the inlet to the evaporator. This is a commonly used method of improving system efficiency and ensure proper expansion device performance. It can be applied to all refrigerants but is often used with transcritical R-744 systems.

5.6.1.7 Ejector

An ejector recovers some of the energy potential during refrigerant expansion compared with typical throttling valves. The most common use of an ejector is to compress the vapour (and liquid) exiting the evaporator with the energy of the throttled liquid from the high-pressure side. Two important effects are realised; the evaporators can be operated flooded, without superheat, thus increasing the evaporation temperature and; secondly that the pressure at the inlet of the compressor can be increased, reducing the power input for the compression due to lower compression ratio. System efficiency may often be increased by 20 % (Hafner, 2014b). This concept is also implemented for R-744 to achieve high efficiency for systems used in high ambient temperature conditions (Gullo, 2018).

5.6.1.8 Vapour injection

This is another method to lower the temperature of the liquid out of the condenser, but instead of using an external heat sink, the refrigerant itself is used to lower the liquid temperature. This method of efficiency improvement in systems has become quite common in developed countries and the flash tank described in the booster system is one example of this technology. Heat exchangers are also commonly used and the vapour from the flash tank or the heat exchanger is compressed from an intermediate pressure to discharge by injecting the vapour into system's compressor (common in scroll and screw compressors).

5.6.1.9 Parallel compression

Parallel compression is a method to reduce the power consumed in taking the vapour from the flash tank (described above) and compressing this to the higher pressure in the condenser. This method of improving efficiency is most commonly used with R-744 transcritical systems.

5.6.1.10 Suction line heat exchanger

A suction line heat exchanger may improve the system efficiency for certain refrigerants if the benefit of subcooling exceeds the extra compression power resulting from superheat of the suction gas. Heat is removed from the warm liquid before entering the expansion device by the cool vapour leaving the evaporator coil through a simple heat exchanger. This has the dual effect of improving efficiency and preventing liquid from entering the compressor which can also help improve the system's reliability.

5.6.2 Existing equipment

Retrofit refrigerants are approved by equipment manufacturers to be as close in performance to the ones that are being replaced and therefore, energy efficiency is often not looked at closely when making a choice. Existing equipment, however, makes up the bulk of the energy consuming devices and it is important that steps are taken to ensure that the energy consumed is not significantly higher. Fortunately, the refrigerants mentioned thus far all have as good or better performance than the ones being replaced, especially when equipment manufacturers make these recommendations. Additional steps that can and should be taken at the time of retrofit are well documented in best practices documents and some of them are listed below. It is important to note that flammable refrigerants cannot be used as a retrofit refrigerant in an existing system designed for an A1 (non-flammable) refrigerant.

5.6.2.1 Proper retrofit process

Selecting the right refrigerant is the most important first step. The right retrofit refrigerant should deliver the same refrigerating capacity as the original and the energy consumption should be equal or less. Matching the refrigerant to the compressor and the expansion valve is an equally important second step in the process. It is also necessary to check the guidelines published by the refrigerant and component (for example, compressor) manufacturers to change compressor oil, filter driers, gaskets etc. as needed. Finally, if a refrigerant exhibits temperature glide, then adjusting the refrigerant charge, superheat and subcooling taking this glide into account is critical to the retrofit success.

5.6.2.2 Proper refrigerant charge

Retrofitting is a good time to ensure that leaks, if any, are identified and repaired. Filling the correct mass of refrigerant charge as recommended by the manufacturer is important for the performance of the system and its reliability. Higher or lower refrigerant charge will lead to poor performance and efficiency loss.

5.6.2.3 Recommissioning or set-points adjustment

The temperature and pressure set points in the system drift with time for various reasons and adjusting them all back to manufacturer recommended values will help minimizing energy consumption in the equipment.

5.6.2.4 Adequate air flow over cooling and condensing coils

Inadequate air flow over the evaporator and condensing coils are another leading cause of poor energy performance in a system. Condenser and evaporator coil fouling and poor product loading in the display cases are two of the primary causes for this inadequate air flow. Poor airflow over evaporator coils can lead to icing and increase run time as well as power consumption. Evaporators and condensers should be regularly cleaned to ensure that there are no barriers to free air flow over them as per manufacturer's requirements.

5.6.2.5 Adequate defrost cycles

Too few or too many defrost cycles will lead to higher energy consumption. Getting the recommended frequency and duration of defrost cycle is important for efficiency.

5.6.2.6 Addition of doors and door heaters

As indicated before, doors on refrigerated display cases can reduce the energy consumption by as much as 65 % and adding anti-sweat heaters on doors will keep the doors functioning well, increase product visibility and reduce the need for frequent defrost – all leading to reduced energy consumption and improved efficiency. Important to note that the heaters will increase power consumption but, this can be mitigated through smart controls that consider ambient conditions and usage factors.

5.6.2.7 Conversion to LED lighting

This is a good energy saving option that can be retrofitted to existing display cases which do not have low energy LED lighting. Utilities and government agencies often offer incentives to retrofit the lighting as well. LEDs are more efficient and therefore put out less heat, thus making the refrigerated display case work better to maintain temperature and reducing the refrigeration load.

5.7 Concluding remarks

Several countries and regions have started adopting some form of controls on the use of high-GWP HFC gases in food retail and food service applications. The F-gas regulation 517/2014 in Europe and the Canadian regulations released in October 2017 have been in effect for some time, whereas in the U.S., the American Innovation in Manufacturing Act of 2020 (AIM Act) was signed into law on Dec 27, 2020. This is significant as the bill directs the US Environmental Protection Agency (EPA) to phase down the use of HFC gases as per the same schedule as the Kigali Amendment and gives the EPA specific authority to control the use of HFC gases in all applications.

The commonly used HFCs in existing food retail and food service are R-404A and HFC-134a and in many Article 5 parties HCFC-22 is also used. Ultralow-, low- and medium-GWP alternatives for these refrigerants are now available in the European Union and North

American markets and we can expect these to grow in Article 5 parties as well, as refrigerants and components become readily available.

Non-halocarbon refrigerants such as R-744 are increasingly being used in food retail systems worldwide – both in cascaded systems (R-744 for low side cascaded with a second refrigerant like HFC-134a, R-450A, R513A, HFO-1234ze, or R-717 and HC-290 in limited cases) and in transcritical all-R-744 systems. Transcritical systems are being modified extensively to reduce their energy penalty at high ambient conditions with different component and system technologies. R-744 is also beginning to see its use in food service applications with condensing units.

Commercial stand-alone systems, which are commonly used in food retail and food service establishments, have for the most part transitioned to HC-290, with some exceptions where the properties of the halocarbon blends are needed for achieving performance (covered in Chapter 4).

Meanwhile, several lower GWP HFC/HFO blends (both A1 and A2L) are also being approved for use worldwide in various equipment types. A1 blends such as R-448A, R-449A, R-449B, R-452A, and R-407H are used as alternatives to R-404A. A1 blends R-450A, R-513A, and R-515B are used as alternatives to HFC-134a. These alternatives have GWPs ranging between one third to one half of the GWP of HFCs being replaced. These blends are also important for retrofitting existing R-404A and HFC-134a equipment to lower GWP alternatives classified under A1 category. Retrofitting is a growing trend in Europe and North America, where the recovered and recycled or reclaimed R-404A and HFC-134a are used for service. Managing the refrigerant in the existing fleet of equipment as an asset is a positive trend. A2L refrigerants like R-454A, R-454C, and R-455A are beginning to be used in Europe and elsewhere. Pure HFO refrigerants with GWP of 1 are also finding use in the upper stage of R-744 cascade systems as well as medium temperature remote condensing unit and distributed systems.

It is important for owners of food retail and food service equipment to focus on reducing both the direct (GWP) and indirect (energy) components of the greenhouse gas emissions from the use of their equipment. With growing attention on sustainability, a sustainable cold chain in the food retail and food service refrigeration is important for reducing both the direct and indirect environmental impact of the equipment.

Best-practices for new equipment discussed in this chapter include:

- Reduce refrigeration load through proper design practices
- Reduce refrigerant charge
- Reduce joints and opportunities for leaks through use of leak-tight design
- Use as low a GWP refrigerant as possible, whether A1, A2L or A3
- Use components and systems with as high energy efficiency as possible

While for existing equipment best practices include:

- Good preventive maintenance practices to maintain operation at peak efficiency without refrigerant leaks
- Retrofit from high-GWP to lower GWP refrigerant, keeping in mind the safety class of the refrigerants
- When removing refrigerant from a system, recover, recycle, and reclaim the refrigerant

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Chapter 6

Transport refrigeration

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6 Transport refrigeration

6.1 Introduction

6.1.1 Types of equipment and applications

Transport refrigeration is a relatively small but important segment aiming at preservation of chilled and frozen food, pharmaceutical products, and other temperature-sensitive goods on various routes. The equipment comprises refrigeration units for trucks, trailers, light commercial vehicles (vans), marine containers, and air containers. They are usually designed for multiple modes of transport. For example, marine containers are carried onboard ships, but they are also frequently carried on road trailers and flatbed rail cars.

This chapter also covers all kinds of refrigeration onboard ships, including cooling of food for the crew and passengers, various process applications (liquified gas carriers, fish processing trawlers, etc.), and air conditioning systems for comfort. These systems include various industrial installations and chillers (cruise ships) that are described in detail in chapter 8. Furthermore, this chapter also covers the air conditioning systems for passenger railcars which share design features of refrigeration units for the road equipment. This chapter, however, excludes the air conditioning systems for buses. Despite similarities with railcars, bus applications are closer to those of passenger cars, and they are hence described in chapter 9. Information about technology options for other elements of the refrigerated cold chain, such as cold stores or commercial systems, is covered in other chapters of the report.

We have attempted to estimate the size of banks and emissions from transport refrigeration in previous reports (UNEP, 2010). In principle, the data may not be very different today. If these assumptions are true, the largest subsegment is that of ships, followed by road transport. Marine containers, where hermetic compressors and microchannel condensers are now common, aircraft containers due to their small capacity and quantity, and railcars due to hermetic compressors and small quantity, have a much smaller share.

Requirements for all transport refrigeration and air conditioning systems are extremely complex. First, the equipment must be small and compact, lightweight, yet have a high cooling capacity and low power consumption, which all impacts fuel consumption. The equipment must withstand shocks and vibrations on (rail) roads and environmental degradation due to corrosion (sea water, rain), UV light and extreme temperatures. Safety, for which manufacturers and, in operation, the responsible owner or stakeholder of the equipment are liable, must not be compromised despite various use modes, such as operation in tunnels or ship holds, cargo loading and unloading, etc.

The lifecycle of the equipment depends on the lifecycle of the vehicle to which it is attached. It is approximately 9 to 12 years for road vehicles, 15 to 18 years for marine containers, and 30 years or more for railcars and ships, assuming mid-life overhauls and upgrades. Even in such cases, the overall layout of the vehicle is usually given and cannot be easily changed, which thus may restrict the application of new technologies for the years to come.

6.1.2 Service technician qualification

Properly operated and maintained refrigerating systems are reliable and safe. Transport systems are unique in that the knowledge, competence for safe service and spare parts, as well as relevant safety processes and procedures, must be available along the transport routes.

The ISO committee TC 86/SC1 Safety and environmental requirements for refrigerating systems is currently developing the standard ISO 22712 (previously EN 13313), which defines the activities related to refrigerating circuits and the associated competence profiles and establishes procedures for assessing the competence of persons who carry out designing, installing, service and maintenance, leak detection, and finally dismantling the system at end of service life (prEN ISO 22712, 2018) – Table 6-1.

In the case of marine containers and ships, competent personnel must be available in all ports and hubs. Regarding road transport, the same applies to depots and service stations. For example, a large manufacturer of refrigeration equipment for road transport offers such services through 275 dealerships in North America and 404 dealerships in Europe. All these places must be ready when a new product is launched.

Table 6-1: The tasks covered by prEN ISO 22712, 2018

Tasks	1	Design
	2	Pre-assembling
	3	Installation
	4	Putting into Operation
	5	Commisioning
	6	Operating
	7	In-service Inspeaction
	8	Leakage Checking
	9	General Maintenance
	10	Circuit Maintenance
	11	Decomissioning
	12	Removing Refrigerant
	13	Dismantling

6.1.3 Article 5 vs. non-Article 5 parties

In terms of equipment design, there are no substantial differences among regions, and the same refrigeration units are operated in the high ambient countries as well as low ambient countries. Road vehicles frequently travel large distances from warm climates where food is produced to colder climates. Marine containers and some ships travel across the globe all the time. The main differences are related to different regulations (i.e., refrigerant GWP, diesel emissions) and, according to our information, the latest low-GWP refrigerants are not easily available outside developed countries and there would be a barrier for implementation because of their cost. This could continue unless there are controls imposed by local governments.

6.2 Refrigerant options for new and existing equipment

6.2.1 Truck, trailers, light commercial vehicles (vans)

The majority of trucks and trailers today uses R-404A or R-452A. R-404A is still used in new equipment in some countries and represents a major part of the global fleet. HFC phasedown regulations have encouraged manufacturers to offer lower GWP alternatives since 2017, so today most new trucks and trailers in Europe and North America have transitioned to R-452A. R-452A is an A1 refrigerant with properties very close to R-404A. However, the GWP of R-452A is still considered high compared to suggested acceptable long term GWP values. There is a small number of trucks and trailers that use cryogenic liquid CO_2 or liquid N_2, but their use and market penetration depends on the availability of the cryogens.

Due to environmental reasons, the GWP for truck, trailer and light commercial vehicles is expected to come down consistently in the coming years with present and future legislation; the pace at which the transition will occur is unclear. As small systems utilizing HC-290 or R-744 became available on the market (www.pbx.at, 2022, greencold.co.uk, 2022), experts predict that HC-290 or R-744 will prevail in the long-term. However, other experts and manufacturers are concerned about technical and/or cost challenges related to flammability or high pressure, and because of this, are investigating A2L or A1 blends, with GWP levels below 500, for example R-454A or R-454C. Besides direct expansion systems, indirect systems described in ISO 20854 (2019) and prEN 17893 (2022) have been proposed. The indirect systems reduce the refrigerant charge and avoid the possibility of refrigerant leakage into the cargo space.

An additional trend is the attention to reduce or eliminate all the possible leak points in the refrigeration system. The trend towards hermetic compressors, fewer joints, mandatory periodic inspections is expected to continue, aimed at reducing direct emission.

The majority of installed base and new production of truck and trailer refrigeration machines use a dedicated diesel engine as their source of power. As these emissions have environmental impact, and there is limited space for their control, manufactures are looking at alternative ways of powering the refrigeration system, for example, from the trailer axles with battery backup or electrically from the main tractor unit drive system or a fuel cell. Recently, some manufacturers have introduced systems electrically powered via batteries or with cryogenic (open loop) CO_2, eliminating the need for the diesel engine. These systems still represent a very small portion of the market, but their penetration is growing fast, particularly in Europe.

Light commercial vehicles (LCV) typically use the euro 6 engine of the main vehicle to belt-drive the compressor. The installed base uses mainly HFC-134a, while some new platforms will use HFO-1234yf. Some manufacturers have introduced electric drive hermetic compressor systems, and we expect their penetration to increase, one reason being the smaller refrigerant charge.

Insulated roll cages either use blast frozen eutectics or dry ice or sometimes a small HFC refrigeration system or Peltier electronic cooling.

6.2.2 Marine containers

The majority of marine container refrigeration units in service operate on HFC-134a, though one manufacturer has a unit that operates on R-404A. The latest of these units are being offered as being retrofittable to R-513A or R-452A, respectively. The manufacturer of the refrigeration unit operating on R-404A now offers their unit to operate on HFC-134a with a retrofit option to R-513A. In Europe, R-404A is difficult to obtain; therefore, there are more of these units retrofitted to R-452A.

The standard ISO 20854 (ISO, 2019) provides the framework for the use of flammable refrigerants (currently classified as A2, A2L, A3 by standard ISO 817, 2014) in marine containers. In the future it is likely that HFO-1234yf will be used and even further ahead HC-290, though as yet no manufacturer has such a unit commercially available.

A marine container unit operating on R-744 unit exists and is commercially available; up until the present time there has been a limited uptake with only a few thousand units in service. New solutions are not being adopted due to reasons such as the conservative nature of shipping serviceability (education, training), spare parts and their inventory and availability of parts globally, or other.

Five to ten thousand so-called super freezers exist for the shipment of tuna at -60 °C, these units are a refrigerant cascade with HFC-134a in the high side and HFC-23 in the low side. R-744 based mixtures as R-469A and R-473A, or hydrocarbons as HC-170 could be considered as alternatives.

6.2.3 Swap bodies and oversized containers

Swap bodies are a type of container with self-supporting legs and can either have truck refrigeration unit or marine container refrigeration unit installed. These refrigeration units are identical to those installed in containers and trucks – see sections 6.2.1 and 6.2.2.

A new family of oversized containers have emerged that are usually longer than the standard ISO containers. These have logistic advantages in certain markets but use standard industry-wide refrigeration machinery as above.

6.2.4 Ships (refrigeration and comfort cooling)

Since the last report, the discussions in the International Maritime Organization (IMO) about decarbonizing container ships has changed dramatically. Shipping line Maersk has now placed an order for 9 ships using methanol and possibly ammonia or hydrogen in the long term as fuel. This is a huge investment but far from enough if the industry is to be decarbonized before 2050. In this context it is worth mentioning that Maersk alone has 700 ships and shipping line MSC is equally large with a similar number of ships, but they have not yet committed to decarbonize.

The announcement of ships powered by methanol, or alternatively hydrogen, has opened for the wider use of flammable refrigerants in the machine room. If hydrogen is to be used, it is foreseen that the ship will bunker ammonia and process it to hydrogen on board before use in an internal combustion engine or fuel cell. This has made the entire machine room more open to the use of ammonia in the refrigeration circuit. The current barrier are the shipyards and the classification/insurance companies which have been reluctant to accept the changes in working fluids. The main challenge of hydrogen is the hydrogen embrittlement and flammability and the ability to leak through most of the sealing normally used in refrigeration systems. Hydrogen embrittlement is the change in brittleness caused by the penetration and storage of hydrogen in a metal lattice. The consequential corrosion is similar to material fatigue - the result is hydrogen-related cracking, which limits the use of susceptible materials typically used in refrigeration.

The discussions on decarbonization are still ongoing in the IMO and a final decision has still to be taken. Time is short, and it is not clear if the current motor technology can be retrofitted to the new fluids or if it is a whole new engine package that needs to be installed. To this can be added the discussions about availability of the new fuels globally because an existing distribution network also needs to be in place as does the production capacity.

On board different types of ships, you will find that different types of refrigerants are used. With fishing vessels, HCFC-22 was previously often used, in the period from 1970's to about 2000, both for the food for the crew and for the holds. Before the mentioned period, ammonia had taken over the position as the most used refrigerant from CO_2 which is now seeing a revival. The debate is about what the future will be, as many fleet owners seek advice from their suppliers and shipyards, who are often equally uncertain of what to do. Larger companies in the container ship industry are now looking for new solutions excluding some types of working fluids and have preference for low-charge chillers based on low or very low-GWP working fluids (Maersk, 2021). CO_2 systems are finding their way to these market segments both for chilling water and for food storage systems.

Cruise ships have traditionally been heavily reliant on HFC-134a and R-410A as working fluids for the air-conditioning systems. These systems often have a large cooling capacities, typically around 24 MW. Newer cruise lines have been investing in some chillers using HFO-1234ze(E) but there are still some concerns from the insurance/classification companies on how to handle the flammability of this type of fluid. Another trend is to use CO_2 as a working fluid but again classification companies are still discussing how to handle piping and the higher pressures seen in this type of equipment, especially in sleeping accommodation. Here, chilled water is the solution and limiting the charge and requirements for the piping. One of the advantages of the absorption systems is the possibility of cooling without using too much electricity which saves fuel (Hafner et al., 2019). However, for cruise ships this is not always a useful solution because the heat required to drive the system is not constant while the heat load for cooling is high.

Absorption systems have been the centre of different studies for recovering the heat from the main engines. For some vessels this is an option because the cooling load and the heat from the engine coincide, e.g., on-board fishing vessels and merchant ships. The possibilities are there but how often it is used is still unclear. Roll and pitch movement of vessels is a challenge, which is not an issue for stationary systems.

For air-conditioning of ships, different technologies have been used depending on the capacity required and with these also different refrigerants. A vessel needs as a minimum the motor power and electricity to supply the energy needed to run the system. In 2012, an absorption chiller was installed on the cruise ship AIDAmar. The heat source is waste heat from the diesel engine's cooling water (around 80–90 °C), and the cooling capacity is 1,200 kW. The absorption chiller is also connected to the desalination unit for production of drinking water (Hafner et al., 2019).

For vessels with large air-conditioning requirements, HFC-134a is being retrofitted to use R-513A, or new systems are installed with HFO-1234ze(E). Also, the use of desiccant wheels or heat recovery wheels, as they are also called, are used but the saline environment can make it difficult to use in all applications.

Reefer ships built before 1970 were often based on ammonia but in 1972 the first reefer ships emerged with HCFC-22, and this was the solution up until the phaseout of HCFC-22. In some cases, the refrigerant was confined to the machine room, cooling a calcium chloride brine which was pumped around, and in other cases the HCFC-22 was circulated to the holds and where cooling was needed. These systems are now using different types of HFC or HFC blends. Several reefer ships using R-717 were reintroduced in the 1990s fitted with a scrubber in case of leaks; owners of new builds are now again considering other solutions such as R-717 or R-744 and a secondary fluid. The classification companies have to find out what is acceptable from their point of view.

Carriers for tuna fish operating at -60 °C in the freezing cells used HFC-23 as the second-stage refrigerant but new solutions are emerging, e.g., R-473A. In land-based systems some plants for -80 °C have been using HC-170 on the low stage, but the classification companies have not developed guidelines for this solution on board ships.

Trawlers and factory ships traditionally use R-717 or R-717/R-744 cascade, but few vessels built in the Nordic area have been using transcritical R-744 systems, which in cold waters rarely operate in transcritical mode. This gives a favourable efficiency. One vessel was sold later for use in the Indian Ocean and was reported to be working under these conditions, but no reports about the efficiency in the warmer waters are available. Plate freezers using R-717 and R-744 in cascade systems are on the market for refrigerated shipping (EIA, 2021).

6.2.5 Gas transport

Liquified natural gas (LNG) is transported at a temperature of -160 °C. Over the years the LNG carriers have changed. Originally there were vessels with large spherical tanks, but modern carriers have the hull built as an entire storage vessel. This gives some constructional challenges, but they are understood and dealt with.

Early designs were to cool by boiling some of the gas and then burning it in the ships' engines instead of simply releasing the gas to a flare.

More modern ships have been using a variety of cooling systems to maintain the temperature and thereby also the pressure. One way has been to use a multistage compressor compressing the gas to a level where another refrigeration system could cool the gas and send it back in the tanks, a kind of cascade system often referred to as an auto-cascade system. LNG auto-cascade systems utilize one compressor and a mixture of refrigerants with different boiling points (Aprea and Maiorino, 2009).

6.2.6 Rail air-conditioning

Rail air-conditioning is a subsegment consisting of passenger and driver thermal comfort systems customized for various types of vehicles, such as tramways, metros, intercity, high-speed, or locomotives. Each application has specific requirements. The units typically feature self-contained hermetic circuits with HFC-134a or sometimes R-407C in applications where high cooling capacity and compact size are necessary. In Europe, the industry has started to gradually introduce R-513A as alternative to HFC-134a in recent years. The product life is typically 30 years.

The F-gas regulation No 517/2014 (EU, 2014) is a driver for evaluation of alternatives in Europe, however, strict requirements to ensure safety in public transport are to be followed. Some customers in Germany, Switzerland, Austria, and in the Scandinavian countries have questioned the long-term availability of the HFC refrigerants and they have demanded alternatives. Already for years, the German railway has operated a limited fleet of high-speed trains with an air cycle system. These systems were also tested in France (Liebherr, 2015). However, they are not being adopted on a larger scale. Companies have also developed and are testing systems based on R-744 (Liebherr, 2022; CPA, 2022) and HC-290 (Wabtec, 2020; Knorr-Bremse, 2021). Alternatives to R-407C such as R-454C have emerged since the last assessment and could be considered.

Development of safety concepts for the various rolling stock applications need to continue hand in hand with the development of related international standards, which has not started in this subsegment.

6.2.7 Rail refrigerated transport

The equipment is either a marine container with a diesel generator set, or a refrigerated boxcar which typically has a road transport trailer units installed (BNCF, 2022). In Europe, refrigerated boxcars are no longer built. The refrigerants used are R-404C, and R-452A in new units – see chapter 6.2.1.

6.2.8 Aircraft

Passenger aircraft air-conditioning is mainly based on air cycle systems driven by bleed air from engines. Smaller aircrafts and helicopters may utilize vapour compression cycles with HFC-134a. Besides comfort, there is a need for supplemental cooling for food beverage and entertainment electronics. Larger dual-aisle aircraft are equipped with larger capacity supplemental systems with HFC-134a and secondary systems either with water glycol or other heat transfer fluid.

Transport of perishable and temperature sensitive cargo by air is managed by means of either active or passive containers because electric power is not available in aircraft holds. The active containers have rechargeable batteries and hermetic HFC-134a cooling and heating systems. The passive containers are insulated boxes, sometimes with solid CO_2 (dry ice) but more usually eutectic packs. The market is very small, and safety is paramount.

6.3 Energy efficiency

In all transport refrigeration and air-conditioning systems, the trend towards higher efficiency is continuing, driven by various factors:

- Electrically powered systems need very high efficiency systems to minimize the size and weight of batteries and power generation in general,
- In the case of diesel systems, there is the need to reduce or eliminate diesel engine fuel use to meet emission targets and to reduce cost of ownership,
- Manufacturers are driving towards sustainability goals, and reduction of the power consumption helps in this direction.

New components and system solutions are becoming more and more available and facilitate the move towards higher efficiency systems. Some examples: high efficiency compressor, variable speed drives, high efficiency microchannel heat exchangers, electronic expansion valves, high efficiency fans, and smart control logic that optimize the band of temperature depending on the type of good transported.

6.4 Safety considerations

The engineering tools for determining the system safety have been an established practice for decades. In transport refrigeration, the risk assessment methods have become available following the introduction of HFO-1234yf and R-744 in the car industry (ISO 13043, 2011) and the investigation considering flammable refrigerants for marine containers (see below).

The basis for understanding risks when using flammable fluids rely on experience and assumptions about leakage. Transport refrigerating systems must have a high level of leak tightness for correct function. The requirements for system tightness are designed by the manufacturers and represent the state of the art. The design must be such that a high degree of tightness can be maintained throughout its life with correct maintenance. A system according to EN 1127-1 (2019), i.e., a sealed system construction with enhanced tightness, does not create any hazardous areas in its surroundings during its intended use.

As leaks inevitably occur during operation, the procedure for classifying leaks and performing a risk analysis related to the occurrence of leaks, the frequency of such events and to assess the consequences is a mandatory process for the stakeholders (manufacturer, owner, operator, etc.). Catastrophic leaks due to an accident or rare malfunction are an important safety design and operation consideration.

In the past, flammable refrigerants were considered as a barrier just based on the chemical nature of the fluids. Nowadays, the consideration and evaluation of risks is increasingly seen as a driver of innovation and the opportunity to develop unique selling points. The main and most important aspects regarding safety in operation are safe handling, maintenance, and service.

While ISO 5149 (2014) and EN 378 (2016) do apply also to most types of transport systems, new standards for the safe use of flammable refrigerants are becoming available. ISO 20854 (ISO, 2019) describes the industry's best practices for the safe operation of flammable refrigerants in refrigerating systems used in marine containers operated on board ships, in terminals, on road, on rail, and on land. CEN TC 413/WG1 is developing a standard for trucks, trailers, and vans (prEN 17893, 2022). It is currently in enquiry state and expected to be published in 2023. The development of safety standards for other subsegments as needed is yet to be seen.

6.5 Concluding remarks

The transport refrigeration industry is continuing the journey to more sustainable solutions via progressive reduction of refrigerant GWP and leaks, energy efficiency improvements and diesel emissions reduction or elimination via introduction of hybrid or fully electric truck/trailer systems.

Regarding refrigerants, differences among regions are still relevant and, in general, a progressive conversion from R-404A to R-452A is happening. However, as the GWP of R-452A is still relatively high by current measures, additional steps towards very low-GWP and/or natural solutions are expected for the coming years.

The trend towards lower GWP refrigerants is supported by the progress in relevant safety standards that are making the design and application of equipment using A2L or A3 systems more acceptable and safer via specific design, operation, service, and risk assessment approaches. Particularly relevant is the progress on standard ISO 20854 (ISO, 2019) for marine container, and parallel activity on truck/trailer refrigeration systems (prEN 17893, 2022).

The reduction of energy consumption via equipment and system design and advanced control logics is continuing, also driven by the need to reduce the size of the diesel engine or eliminate the diesel engine completely for obvious environmental reasons and/or emission regulatory requirements, with the introduction (although yet in very small numbers) of fully electric truck/trailer units.

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Chapter 7

Air-to-air air conditioners and heat pumps

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7 Air-to-air air conditioners and heat pumps

7.1 Introduction

Air conditioners (ACs) and reversible air-to-air heat pumps (sometimes defined as "reversible heat pumps") ranging in size from 1 kW to around 1,100 kW comprise the vast majority of the air conditioning market (the bulk of which are less than 20 kW).[17] This broad category is sometimes referred to as air-cooled or unitary equipment. These systems cool and/or heat indoor spaces ranging from single rooms to large exhibition halls. Essentially, most are electrically driven vapour-compression systems using hermetic rotary, reciprocating or scroll compressors with single or multiple circuits for units with capacities up to about 100 kW and single or multiple semi-hermetic reciprocating, scroll or screw compressors for units with capacities up to around 1,100 kW. For cooling, air is drawn over a heat exchanger containing evaporating refrigerant. For heating, the heat exchanger contains condensing refrigerant, thereby giving up its heat to warm the air. In many systems, the circuitry enables the evaporator and condenser to be reversed to provide either heating or cooling. In some larger systems, both cooling and heating (sometimes by means of electric resistance heaters) are used to better control the humidity of the air.

Nearly all ACs, manufactured from the 1950s through to 2000, used HCFC-22 (UNEP, 2022a). The transition away from HCFC-22 is complete in non-Article 5 parties (UNEP, 2022b). The phaseout of HCFC-22 in the manufacturing and import of new products in the EU and Japan was ahead of the Montreal Protocol commitment dates, being completed by 2004 and 2010, respectively, whilst in North America and Australia/New Zealand use of HCFC-22 in new systems was prohibited from 2010 and 2016, respectively. The shift was primarily to R-410A and, to a much lesser extent R-407C and in some smaller systems, HC-290. It is noteworthy that technical options chosen at the time of the phaseout in these countries were focused on the protection of the ozone layer and not on the mitigation of climate impact. In addition, certain Article 5 parties such as the Republic of Korea also pursued an accelerated phaseout similar to non-Article 5 parties. The Kingdom of Saudi Arabia had a phaseout date of 2016 while it was 2017 in The Hashemite Kingdom of Jordan. India has banned the import of HCFC-22 in new systems from 2015 and its use in domestic production of new systems by 2025. Most other Article 5 parties are following the Montreal Protocol phaseout dates, being a prohibition in manufacturing from 2030.

Globally, as of the year 2022, one-third of the installed ACs stock use HCFC-22 while 90 % of new units use non-ODP refrigerants. An estimated 400 to 600 million HCFC-22 ACs were operating worldwide, representing approximately 0.8 Mt of HCFC-22.

Global energy demand from ACs is 8 – 10 % of the worldwide electricity production (IIR, 2019) and the total demand of air conditioning is expected to triple by 2050 while the energy demand from ACs in some countries like Saudi Arabia is 70 % of the total generated according to general authority for statistics in Saudi Arabia. According to JRAIA, the global units in use at the end of the year 2016 was 1.6 billion and the estimated yearly production is about 110 million units per year. The stock of ACs is expected to grow from the current 1 billion to 5.6 billion by 2050 (IEA, 2018). Improving energy efficiency of new units including those for replacement is thus of utmost importance.

The scope of this Chapter includes an overview of the common types of air conditioning equipment, their characteristics and where they are normally applied. The sub-sections of this

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[17] In this chapter the term "air conditioning" or "AC" applies to both air conditioners and air-to-air heat pumps.

chapter highlight the alternative refrigerants currently being used and those that are under evaluation for wider use, examining factors such as safety, climate impact, performance, cost implications, accessibility and availability of components and systems, lubricants, operation, and maintenance. In addition, issues related to refrigerant charge reduction and renewable energy technologies applied to ACs are also covered. Alternative refrigerants for existing equipment, options for refrigerant replacement (only) and retrofit are summarised and implication of refrigerant choice for new systems used in high ambient temperatures (HAT) is also addressed. Chapter 3 should be referred to for information on the ODP and GWP refrigerants and Chapter 2 for broader discussion on environmental matters.

The main developments compared to the last assessment report are related to the greatly increased substitution of HCFC-22 and the greater consideration of use of medium- and low-GWP alternatives. Non-Article 5 parties have completed final phaseout of HCFC-22 in new systems and most major Article 5 parties have initiated their transition from HCFC-22. Previously, medium- and low-GWP alternatives were not given major consideration (except hydrocarbons (HCs) such as HC-290) whereas now some manufacturers are proposing and adopting HCs. Moreover, there is considerable uptake of HFC-32 in most countries. Manufacturers are also considering the variety of new HFC/HFO blends. There are also new additions to information relating to refrigerant performance under normal and high ambient temperatures (HAT). Otherwise, implications on the use of alternative refrigerants and design of systems suitable for HAT are applicable to air conditioning as well as other applications.

7.2 Equipment types

ACs generally fall into six categories, based primarily on capacity, construction, and application, as detailed in Table 7-1.

A new class of AC that has been subject to recent research and development is a so-called “personal cooling system” (PCS), which is essentially a small robot that shadows a room occupant whilst providing local conditioned air directly to them. PCSs have considered HFC-134a, HC-290, HFC-32, HFO-1234yf and HFO-1234ze(E) (Dhumane et al. 2017; Qiao et al., 2018).

Table 7-1: Typical configurations of AC type

Type		**Primary configuration**	**Capacity range (kW)**	**HCFC-22 charge range (kg)***
Small self-contained (SSC)	Window	Small self-contained	1 – 10	0.3 – 3
	Portable	Small self-contained	1 – 10	0.3 – 3
	Through-the-wall	Small self-contained	1 – 10	0.3 – 3
	Packaged terminal	Small self-contained	1 – 10	0.3 – 3
Non-ducted single split		Non-ducted split	2 – 30	0.5 – 10
Ducted residential split		Ducted split	4 – 17.5	1 – 7
Ducted commercial split		Ducted split	10 – 1,100	5 – 300
Multi-split		Non-ducted and ducted split	4 – 300	2 – 150
Packaged ducted		Ducted self-contained	5 – 1,100	5 – 250

** HCFC-22 is used as the reference refrigerant. Whilst the majority of many types of ACs have already transitioned away from HCFC-22, it is retained as the reference refrigerant for convenience. The approximate charge for other refrigerants can be from adjusting the HCFC-22 value: 100 % for most HFCs, 75 % for HFC-32, 40 % for HC-290, for those that are applicable.*

7.2.1 Small self-contained ACs

Small Self-Contained (SSC) ACs are small capacity units in which all of the refrigeration system components are contained within a single package. These products have cooling capacities typically ranging from 1.0 kW to 10 kW, having an average size of 2.7 kW. This category of products includes the following common configurations:

- Portable air conditioner (PAC)[18]
- Window mounted room AC,
- Packaged terminal air conditioner (PTAC) and packaged terminal heat pumps (PTHP).
- Through-the-wall (TTW) AC

Figure 7-1, Figure 7-2, Figure 7-3, and Figure 7-4, depict portable, window, PTAC/PTHP and TTW types, respectively.

Small self-contained ACs are designed to heat or cool single spaces, such as bedrooms, living rooms, small shops, small restaurants and offices and other multi-unit buildings. Self-contained ACs, because of their size and relatively low cost, have often been the first individual comfort electrically driven vapour-compression systems to appear in emerging air conditioning markets. However, non-ducted split type room ACs (see 7.2.2) are being selected more frequently as the first option in most countries, resulting in a global decline in the demand for small self-contained ACs. The majority use hermetic rotary compressors.

Most small self-contained ACs historically used HCFC-22. The majority of products with non-ODP refrigerants use R-410A or HFC-32 with differing proportions using HC-290, depending upon region. HCFC-22 and R-410A systems have specific refrigerant charge levels of approximately 0.25 kg per kW of cooling capacity, for example, 0.75 kg of HCFC-22 for the average size unit of 2.7 kW, whereas those with HFC-32 is around 0.2 kg per kW and HC-290 use around 0.10 kg per kW of cooling capacity. Within Europe, a shift to HC-290 in PACs was accelerated by the European F-gas regulation.

Globally about 17 million SSC ACs are currently produced annually (JRAIA, 2022), approximately equally split between Article 5 and non-Article 5 parties. With service lives over 10 years, it is estimated that more than 200 million SSC ACs remain in operation globally.

Figure 7-1: Portable

Figure 7-2: Window

Figure 7-3: PTAC/PTHP

Figure 7-4: TTW

7.2.2 Non-ducted single split residential and commercial ACs

In many parts of the world, residential and light commercial air-conditioning are done with

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[18] Portable ACs are a special class of room ACs that can be rolled from room to room. They exhaust their condenser air through a small flexible conduit, which can be placed in an open window. Some portable ACs use a separate outdoor condenser, which connects, to the indoor section with flexible refrigerant piping.

non-ducted split ACs. Non-ducted split ACs are widely applied in commercial buildings, schools and dwellings and range in capacity from 2.0 kW to 20 kW (average size of 3.8 kW); see Figure 7-5, Figure 7-6, Figure 7-7, and Figure 7-8, which show an outdoor condensing unit, an indoor wall unit, an indoor ceiling cassette and an indoor floor unit, respectively.

Non-ducted split ACs comprise a compressor/heat exchanger unit (condensing unit) installed outside the space to be cooled or heated. The outdoor unit is connected via refrigerant piping to an indoor fan-coil unit located inside the conditioned space. Wall-type indoor units are most common, but ceiling and floor-mounted designs are also widely used. Smaller single split systems often have the expansion device positioned within the condensing/outdoor unit. Compressors are typically hermetic rotary although scrolls and reciprocating are sometimes used for larger capacities. Improvements in efficiency have arisen from introducing inverter compressor technology and is currently used in about half of new mini-split units but only about 10 – 20 % of larger systems.

Reversible ACs (i.e., with heat pump function) are gaining market acceptance and are often being effectively mandated by minimum efficiency legislation (e.g., within the EU and North America) in cool and cold climates. These units are designed to provide high efficiency and adequate capacity at low ambient temperatures, often down to -30 °C. Reversible ACs are a common means to reduce indirect CO_2 emissions by providing an efficient and cost-effective alternative to electric resistance and fossil fuel heating. Reversible non-ducted split units designed for cold climates utilise one or more technologies, such as multi-stage or enhanced vapour injection (EVI), variable speed compression, larger heat exchangers and enhanced control strategies, to improve their low ambient performance.

The vast majority of non-ducted split ACs, manufactured prior to 2000, used HCFC-22 refrigerant. They have HCFC-22 specific charge levels of approximately 0.25 to 0.30 kg per kW of cooling capacity. The majority of non-ODS refrigerants that have been applied to these products are HFCs such as R-410A and more recently HFC-32 and to some extent, others e.g., HC-290, whilst HFC-134a has been more dominant in regions that experience HAT.

The current global market for these types of split systems is around 80 million units per year (JRAIA, 2022), with approximately 20 % going to non-Article 5 parties and 80 % to Article 5 parties. The installed population is estimated to be around 1 billion units.

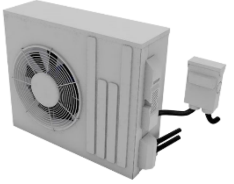

Figure 7-5: Outdoor condensing unit

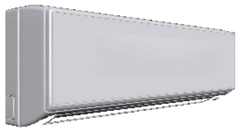

Figure 7-6: Indoor wall unit

Figure 7-7: Indoor ceiling cassette

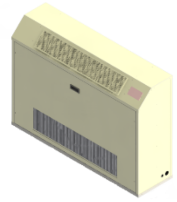

Figure 7-8: Indoor floor/ceiling unit

7.2.3 Ducted split residential ACs

Ducted split residential ACs are typical of residential installations in North, Central and South America, but also used in other countries where central forced-air heating systems necessitate the installation of a duct system that supplies air to each room of a residence or small zones. A condensing unit (compressor/heat exchanger), outside the conditioned space, supplies refrigerant to central indoor heat exchangers (“coils”) installed within the duct system. Air from the conditioned space is cooled or heated by passing it over the coil and is then re-distributed to the conditioned spaces by the duct system. An example is provided in Figure 7-9. Compressor types typically include hermetic rotary, reciprocating and scrolls. The most common refrigerant in these systems was HCFC-22 until the period 2005-2010, where the majority has transferred to R-407C but mainly R-410A. For residential systems, capacities range from 5 kW to 17.5 kW (average size around 10 kW), and each has an average HCFC-22 charge of 0.26 to 0.35 kg per kW of cooling capacity (from product catalogues). Current annual output is about 5 million units (JRAIA, 2018), with about one-third in Article 5 and two-thirds in non-Article 5 parties. The estimated installed population is around 70 million.

Figure 7-9: Example air handler and condensing unit for ducted split system

7.2.4 Ducted commercial split ACs

Ducted commercial split ACs are used widely in commercial and institutional buildings. In principle, they are similar to the ducted residential split system, where there is a centralised air handling unit which forces conditioned air through a duct system that supplies air to small zones within the building. Again, a condensing unit (hermetic rotary, reciprocating or scroll compressor and heat exchanger) is located outside the conditioned space and supplies refrigerant to one or more indoor heat exchangers installed within the air handler. With commercial systems, a dedicated air handler is often used, which not only contains the refrigerant-to-air heat exchanger, but also air filters, humidifiers, resistance heaters and other elements used for treating the air. Indoor air from conditioned spaces is drawn through ducting into the air handling unit, usually along with some fraction (and in some cases, 100 %) of outdoor air and combined is then treated in the air handling unit. Conditioned air is then re-distributed to the spaces via the duct system. Depending upon the region and design, systems can be reversible. Examples of an air-handler and condenser are shown in Figure 7-10. As with ducted residential systems, the most common refrigerant was HCFC-22 until about 2010, whilst over the past few years the majority has transferred to R-410A. Capacities range from about 5 to 1,100 kW with a current annual output of about 12 million units (JRAIA, 2022), with about one-third in Article 5 and two-thirds in non-Article 5 parties and an estimated installed population is around 80 million.

Figure 7-10: Air handler (left) and condenser (right) for ducted split system

7.2.5 Multi-split ACs for commercial and residential

Multi-split systems are similar to single split (e.g., 7.2.2) but a single condensing unit may feed two or more indoor units, although typically with a 30-kW unit up to 50 indoor units can be used with over 1 km of piping; see Figure 7-11. Whilst dual indoor unit models may be used for residential applications, this category of split systems is more often used in commercial buildings. As with single splits, non-ducted and ducted, multi-splits also offer reversible (heating) options. Specific HCFC-22 charges tend to be from around 0.3 kg/kW upwards (from product catalogues), depending upon the installation characteristics.

“Variable refrigerant flow” (VRF) is a sub-category of multi-split systems and are distinguished from regular multi-split systems by the ability of the outdoor unit to modulate the refrigerant flow in response to the indoor unit demand. In some configurations, these systems can have independent cooling or heating functionality for each indoor units thus simultaneously heating and cooling separate indoor spaces. The outdoor unit modulates the total refrigerant flow using various compressor capacity control methodologies, with compressor types generally being variable speed rotary or scroll type. VRF systems have capacities ranging from 10 kW to over 150 kW, with an average (module) capacity of about 20 kW (noting that modules are often multiplexed to provide greater capacities). Although systems produced before 2000 tended to use HCFC-22, there has since been widespread use of R-410A even in Article 5 parties, with typical charge levels of 0.30 – 0.70 kg/kW of cooling capacity (from product catalogues) and now with some transition to HFC-32.

Approximately 2 million systems (outdoor modules) are produced each year (JRAIA, 2018) of which one quarter go to non-Article 5 parties and three-quarters to Article 5 parties. The installed population is estimated to be around 10 million.

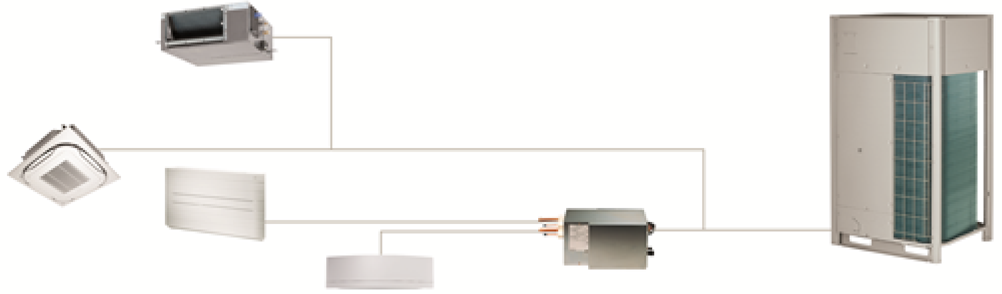

Figure 7-11: Example arrangement of multi-split equipment

7.2.6 Packaged ducted commercial ACs

Packaged ducted commercial ACs (widely termed “rooftop” units) are single self-contained units, which comprise an integral fan and heat exchanger assembly which is connected by return and supply ducting to the air distribution system of the building. The other part of the package is the condensing unit, normally with an air cooled or water condenser and compressors, which are often hermetic scrolls, although hermetic and semi-hermetic reciprocating and screw machines are sometimes employed. An example unit is in Figure 7-12.

The majority of packaged ducted commercial ACs are mounted outside on the roof or on the ground of offices, shops, ground-support aircraft air conditioning systems, restaurants, or institutional facilities. In some Middle Eastern countries, such units are also used for dwellings, where they are installed on the roof of large single home residences providing easy access for service without technicians having to enter the living space. Multiple units containing one or more compressors (with or without inverter drives) are often used to condition the enclosed space of low-rise shopping centres, shops, schools, or other moderate size commercial structures.

Most ducted systems historically used HCFC-22, whilst in non-Article 5 parties R-410A is mainly used and R-407C and HFC-134a in regions with higher ambient conditions. R-744 is offered in some Northern European countries and recent developments have yielded HC-290 in smaller models of up to about 20 kW (e.g., Colbourne et al., 2018).

Packaged ducted commercial ACs are offered in a wide range of capacities from around 7 kW to over 700 kW and have HCFC and HFC specific refrigerant charges of around 0.3 to 0.5 kg per kW of cooling capacity. For HC-290 systems specific charge is around 0.05 – 0.15 kg per kW of cooling capacity.

Annual market is currently about 14 million units (JRAIA, 2022), with about one-third in Article 5 and two-thirds in non-Article 5 parties. The estimated installed population for the last 8 years is around 100 million according to JRAIA market data

Figure 7-12: Example of ducted commercial packaged unit

7.2.7 Ground- and water-source heat pumps

While the subject of this chapter is "air-to-air air conditioners and heat pumps," reflecting the majority, some equipment uses the ground or surface water or air (ambient) for dry cooling systems as the heat source and/or sink. The ground heat pumps include several varieties:

- Groundwater, where heat is extracted from and rejected to pumped well water rather than air. The unmodified, except thermally, groundwater is then returned to the ground in a second well; rejected to a convenient stream, lake, or other body of water
- Ground-coupled in which a closed loop of pumped water is installed underground and flows through a heat exchanger (evaporator in heating mode or condenser in cooling mode.
- Direct exchange for which the refrigerant heat exchanger is buried underground, again in horizontal or vertical configuration, without use of an intermediate water loop. The vertical configuration often entails placement of a heat exchanger loop in a well bore drilled specifically for this purpose.

Another variant employs evaporative condensing, particularly in hot dry climates. The use of evaporative condensing reduces the condensing temperature and thereby improves efficiency but requires both water (to replace that evaporated) and water dilution and/or treatment (to control the residual mineral levels). The make-up and dilution water may be at a premium in the hot dry climates where evaporative condensing offers the greatest benefits.

In HAT regions with limited water resources, dry coolers are employed to provide heat rejection though ambient temperature rather than through evaporative condensing.

Refrigerants used are nearly the same as for other unitary air-conditioners and heat pumps with exception of direct exchange ground-source systems, for which the added volume from the ground heat exchanger may limit flammable refrigerants since the refrigerant flows through one or more exchangers serving (heating and cooling) the indoor space.

The refrigerant options and issues are addressed in section 7.3 below.

Figure 7-13: Example of water-source packaged unit

7.3 Refrigerant options for new equipment

As discussed in chapter 3, there are several factors that should be considered when selecting an alternative refrigerant. Accordingly, this section provides a summary of the most viable replacement candidates for HCFC-22 and R-410A in new ACs, based on current information.

Since HCFC-22 was previously used almost exclusively in AC systems, it has been the refrigerant upon which many proposed alternatives were compared against. However, in many regions where R-410A has become the most common option, this has also become the reference refrigerant for such comparisons.

Several single component HFC refrigerants have been investigated and adopted as alternatives in ACs, including HFC-134a and HFC-32 and HC-290 as a single component HC.

A number of HFC blends have emerged as replacements in AC systems. Various compositions of HFC-32, HFC-125, HFC-134a and HFO-1234yf are being offered as non-ODS replacements. Hitherto, the two most widely used HFC blends used in ACs are R-410A and to a lesser extent, R-407C, however, both these have GWPs close to that of HCFC-22 and are therefore considered too high for long-term use within the context of the Kigali Amendment.

Note that various refrigerants discussed (HFC-143a, HFC-134a, HFO-1234yf, HFO-1234ze(E), etc.), which are also components of several blends discussed below, decompose to some extent to trifluoroacetic acid (TFA). Refer to chapter 3 for further details and their impact.

Of the various alternative refrigerants with medium- and low-GWP, the majority are flammable. For these refrigerants, appropriate measures must be applied to mitigate flammability risk, as described in section 7.7. In general, risk assessment should be used to ensure that the risk of ignition is below tolerable levels and at a minimum, the requirements of national regulations and/or appropriate safety standards (where they exist) are met; such rules are continuously under development and refinement. Therefore, it is necessary to ensure that the risk of ignition is below tolerable levels regardless of the current requirements of safety standards. Stakeholders must also be aware that current standards do not cover equipment lifetime, thus lifetime risk assessment and management is an important consideration. A comprehensive overview is detailed in the Task Force (TF) report under Decision XXVIII/4 “Safety Standards for Flammable Low global warming potential (GWP) Refrigerants” (UNEP, 2017), noting that some standards have been updated since all are subject to an ongoing revision process.

Within the discussion of the various refrigerant options, numerous studies on performance have been reported on. There are a wide variety of relative results amongst different units and conditions inferring that the influence of specific system design has a more pivotal influence on performance than any one refrigerant candidate. Broadly, for results that are within ±5 % of the baseline, performance can be considered as comparable. Measurements considering HAT have also been reported upon, where available. ***Table 7-2*** provides an overview of the viable options as discussed below.

Table 7-2: Overview of viable low-, medium- and high-GWP options for ACs (based on authors' assessment accounting for typical refrigerant charge and current safety standards)

Refrigerant	Small self-contained	Non-ducted single split		Ducted residential split		Ducted commercial split		Multi-split		Packaged ducted	
Circuit size	≤ 15 kW	≤ 20 kW	> 20 kW	≤ 20 kW	> 20 kW	≤ 20 kW	> 20 kW	≤ 15 kW	> 15 kW	≤ 20 kW	> 20 kW
HFC-32	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
HFC-152a*	✓	✓		✓		✓		✓		✓	
HFC-161*	✓	✓		✓		✓		✓		✓	
HC-290*	✓	✓		✓		✓		✓		✓	
R-407C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-410A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-444B	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-446A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-447A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-447B	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-452B	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-454A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-454B	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-455A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-459A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-463A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-466A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-511A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
R-744	✓									✓	✓
HFO-1234yf	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
HC-1270*	✓	✓		✓		✓		✓		✓	

* Larger charge quantities on account of revised IEC 60335-2-40 standard. Note that the capacity bands are an approximation; for example, for class A2 refrigerants the capacity boundary may be 20 – 30 kW whereas for class A3, 10 – 20 kW, depending upon specific refrigerant, system configuration and function.

7.3.1 R-407C

Since R-407C requires only modest modifications to existing HCFC-22 systems, it has been used primarily as a transitional refrigerant in equipment originally designed for HCFC-22. However, since around 2004, R-407C systems have been redesigned for R-410A to achieve size and cost reductions. An exception is when the target market's standard conditions are HAT, such as above 40 to 55 °C. Further discussion on R-407C can be found in (UNEP, 2019).

7.3.2 R-410A

R-410A is the most common alternative for new equipment and the operating pressures and capacity are around 50 to 60 % higher than HCFC-22. Due to its thermophysical properties, the design of R-410A units can be more compact than those using HCFC-22 (and R-407C). To address the higher operating pressures of R-410A, system and component designs employ thicker walls for compressor shells and pressure vessels (accumulators, receivers, filter driers), system piping, etc. In addition, as per the lubricant requirements for most HFCs, POE or PVE have to be used.

Another concern is its low critical temperature that can result in degradation of performance at high condensing temperatures. Whilst R-410A systems have been demonstrated to operate at ambient temperatures of up to 52 °C, the performance (capacity and efficiency) of R-410A air-conditioners decreases more rapidly than HCFC-22 systems at ambient temperatures above 40 °C. There have been numerous studies examining the performance of R-410A and particularly with respect to HAT. Most results indicate 5 to 20 % degradation in performance relative to HCFC-22 at HAT conditions; these are described in detail in (UNEP, 2016; UNEP, 2018; UNEP, 2019). Even with optimised designs, for systems that will operate a significant number of hours at HAT, the system design should take into consideration the reduced capacity when sizing the components. For cases, where the base capacity of the unit would need to be increased to meet the building load at HAT, the increase in cost can be approximated as proportional to the respective capacity degradation. Increasing concerns over R-410A's GWP rendered it as a less attractive or even banned in some equipment types in some regions. Therefore, there is now a transition away from R-410A.

7.3.3 R-454B

R-454B is increasingly being used in various air-to-air systems in various regions. It requires modest modifications to existing R-410A systems and is a medium-GWP alternative with safety class A2L. In tests, refrigerating capacity was found to be within ±5 % of R-410A, and efficiency in two different units about 5 % higher than R-410A, at both normal and HAT conditions (Wang and Amrane, 2016; EGYPRA, 2019). Another study (Shen et al., 2022) found that whilst capacity was lower than R-410A, seasonal efficiency was greater. Newer compressors (e.g., scrolls) are being produced for multi-refrigerants, e.g., R-410A and R-454B.

7.3.4 R-452B

R-452B is beginning to be used in larger air-to-air systems in Europe. It requires modest modifications to existing R-410A systems and is a medium-GWP alternative with safety class A2L. Both refrigerating capacity and efficiency are similar to R-410A, with improvement in both by up to 10 % relative to R-410A as conditions approach HAT. Some studies found that whilst capacity was lower than R-410A, seasonal efficiency was higher (Shen et al., 2016; Shen et al., 2022; Harrington and Fortunato, 2022).

7.3.5 HFC-32

HFC-32 is a replacement for R-410A due to its medium-GWP and similar capacity and efficiency. Due to lower liquid density, the specific refrigerant charge (per kW of cooling capacity) is around 10 to 20 % less that R-410A. Depending upon the product group and capacity, R-410A systems can be redesigned for HFC-32 with some modifications and with additional safety measures given its class 2L flammability (see section 7.7 and Annex to Chapter 3). Current POE and PVE lubricants used with R-410A have insufficient miscibility with HFC-32, but some POE lubricants with poor miscibility with R-410A are already used and therefore the same oils may be selected in addition to modified oils.

There have been a large number of studies published on the relative performance of HFC-32 and R-410A (UNEP, 2015 and UNEP, 2019). Overall, COP variation ranges from -3 to +10 % compared with R-410A, whilst capacity is within -1 to +6 %.

At HAT conditions, HFC-32 has been found to have a marginally higher efficiency and capacity compared to R-410A, although worse than HCFC-22, where the capacity is approximately 2 % less and COP 5 % lower in theoretical cycle calculations (UNEP, 2015). At these conditions, discharge temperatures can be 5 to 30 K higher than R-410A or HCFC-22. However, this can be managed by refrigerant liquid injection technology or wet suction control, although these imply a cost and/or performance penalty. It can also be tackled by adjusting the viscosity of oil, although this may impact reliability. Again, several studies have compared performance at HAT conditions and found COP ranging from -10 to +10 % relative to HCFC-22 (UNEP, 2015).

Whilst most studies report on HFC-32 performance in single-split ACs, Ikeda et al. (2019) presented its use in a VRF system. The system described is a hybrid between chilled water and VRF system; the refrigeration system uses an intermediate “branch controller” that contains plate heat exchangers that cool or heat a secondary fluid (water) that is pumped to indoor units. System efficiency of HFC-32 was 2 % lower than a conventional R-410A VRF (considering both heating and cooling). The hybrid system was reported to use about half of the refrigerant charge of the conventional VRF system. As with all systems it is necessary to comply to applicable regulations and the charge limits required by safety standards.

Currently, ACs using HFC-32 are produced in many countries located in Asia, Europe, and Africa. However, the GWP is still relatively high compared to other candidates and for this reason HFC-32 is deemed to be a transition refrigerant.

7.3.6 HC-290

HC-290 systems are commercially available in low charge ACs such as non-ducted splits, window and portable ACs and more recently in small split and small packaged (rooftop) ducted systems. When used to replace HCFC-22, HC-290 has performance characteristics which tend to yield slightly higher energy efficiency and lower cooling and heating capacity, thus demanding greater compressor displacement. In terms of improvements in system COP in split type and window ACs with HC-290, values range from around -4 to +20 % and capacity varies within -10 to +10 %, as detailed in (UNEP, 2015; UNEP, 2019). In a recent study with a “double duct” AC (comparable to TTW type) and a specific charge of 55 g/kW, HC-290 had about 5 % higher COP than R-410A whilst achieving the same cooling capacity (Righetti et al., 2019). Another concept has been proposed by Wan et al. (2020; 2019), for a ducted unit that employs damper controls to prevent transfer of leaked refrigerant into ducting. For all conditions, HC-290 had an annual performance factor (APF) 2 – 7 % higher than HFC-32 and R-410A. For HAT, capacity is around -4 % and efficiency -3 to +10 %, relative to HCFC-22 (UNEP, 2019).

Since HC-290 has lower density and higher latent heat, the charge quantity is about 45 % of HCFC-22; typically, around 0.05 – 0.15 kg/kW of rated cooling capacity from the literature (e.g., Andersson and Palm, 2022; Colbourne et al., 2018; Shen and Fricke, 2020; etc.) and product datasheets. In addition, HC-290 has reduced compressor discharge temperatures and good heat transfer due to favourable thermo-physical properties.

Some major Chinese and one Indian manufacturer have had commercially available HC-290 products since 2012 and systems are available in Asia, Australia, Europe, South America, and Africa. To date, output is limited with more than 2 million units, whilst conversion of more than 20 production lines from HCFC-22 to HC-290 has been completed in China. At least five manufacturers have HC-290 split systems available. Manufacturing in China of certain SSC units with HC-290 is extensive, primarily aimed at the European market. Small capacity ducted split and rooftop units have been launched in South America.

With an ultralow-GWP, HC-290 is considered a long-term alternative for ACs, primarily with capacities below around ≤ 15 – 20 kW per circuit in direct systems. For reversible, high efficiency systems, the higher capacity range is likely to be lower.

7.3.7 Other single component refrigerants

There are several other refrigerants that are considered, or are used to a limited extent, in air conditioning systems. Further discussion on the refrigerants is within previous RTOC reports (e.g., UNEP, 2019).

HFC-134a has lower capacity and energy efficiency especially for room ACs and thus implies higher cost than HCFC-22 and R-410A. Although seldom used, it is more commonplace in various air-to-air systems, such as medium and large capacity ducted split and rooftop units, in regions that experience HAT.

R-744 has low-GWP and high capacity, however, due to its low critical temperature, it suffers efficiency losses when applied to typical rating conditions for ACs. System needs to be designed with substantial differences compared to conventional refrigerants. Air-to-air R-744 systems are available in capacities from 3 to 300 kW, mainly in northern Europe.

HFO-1234yf has flammability class 2L and has a relatively low volumetric refrigerating capacity and therefore is unlikely to be used as a widespread replacement. A recent overview is provided by Pabon et al (2020).

HFC-161 and HFC-152a are flammable, class 3 and 2, respectively, have low-GWP, good capacity and have been shown to exhibit high efficiency and as such remain longer-term options but there have been no significant developments since the previous report (UNEP, 2019). Neither HFC-161 nor HFC-152a are known to be used commercially by any manufacturer.

HC-1270 is class 3 flammability and has favourable thermodynamic and transport properties. Cooling capacity is up to 10 % and COP up to 4 % higher than HCFC-22 (UNEP, 2019).

7.3.8 New refrigerant blends

There are a number of new refrigerant blends proposed and already in use for ACs, including: R-444B, R-446A, R-447A, R-447B, R-452B, R-454A, R-454B, R-455A, R-459A, R-466A and R-511A. All have saturated vapour pressure and volumetric refrigerating capacity characteristics that approximately span the capacity range between HCFC-22 and R-410A. All have class 2L flammability, except R-466A that is A1 and R-511A, which is an A3 refrigerant and thus has maximum charge size limitations discussed in Chapter 3. Other flammability considerations are discussed in section 7.7. For all these blends, cost implications should be comparable to those of HCFC-22 and R-410A. Currently manufacturers and institutes across several countries are testing and evaluating these various blends. More details can be found in (UNEP, 2019).

Heredia-Aricapa et al. (2020) reviewed various blends as alternatives to R-410A, including R-446A, R-447B, R-452B, R-463A and R-466A, discussing the potential benefits of each. Devecioğlu (2017) compared the seasonal performances of various blends (R-452B, R-454B, R-447A and R-446A) against R-410A and found that they were similar. One global company is promoting a range of AC products using R-463A.

R-466A has received much attention due to its A1 safety classification, but so far, its use in air-to-air systems has not been reported, likely due to concerns over material compatibility issues and the non-zero ODP of one of its components, HCFI-13I1; refer to section 3.4.3 for more details. Schultz (2019b) found that the charge of R-466A was 15 – 25 % higher than R-410A, cooling capacity was within ±3 %, depending upon conditions and that COP and discharge temperature were almost similar to R-410A.

New blends reported on since (UNEP, 2019) include the work of Low (2020) proposing two proprietary blends for ACs where the cooling/heating capacity and COP were within ±20 % of the baseline R-410A system, depending upon whether the system was in heating or cooling mode. Other potential blends of HCFI-13I1 (CF3I), HFO-1123 and HFO-1132a, HCO-1130(E) with GWPs below 300 have also been discussed by Schultz (2019a).

7.4 Refrigerant options for existing equipment

As the HCFC phaseout proceeds in Article 5 parties, there remains a need to service the installed population of products until the end of their useful lives. When servicing these products, the treatment of refrigerant can fall into the following categories:

- Use existing refrigerant
- Refrigerant replacement only[19]
- Retrofit (refrigerant change and system components)
- Conversion (to flammable refrigerant)

Most of these categories are likely to be important for Article 5 parties because systems are often recharged or repaired several times in order to extend their useful life. There are a large number of Low Volume Consuming (LVC) countries, which import rather than manufacture ACs, where most of the HCFC consumption is to service the installed base. In these countries, HCFC consumption can be reduced by the use of service refrigerants or by retrofitting to non-ODP refrigerants. An additional option would be to replace the existing equipment before the end of its useful life. In non-Article 5 parties, unit replacement is more common because the costs associated with performing a major repair or retrofit can not only be closer to the cost of product replacement but also because the operational cost benefits of having new, higher efficiency systems can be more financially attractive. The need for retrofit and replacement refrigerants will largely be determined by the size of the installed base of HCFC-22 products, the availability of HCFC-22 and the recovery and reclaim practices in place leading up to the phaseout. The installed base has a service life varying between 5 to 20 years, depending on local conditions. Therefore, implementing recovery and reclaim programmes, coupled with the availability of replacement, and retrofit refrigerants, could help reduce the demand for HCFC-22 and currently used higher GWP HFCs.

Using the existing refrigerant following a repair can follow normal practices using virgin, recycled or reclaimed refrigerant (i.e., typically HCFC-22).

For refrigerant replacement only, HCFC-22 can be replaced with a blend which closely matches the saturated vapour pressure characteristics of HCFC-22, but without changing the lubricant used in the original equipment or any other system component. Refrigerants used for this activity are sometimes referred to as “service blends” or “drop-ins” (see sections 7.4.1 and 7.4.2 below). Such a change in refrigerant in most cases results in a lower capacity and/or efficiency, different operating pressures, temperatures, and compressor power compared to HCFC-22.

In the case of refrigerant replacement and retrofit in HCFC-22 systems, the GWP should also be given consideration as many such blends have a GWP higher than that of HCFC-22. This has become a significant issue following the Kigali Amendment. In all cases, before changing the refrigerant it is recommended that the system manufacturer be consulted.

Some compressor and manufacturers of larger systems carry out evaluations of refrigerant options and provide recommendations as to which they believe are suitable for use in their HCFC-22 equipment, whilst in other cases manufacturers explicitly warn against using such replacements. Information on the application of these blends can be obtained from manufacturers.

7.4.1 Replacement only refrigerants

There are several refrigerants currently introduced to replace HCFC-22 for servicing. They generally combine two or more HFC refrigerants with a small amount of HC (or certain HFC refrigerants, such as HFC-227ea), which are added to the blend to improve the miscibility with the naphthenic mineral oil and alkyl benzene lubricants, which were historically used in

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[19] Usually the term “drop-in” is used for this type of replacement. However, since there are no alternatives with identical thermophysical, safety and chemical properties as the existing refrigerant (e.g., HCFC-22) then the phrase “refrigerant replacement only” is used to substitute the term “drop-in”.

nearly all HCFC-22 air conditioning systems. Although these refrigerants are supposed to mimic the performance of HCFC-22, they seldom perform as well as HCFC-22; having either lower capacity, efficiency or (usually) both. Such studies reported earlier (UNEP, 2015), were found to exhibit worse performance (cooling capacity and COP) than HCFC-22. All of the blends are zeotropes so a temperature glide will be introduced to the cycle which the system was previously not designed for.

In addition to the performance and efficiency impacts, the blends may not perform well for oil return. Whilst HCs or HFC-227ea may be added to allow for the oil return, it may not be as effective and problems could result at lower loads and extreme operating conditions, e.g., seen during HAT and heat pump operation. A non-exhaustive selection of the many commercially available HCFC-22 replacement blends include: R-417A, R-417B, R-422A, R-422B, R-422C, R-422D, R-424A, R-425A, R-428A, R-434A, R-438A and R-442A.

For several years preceding the launch of HCFC phaseout, some HCFC-22 compressors were produced with synthetic oils, thus enabling pure-HFC blends, primarily R-407C, to be used as a direct replacement. There are a number of criteria that should be satisfied in order for a replacement only refrigerant to be selected and these are discussed in Chapter 3.

7.4.2 Retrofit refrigerants

A number of HFC blends proposed as alternatives to HCFC-22 in ACs, are also possible retrofit including R-407A, R-407B, R-407C, R-407D, R-407E, R-421A, R-421B and R-427A. Whilst many of the proposed blends are seldom used, R-407C has been demonstrated to be an acceptable retrofit refrigerant and has seen widespread use in some regions. Various studies reporting on comparative measurements with HCFC-22 and retrofit refrigerants (mainly R-407C) were summarised in the earlier reports (UNEP, 2015), all of which found a drop in COP and cooling capacity typically in the order of 5 to 10 %.

As indicated, provided that the compressor already uses a mineral oil, a change from HCFC-22 to R-407C requires that the existing naphthenic mineral oil or alkyl benzene synthetic oil lubricant be replaced, and appropriate filter driers should also be installed. The disadvantage of using moderate and high glide blends is the need to remove and replace the entire charge during servicing (even with a partial leak) to avoid substantial composition shift. However, because R-407C has a moderate glide, laboratory and field experience indicates R-407C can be serviced without replacing the entire refrigerant charge with minimal impact on performance. Other HFC blends with a glide less than 10 K will tend to have similar practical implications.

7.4.3 Conversion of existing systems to flammable refrigerants

HC refrigerants such as HC-290, HC-1270 and blends including these as well as HC-170 and R-E170 (e.g., R-433A, R-433B, R-433C, R-441A and R-443A) are being used as conversion replacements for HCFC-22 in some regions, typically in small systems (such as window and single split units) but application in larger systems has also been observed. A similar practice involving replacement of R-410A or other non-flammable HFCs with HFC-32 or other flammable HFC blends including HFC-152a has been reported anecdotally. Some countries have included such an approach in their HCFC phaseout strategies, whilst this practice is explicitly prohibited in other countries (such as in the USA). Although these refrigerants may provide capacity and efficiency close to or better than HCFC-22, this practice can create a significant flammability safety hazard. There is a widespread view that flammable refrigerants should not be used in existing systems that have not been specifically risk-assessed and re-constructed for them. There are guidelines on the utilisation of these refrigerants in such situations (e.g., GIZ, 2010). Nevertheless, local standards and regulations as well as manufacturer recommendations have to be checked and followed before replacing an A1 refrigerant with a flammable substitute.

7.5 Energy aspects and considerations

Energy consumption and energy efficiency matters related to ACs are of ever-increasing importance, especially within the context of the Kigali Amendment. There is a link between efficiency and refrigerant selection, but also technologies that support reduction in refrigerant consumption.

7.5.1 Hybrid systems in ACs

The hybrid system in ACs (air-to-air packaged and central split systems) uses free cooling with an air economiser to increase system energy efficiency; hybrid system can be used either fully with free cooling or partially with the mechanical cooling. The fresh air enters the building through the AC without mechanical cooling when the outside air temperature is lower than the room temperature set point, or the AC can work partially, if the outside air temperature is lower than the return air temperature in the building. These techniques are used to increase the total system energy efficiency. These have been demonstrated using medium- and low-GWP refrigerants, including HFC-32 and HC-290.

7.5.2 Energy recovery systems in ACs

The building sector offers significant opportunities for energy savings as it accounts for as high as 40 % of the total energy demand (IIR, 2021a). Studies (Moore, 2014; Kondepudi, 2015) have shown that the operational cost constitutes about 75 % of the total cost, while the initial cost is about 25 %. AC systems occupy the largest part of the energy consumed in various types of buildings, as it can reach 75 % of the total energy consumed in some buildings, especially in HAT countries and low ambient countries (where reversible systems are used). Therefore, it is necessary to have energy efficient systems. It should be noted that the energy benefits of heat recovery can be very valuable for both building ventilation and process-to-process applications, with energy cost reductions that can exceed 70 % (IIR, 2021b). Types of energy recovery ventilators (ERVs) can be either air-to- air sensible heat exchangers only or total heat exchangers, as per the following:

- Air-to-air sensible heat exchanger:
    - Fixed plate heat exchangers
    - Heat pipe heat exchangers
    - Thermosiphon heat exchangers
    - Run-around coil heat exchangers
    - Alternate flow heat exchangers
    - Rotary heat exchangers
    - Thermodynamic energy recovery heat exchangers
- Air-to-air total heat exchanger types:
    - Membrane plate exchangers
    - Rotary enthalpy heat exchangers
    - Twin tower enthalpy recovery system

For more details about these energy recovery heat exchangers used in air-to-air systems please refer to IIR (2021b).

7.5.3 Selection of efficient components

Selecting high efficiency compressors using inverter results in higher energy efficiency level at both full load and part load conditions. The compressor must be optimised for the chosen refrigerant and the same thing must be considered for the heat exchangers and other refrigeration circuit components. The condenser fans and evaporator fan motors should be either electronically commutated (EC) type or Inverter type to increase the efficiency. Additional heat exchangers such as desuperheater, subcooler, suction line heat exchanger and heat exchanger accumulator can be added to the refrigeration circuit to enhance the overall system efficiency.

The methods and related costs to increase energy efficiency of ACs are detailed in the TF report under Decision XXIX/10 on issues related to energy efficiency while phasing down hydrofluorocarbons (UNEP, 2018) and Decision XXXI/7 on continued provision of information on energy-efficiency and low-GWP technologies (UNEP, 2020).

7.5.4 Minimum energy performance standards (MEPS)

Most countries are implementing MEPS as mandatory or voluntary along with labelling schemes to improve customer awareness. MEPS and energy/efficiency labels are designed based on the country- or region-specific climate conditions, thus making it difficult to compare values applied to different countries (Park et al., 2020). Labelling programmes encourage higher efficiency products and are usually also prescribed by regulation. Typically, MEPS and labelling programmes are periodically adjusted upwards to help elevate efficiencies to incrementally higher levels. Moreover, such schemes are increasingly being based on “seasonal” efficiencies, which are designed to represent regional temperature and thermal load profiles over a year. In China at least one manufacturer with HC-290 and a few manufacturers with HFC-32 launched products that had higher seasonal efficiencies than MEPS. In India HFC-32 and HC-290 ACs are available for the currently highest energy rating.

7.6 Considerations for HAT countries

There are several important aspects to consider when designing or adapting equipment for use in HAT conditions (see, for example, UNEP, 2016; UNEP, 2018; UNEP, 2019). The most important parts in the refrigeration circuit in air-to-air AC which affect the performance in HAT are the heat exchangers (condenser and evaporator) and their design and physical characteristics like coil face area, number of rows, fin density and refrigerant circuit.

Usually, heat exchangers are designed to provide high cycle efficiency and to ensure the compressor does not exceed its operating envelope even under HAT conditions. Further design considerations are to achieve the lowest possible refrigerant charge. Micro-channel heat exchangers enhance the heat transfer. Larger condenser coils and special fans can be used to reduce the condensing temperature at HAT conditions. Controlling the subcooling with dedicated subcooling circuits is vital in HAT conditions to enhance the efficiency.

Special types of compressors are needed for R-744. Some scroll compressor manufacturers approve to the use of R-410A compressors for HFC-32 on medium and HAT applications. For R-407C and HC-290, larger displacement compressors (~10 %) can be used to compensate for the lower capacity resulting from using these refrigerants.

Capillary tubes for small ACs are not desirable, especially at high ambient conditions. The wide range of temperatures make the use of capillary tubes impossible for sufficiently accurate control of superheat; thermostatic or electronic expansion valves are suitable alternatives.

7.7 Safety considerations

Safety in ACs concerns a range of hazards, including those associated with electricity, pressure, toxicity/asphyxiation, and mechanical (such as from moving parts, sharp surfaces, etc.). However, with the shift from conventional refrigerants to flammable refrigerants, risk arising from leaked refrigerant has become a major consideration with many implications

(IIR, 2017). This applies to many of the refrigerant options discussed in section 7.3: HFC-32, HFC-161, HFO-1234yf, HC-290, HC-1270, R-444B, R-446A, R-447A, R-447B, R-452B, R-454A, R-454B, R-455A, R-459A and R-511A. In general, safety requirements are handled by national, regional, and international safety standards and these are described in section 3.3. However, safety standards tend to lag technical developments owing to procedural issues. Lifetime risk assessment is necessary, i.e., including production, distribution, storage, service and maintenance and end-of-life stages.

This section summarises considerations for several subject areas: flammability risk assessment, refrigerant concentration following leaks, hydrofluoric acid decomposition products of HFCs combustion, appropriate refrigerant charge size limits and refrigerant handling. Since other hazards such as pressure, electrical, toxicity and other mechanical hazards are equally applicable to conventional refrigerants, they are not addressed further.

7.7.1 Risk assessment

Risk assessments may take the form of systematic quantitative studies or examining certain behaviour of elements within the causal chain, such as those related to leakage, dispersion of a leak, ignition, and consequence of ignition events. A substantial study addressing the flammability risk of A2L refrigerants has considered (amongst others) single-split, VRF and ducted ACs (JRAIA, 2017). This stated that for single splits the ignition frequency was very small and that for VRF systems, provided certain mitigation measures were implemented (such as leak detection combined with room ventilation, alarms, etc., the risk could be lowered to equally tolerable levels.

Risk analyses of HCs in ACs suggest that when the requirements of safety standards are met, the probability of ignition during normal operation is extremely low, i.e., well below the residual fire risk associated with common electrical and gas-fired equipment. One study demonstrated that the flammability risk associated with split ACs in-use is around 100 times lower than with HC-600a domestic refrigerators, which are widely acknowledged to present minimal risk (Colbourne and Suen, 2015). The highest risks are likely to occur during refrigerant handling activities, particularly when technicians are not suitably competent; see Chapter 13 for further details.

Baba et al. (2019) conducted a risk assessment on an outdoor unit of an HC-290 split AC installed on a balcony. They concluded that that ignition risks may be intolerable when three certain conditions coincided (presence of a low-level permanent ignition source such as an adjacent boiler pilot light, a catastrophic leak, and no wind). Kim and Sunderland (2017) assessed a large number of potential ignition sources for A2L refrigerants. Similarly, Tamura et al. (2020a) and Tamura et al. (2020b) evaluated the effectiveness, presence, and location of various potential ignition sources with respect to HC-290 use in a non-ducted split AC. Such studies aim to provide input information for application risk assessments.

Leak, ignition, and fire tests by Zhang et al. (2013) demonstrated that even with catastrophic refrigerant leaks, only sources of ignition present in the immediate vicinity of the indoor unit have the possibility to ignite a leak of refrigerant and consequences are insufficient to damage doors or windows.

Studies on dispersion and ignition testing of A2L (AHRTI, 2017) and A3 (AHRTI, 2019) refrigerants have been published. No studies specifically addressing class 2 refrigerants have been found in the literature.

Given the relatively high level of risk, emphasis should be made on risk assessment during servicing and refrigerant handling stages.

7.7.2 Concentration development/approaches to charge determination

To minimise the flammability risk, refrigerant charge limits are imposed which are intended to avoid non-negligible volumes of flammable mixture developing in confined spaces following a refrigerant leak. Such limits are derived based on a variety of assumptions and often extensive testing. Further studies, improvements to the understanding and application of these limits are ongoing.

Li (2014a) experimentally observed that floor concentrations were much lower than those inferred by the charge limits in safety standards. Ito et al. (2020) evaluated flammable charge size limits in single rooms and, concluded that HFC-32 poses no risk and HC-290 has a little safety margin.

A framework approach to developing allowable charge limits has been described by Colbourne et al (2020). Further, an improved methodology for calculating charge limits in quiescent rooms but also accounting for the equipment enclosure characteristics is offered in Colbourne and Suen (2021) and for equipment using indoor unit circulation airflow in Colbourne and Suen (2022) and Hu et al. (2018). Ram Prakash et al. (2021) evaluated the presence of numerous room furniture configurations within a room and found that with modest airflow there was little influence on maximum HC-290 concentrations around the room.

Tang et al. (2019) and He et al. (2019) studied leaks of various sizes from a split AC and measured the resulting HC-290 room concentrations and found that flammable concentrations only occurred directly below the indoor unit. In particular, they examined the benefit of using solenoid valves to reduce the released quantities and thus refrigerant room concentrations. This study was notable in that leak rate was not a fixed (i.e., by using a mass flow controller) but was “as was” exiting the system.

Jia et al. (2015) reported on a study where HFC-32 room concentrations after a leak were measured whilst the fan was operating. Their results showed relatively smooth concentration profile (presumably due to the airflow) and only one sensor, which was very close to the leak position. The concentrations exceeded LFL in some locations. A later study (Jin et al., 2017) looked specifically at the effect of exhaust ventilation on releases of HFC-32, showing that downward airflow was substantially better than upwards airflow in terms of mixing and dilution. Ito et al. (2020) evaluated the dispersion of class 2L (HFC-32) and class 3 (HC-290) due to unit integral airflow and found it was extremely effective in terms of risk reduction.

Ignition tests of simulated releases from AC systems were presented by Wand and Gandhi (2018) and found no difference in severity between various A2L refrigerants, including R-452B and HFC-32, although R-457A reacted more quickly than R-455A.Control strategies can be integrated to restrict the amount of refrigerant leaking into the occupied space, which may prevent up to 80 % of the charge being released (Colbourne et al., 2013; He et al, 2019). Furthermore, larger systems (such as packaged units) can use two or more independent refrigerant circuits or a reboiler circuit, although these imply a cost increase.

7.7.3 Charge minimisation

There is a general objective to reduce specific refrigerant charge (i.e., kg per kW), for safety, environmental and cost reasons and the various strategies employed are also explained.

Charge reduction technologies include use of micro-channel heat exchangers and small diameter copper tubes, (for instance, 4 mm and 5 mm copper tubes are becoming increasingly popular in split ACs), compressor design for reduced internal volume and proper oil selection can assist with risk reduction when using flammable refrigerant. Recent technological advances in non-finned, non-circular tube heat exchangers, which were found to reduce charge by up to 30 %, whilst yielding other benefits such as reduced component weight and air and refrigerant pressure loss (Tancabel et al., 2020). Also, a study of Ribeiro and Barbosa (2019) examined the use of heat exchangers using peripheral fins, which helped to reduce total charge by up to 12 %. Andersson et al. (2022) presented a 3.5 kW cooling only split AC that uses only 143 g of HC-290. Whilst microchannel heat exchangers enable significant reductions in charge, they also raise other challenges related to reverse cycle operation and condensate drainage.

The main difficulty with flammable refrigerants is that safety standards limit the indoor charge amount (see Annex to Chapter 3). Current charge size limitations can restrict the capacity size of systems that need to achieve a certain efficiency level, depending upon the specific thermal load (i.e., kW/m^2) of the application. However, with the revised safety standard (IEC 60335-2-40), the restrictions are generally imposed by the upper or capped charge limit rather than the allowable limit as dictated by the room size (GIZ, 2022).

7.7.4 Refrigerant handling

A critical factor that must be considered with flammable refrigerants is refrigerant reclaim and recovery requirements during servicing and at the end of the product's life to protect those servicing or recycling the product. As explained in Chapter 13, current recovery and recycling practices depend largely upon national or regional regulations. For example, in Europe waste legislation implies that HCs must be recovered, whereas in many other countries, venting of HCs may be subject to the discretion of individual technicians. Nevertheless, any such practices should only be done subject to a risk assessment.

7.7.5 Other flammability considerations for service

One particular mechanism for refrigerant-related explosions in compressors is that of the diesel effect. This has been reported most widely in systems using R-410A and HFC-32 but can also occur with some other refrigerants. It is important to identify this issue, in particular to provide a wider context for safety considerations. When the compressor is run (usually to pump-down a system for servicing) and there is an unrepaired leak in the low-pressure side, air is drawn and mixes with refrigerant. When this mixture is compressed, it enters a flammable region and usually (due to that compression) reaches the autoignition temperature of the mixture and thus ignites. Since the resulting maximum overpressure is directly proportional to the initial pressure, which is already rather high due to compression, it can result in a catastrophic explosion, sufficient to blow the compressor and parts of the system apart (Higashi et al., 2017).

Laboratory studies with R-410A, HFC-32, HFC-1234yf, HCFC-22 and HC-290 found that all could lead to such an ignition event, despite some being non-flammable at standard conditions. Whilst for most fluorinated refrigerants, this can occur with concentrations of more than 60 % air, HC-290 requires at least 97 % air. Type of compressor oil was found to have an impact on the occurrence of ignition and more recent work has looked at the effect of certain additives (Saitoh et al., 2020). Avoiding such events is contingent upon technicians adhering to correct servicing procedures, such as removing all refrigerant from the system and purging with nitrogen. Thus, adequate training of technicians and those involved with end-of-life of equipment is of paramount importance.

7.8 Availability and accessibility considerations

Systems, components, and infrastructure associated with implementation of alternative refrigerants are seldom available in all regions and for all types and sizes of equipment. Similarly, the knowhow and expertise required for addressing certain implications associated with transition of certain alternatives throughout the supply chain may be lacking.

This is typical for the early stages of commercialisation of alternatives, for example, as countries begin to regulate high GWP HFCs.

This may be more prevalent in Article 5 parties, although it is also common amongst most non-Article 5 parties to some extent. In certain sectors, some Article 5 parties are at a similar or more advanced level than non-Article 5. The situation is usually strongly affected by national policy, extent of local manufacturing and access to relevant suppliers. Early access to samples and support on alternative refrigerant components can create a significant hindrance in both Article 5 and non-Article 5 parties. Often accessibility depends upon the scale of demand (quantities) for components and systems, be they manufactured locally or imported. Given the already large, and continually increasing number, of medium- and low-GWP alternatives, it is unlikely that all refrigerants, system, components, and infrastructure will be available or accessible for all options.

In addition to equipment, availability of local and regional standards and regulations – whether enabling or mandating – are important for the infrastructure. Similarly, accessibility to training and refrigerant handling equipment is crucial (see Chapter 13). All such aspects are widely available in some Article 5 and non-Article 5 parties, whilst only available to a limited extent in others.

Important aspects include:

- Equipment and materials
    - Medium- and low-GWP systems
    - Medium- and low-GWP components
    - Low charge heat exchangers (narrow tube or micro-channel)
    - Specific alternative refrigerants
    - Service tools
- Infrastructure
    - Minimum efficiency performance standards (MEPS) or regulations
    - Safety standards (see Chapter 3)
    - Mandatory fresh air requirements (ventilation)
    - Mandating free cooling systems (e.g., ANSI, 2016)
    - Local expertise and knowhow
    - Training for engineers and technicians

Table 7-3 indicates the degree of availability of these aspects considering Article 5 and non-Article 5 parties. (Crosses in both columns indicate the range of availability across different countries.)

Ensuring availability and accessibility to all of these is crucial for successful implementation of alternative refrigerants.

Safety and performance standards are available to countries through the ISO and IEC system. Many countries adopt the international standard as a national standard and some countries further mandate them under national legislation.

Development cycle of components and systems is an important consideration when addressing timescales for phasedown, which will include absorption of technology, development of supply chains and capacity development for service technicians; it can be longer than with non-flammable refrigerants. This is especially true for those countries that rely on sourcing imported components for research and development. Accordingly, the scale of demand/quantities of systems and components will dictate whether supplies in relation to a particular alternative will be economically viable.

Whilst potentially available in many regions, the high price of some medium-GWP alternatives acts as a deterrent for system producers to adopt those alternatives, where retaining an existing high-GWP refrigerant is more economically attractive to both system production and the service sector.

Table 7-3: Summary selected aspects in Article 5 versus non-Article 5 country

	Article 5 parties		non-Article 5 parties	
	Available	Widely available	Available	Widely available
Equipment and materials				
Medium- and low-GWP systems	×	×		×
Medium- and low-GWP components	×	×		×
Low charge heat exchangers	×	×		×
Specific alternative refrigerants	×	×	×	×
Service tools	×	×	×	×
Infrastructure				
Minimum efficiency performance standards (MEPS) or regulations	×	×		×
Safety standards	×	×		×
Mandatory fresh air requirements (ventilation)	×	×		×
Mandating free cooling systems (e.g., ANSI, 2016)	×	×	×	
Local expertise and knowhow	×	×	×	×
Training for engineers and technicians		×		×

7.9 Concluding remarks

HCFC-22 and R-410A are presently the most frequently used refrigerants in air-to-air systems. The HCFC-22 refrigerant bank for ACs is estimated to be in excess of 1 million tonnes. HCFC-22 is now only used in new systems in some Article 5 parties, whilst others have ceased using HCFCs in new systems. R-407C along with HFC-134a, R-410A, HC-290 and HFC-32 are used in regions with HAT. HC-290 is being used in split systems, window, and portable ACs and recently in small ducted systems. HFC-32 is being used in split systems and larger ducted, rooftop ducted, and multi-split systems and the use is increasing. Larger, commercial-sized R-744 systems are available in some moderate and low ambient temperature regions.

Increasingly, R-410A is becoming regarded as unacceptable because of its high GWP. There are a large number of new blends being considered, primarily consisting of HFCs and HFOs, such as R-444B, R R-447B, R-452B, R-454A, R-454B, R-459A, R-463A and R-466A. Although there is concern over the use of R-410A in HAT, appropriate design measures can be used to help remedy the relatively greater degradation in performance.

New system concepts are emerging, designed to handle flammable refrigerants, such as specially designed ducted systems and both conventional and hybrid VRF systems. It is expected that new concepts will follow as the sector begins to acknowledge the need to adopt flammables more widely. Similarly, novel heat exchanger designs are also evolving to help handle flammability.

If ACs are to use low-GWP refrigerants, it is inevitable that flammable refrigerants will be used (based on the current options). This will be facilitated with the revised safety standard IEC 60335-2-40 with improved requirements for flammable refrigerants in ACs. Similarly, there is an increased focus on safety studies related to flammability, for instance, risk assessment of ACs, potential sources of ignition, understanding of leakage and dispersion of releases, means to determine acceptable charge amounts and appropriate handling of flammables by technicians. It is expected that this will become a focus of upcoming work for this sector.

Whilst the forthcoming choice of refrigerants for this sector, sub-sectors and regions remains unclear, the underlying rationale for change is clearly lower GWP refrigerants and thereafter ensuring that products achieve the necessary higher efficiency levels. It is likely that different manufacturers and countries will opt for a variety of alternatives before any single option is chosen (if at all). In the meantime, investigations will continue into medium- and low-GWP flammable HFCs, HFC/HFO blends and HCs for normal operating conditions as well as HAT.

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Chapter 8

Applied Building Cooling Systems

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8 Applied Building Cooling Systems

8.1 Introduction

Chapter 8 focuses on applied building cooling and heating systems, i.e., air conditioning systems that require engineering services to apply them in commercial buildings. Most commercial buildings require air conditioning systems for comfort cooling, heating, and other purposes such as data processing centres within the building. By contrast, Chapter 7 focuses on smaller, light commercial and residential air conditioning systems and products that may be supplied without the need for engineering services. These systems and products can also be applied to larger commercial buildings, but then require engineering services to design them.

This chapter explores:

- Applications: The application of various air conditioning systems for comfort cooling of commercial buildings, including special applications not related to comfort.
- Systems and equipment: The types of air conditioning systems and the equipment or products used in commercial building applications. The energy efficiency of systems and equipment is also discussed.
- Refrigerant options for new equipment: New refrigerant options that are becoming commercially available for new equipment.
- Refrigerant options for existing equipment : The refrigerant options that are becoming commercially available for existing equipment. This includes discussion of service and reclaim of refrigerants, which are crucial to minimizing the direct environmental effects of refrigerants.
- Adoption of new refrigerant options: Several noteworthy items that govern the pace and intensity of adopting new refrigerant options, apart from normal market forces.

Good progress has been made with new refrigerant options since the 2018 report. All major manufactures supplying products to commercial buildings have released products that introduce new refrigerants with lower GWP than before. And just as important, they have done so while pushing the state-of-the art in new technology that yields higher full and part-load performance. This is significant accomplishment. While products using refrigerants with lower GWP than their predecessors are offered for sale in all major markets, their production today is a fraction of the total global production. This is normal when new products are introduced. Regulations are necessary to accelerate use of new products.

Calculation of the Life Cycle Climate Performance (LCCP) has shown that the dominant environmental impact from commercial air conditioning is the indirect emissions from energy production, related to the energy used over the lifetime of the equipment. (Calm, 2006). Coal burning power plants dominate power production where the population growth is the largest, namely China and India. This adds another environmental concern, namely air pollution. Energy consumption in commercial buildings is affected by both the choice of the air conditioning system and the efficiency of the products used in the system. So, while this chapter discusses refrigerant options, the system choice and equipment efficiency for comfort air conditioning in applied building cooling systems are important considerations for the environment and cannot be overlooked.

CFCs have been phased out of new equipment in all countries, albeit there is still some small production in Article 5 parties. Similarly, HCFC have been phased out in developed countries but can still be used in Article 5 parties. Still, there is a large inventory of chillers worldwide that will continue to use CFC and HCFC refrigerants for service purposes. Important refrigerants included in the chiller inventory are CFC-11, CFC-12, CFC-114, R-500, HCFC-22, and HCFC-123. The current generation of chillers using zero-ODP refrigerants are dominated by high-GWP HFCs, namely HFC-134a and R-410A. These chillers were introduced 30 years ago and will remain in production for some time to come as a transition to products with new refrigerants occurs driven by regulations and normal market forces.

Chapter 8 focuses on central chilled water systems and the refrigerant containing products used in them, namely chillers. What distinguishes central chilled water systems from other air-conditioning systems is the cooling of a secondary coolant, water, or other liquids, that is then distributed and used to cool air or another substance. The critical distinction is indirect cooling contrasted with direct cooling of air. Small enterprises, such as a retail shops in strip malls and fast-food outlets typically use direct systems called (commercial or light commercial) unitary systems. There are several other chapters that provide complimentary information to this chapter as described below.

- Chapter 10, Industrial Refrigeration and Heat Pumps and Heat Engines: covers some special cooling applications that fall in between "commercial" buildings and "industrial" uses. The main difference between Chapter 10 and this chapter is providing cooling equipment for manufacturing and process loads with special 'industrial' features, versus commercial products with standard or catalogue features.
- Chapter 12, Not-in-Kind (NIK) Technology: covers promising products and technologies that use non-vapour compression technology.
- Chapter 13, Servicing and Refrigerant Conservation: covers a variety of topics related to Section 8.4.

8.2 Applications and equipment

8.2.1 Applications in commercial buildings

A commercial building is any structure in which a business purpose is conducted. This includes both direct uses; where a company conducts business out of the building itself, and indirect uses; where the building itself is the business, i.e., the building space is rented or leased. The word "commercial" — sometimes also referred to as "applied" or "large" within the HVAC industry — goes far beyond typical office and retail uses. Beyond the normal comfort cooling for occupants, the air conditioning systems involved actually serve broader functions such as enabling data processing, communications, display lighting, and similar loads within occupied spaces. Cooling systems can also address life-threatening conditions that may exist in deep mines or hospitals, for example. As such, the words "commercial" and "comfort" used in this chapter understates its real breadth.

The array of commercial building applications is extremely broad, see Figure 8-1, including office, retail, food and beverage, apartments, entertainment, education, medical, hospitality, and others. More detailed guidance can be found elsewhere, for example, in references ASHRAE (2020) and ARI (1998).

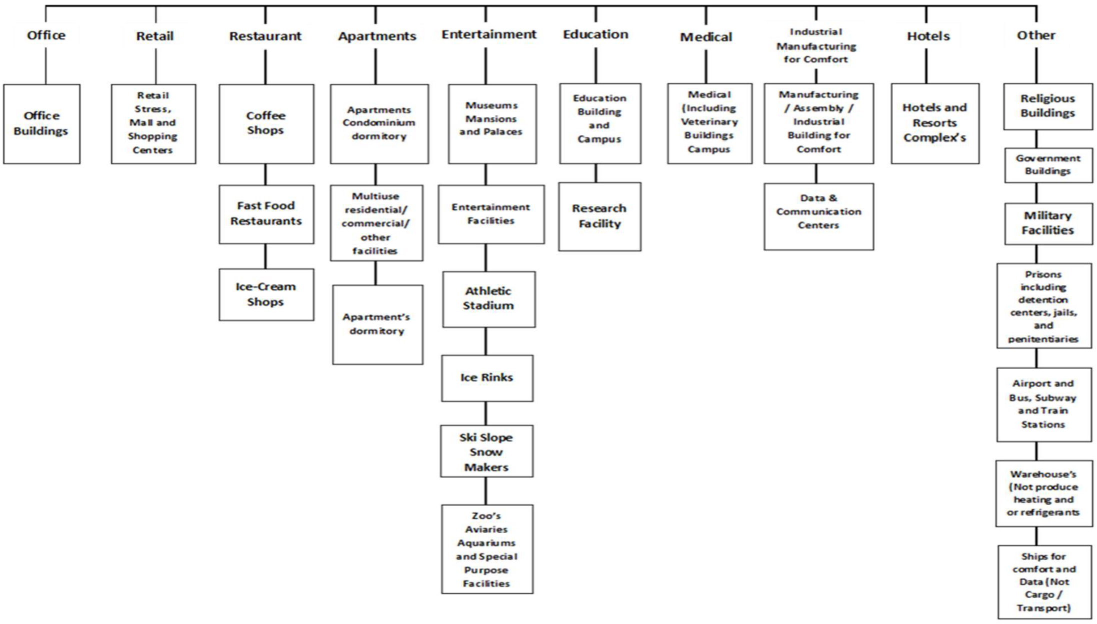

Figure 8-1 : Most Common Applications for Applied Building Cooling Systems

A few other general remarks are important. First, water-cooled chillers installed inside the commercial building envelope that provides cooling (and heating) are normally installed in a mechanical equipment room. If installed outdoors, they may be installed in protective enclosures. Very large enterprises, such as the largest high-rise office buildings, health care complexes, or central systems at a university campus can contain a dozen or more chillers, along with boilers, pumps, and air handling units. These mechanical equipment rooms have special features that isolate it from the building occupants, restrict entry to authorized personnel, and have special refrigerant detection, ventilation, and refrigerant venting requirements according to local building code requirements. The use of special mechanical equipment rooms, along with use of a secondary coolant to the units delivering conditioned air to the occupied space provides isolation of the refrigerant from the building occupants. Accordingly, building codes presently allow unlimited refrigerant charges in the equipment placed in special mechanical equipment rooms. In addition, building codes are changing to give more allowance to the use of new refrigerants, some of which are flammable or have higher toxicity.

Second, mission or life-critical applications typically require other considerations beyond comfort cooling. For example, systems that enable animal survival in zoological parks, aquariums, and similar facilities are life critical for the animals in them. System redundancy, at least partially or even complete redundancy may be necessary. The redundant group may be located separately from the primary one and/or use separate energy sources, such as one set driven by electric motors and the other, back-up set driven by fuel engines. Many strategic militaries and most data and communications centres require redundant systems for reliability. Hospitals, or at least portions of them, also require redundant systems in order to protect against life-threatening conditions when rapid evacuation is not possible, e.g., intensive care units. Backup redundancy can be achieved by other methods, such as storing chilled water underground at multiple levels in dams, to enable continued underground cooling in deep mines where the temperatures from geothermal heat could reach life-threatening levels. Most such systems also include standby power generations at the surface for the deep mine to enable continued pump and fan operation.

And finally, climatic location and internal building loads impact system and equipment selections. Applications in deserts, for example, may require year-around net cooling while those in polar regions require net heating even though building portions in each require the opposite. Applications with favourable opposing loads afford good opportunities for heat recovery or thermal storage.

8.2.2 Systems and equipment used in applied building cooling systems

The focus of this chapter, central systems, use a variety of chiller types to produce chilled liquid that is pumped to central station air handling units or terminal fan/coil units. Typically, boilers provide heat to the building. In its simplest form, chillers produce cold fluids and boilers produce hot fluids to condition the air in commercial buildings. Piping schemes distribute cold and hot fluids throughout the building to central air handling units that then deliver conditioned air through ductwork to the occupied space. Terminal units, such as fan coil units distributed throughout the building are frequently used in place of central air handling units.

Figure 8-2 shows a simple central chilled water system as applied to a small office building. The system has a single chiller and boiler located in a basement equipment room. The hot and cold liquids are pumped to the heating and cooling coils located in air handling units on each floor. The air-handling unit mixes outside air with conditioned air and delivers it to the occupied space through ductwork. Heat from the building, rejected to the chiller condenser, is pumped to a cooling tower located on the roof of the building.

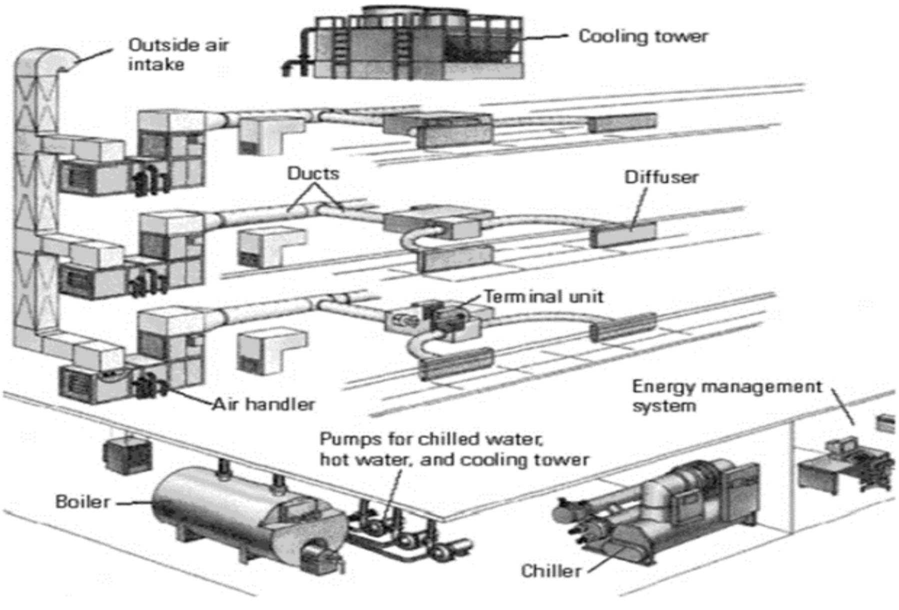

Figure 8-2: Small Central Chilled Water System

Decentralized direct systems, commonly referred to as unitary systems, provide hot and cold conditioned air directly to the occupied space using a variety of air conditioning products distributed throughout a commercial building or on a roof. Figure 8-3 shows a typical packaged rooftop air conditioner delivering hot and cold conditioned air directly to a single zone within the occupied space through ductwork, after mixing with outside air for proper ventilation. The packaged rooftop product contains all the necessary equipment to perform this function.

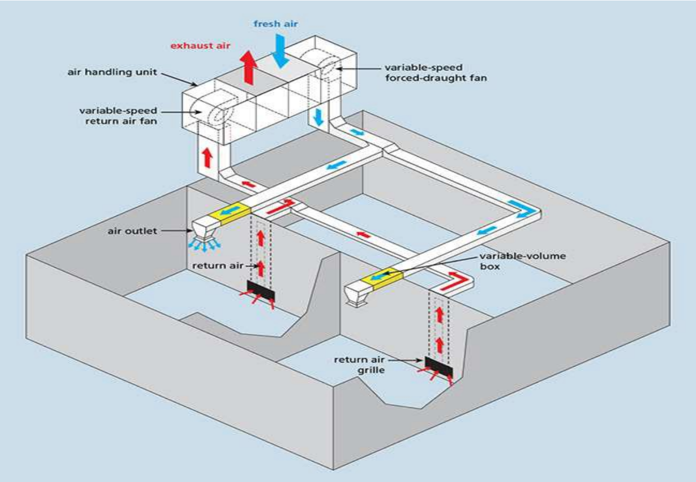

Figure 8-3: Unitary Rooftop System using a Packaged Rooftop Unit – Single Zone

8.2.3 Central systems

8.2.3.1 Typical air- and water-cooled chillers

Figure 8-4 shows several common chiller types. While a change in refrigerants to those with lower GWP is certain, a change in technology in the foreseeable future is not. Mechanical vapour compression technology using centrifugal, screw, scroll, and reciprocating (piston) compressors dominates all chiller types. Continual improvements in compressors, heat exchangers, controls, and other components are common due to efforts by manufacturers and suppliers, and other research efforts. Not-in-Kind Technologies (chapter 12) may be suitable for replacement of chillers in large central systems as a number of these systems have been commercialized.

Large or small, air-cooled or water-cooled, and regardless of the refrigerant, the vast majority of chillers use some form of vapour compression. They use a compressor type that is appropriate to the size range and refrigerant properties. The two basic types of compressors are centrifugal and positive displacement compressors. For purposes of this report, ‘centrifugal compressor’ includes devices whose rotating assemblies result in radial and mixed axial / radial flow compression. Axial-turbo compressors are typically used when water (R-718) is the refrigerant. The positive displacement category includes reciprocating (piston), rotary, screw, and scroll compressors. Not every refrigerant can be used with all compressor types because of cost, design, and manufacturing considerations, and because compressors are designed for specific refrigerants and applications.

There are a number of chiller products using vapour compression technology that use non-fluorinated refrigerants, namely HC-290 (propane) and R-717 (ammonia). Products using these refrigerants are commercially available in air- and water-cooled chillers but are typically located outdoors or in ventilated enclosures due to safety code restrictions. R-717 is seeing some innovation with the introduction of smaller capacity air- and water-cooled chillers. Three other non-fluorinated refrigerants can be used for special applications. These are R-718, R-744, and HC-1270. However, they are not widely adopted for applied building cooling systems. Though trending upward in use in some regions, the total production of all these chiller products is small when compared to the global production of all air- and water-cooled chillers.

a) Small Capacity Air Cooled Chiller

b) Medium Capacity Air Cooled Chiller

c) Medium Capacity Water Cooled Chiller using Screw Compressors

d) Large Capacity Water Cooled Chillers using Centrifugal Compressors

Figure 8-4 Typical air- and water-cooled chillers

Table 8-1 lists the cooling capacity range offered by single packaged units of each type of chiller. Within the product categories, higher capacity is achieved by adding multiple compressors and additional heat exchanger surface within the configured products shown. For large cooling loads, it is common to use multiple chillers as can be seen in Figure 8-4 d).

Table 8-1: Chiller Capacity and Refrigerants used prior to the HFC Phasedown[3]

Chiller type	Capacity range (kW)	Refrigerants presently used (dominant refrigerants in bold[2])
Scroll, rotary, and reciprocating water-cooled	10 - 1,200	**R-410A**,HCFC-22[1], R-407C Less common4 HC-290, R-717, R-744
Screw water-cooled	100 – 3,800	**HFC-134a**, HCFC-22[1] Less common R-717
Screw, scroll, rotary, and reciprocating air-cooled	10 – 1,900	**HFC-134a**, R-410A, HCFC-221, R-407C Less common HC-290
Centrifugal or axial-turbo water-cooled	200 - 21,000	**HFC-134a, HCFC-123**[1] Less common HFC-245faand R-718
Centrifugal air-cooled	200 – 1,600	**HFC-134a**

1. *Available only in Article 5 parties*
2. *"Dominant Refrigerant" means the refrigerant that is most sold in new products on a global, but not local basis, as well as those found in most in existing installations.*
3. *The refrigerants shown are those in use at the time of the 2018 RTOC Report. Since that time, a variety of refrigerant have become available in the market and are in production See section 8.3 and Table 8-3 for a complete discussion of refrigerant options currently available.*
4. *"Less Common" means that the refrigerant is in use, but not widely adopted in the market*

Water-cooled positive-displacement chillers below 700 kW commonly employ direct-expansion (DX) shell-and-tube evaporators with chilled water on the shell side, or brazed plate evaporators. Some manufacturers are using these heat exchangers up to 1700 kW. Large chillers, typically above 700 kW, use flooded/pool-boiler type, falling film, or spray evaporators with the refrigerant on the shell side of the tubes. For flooded falling film evaporators, there is a limit on refrigerant selection. Zeotropic refrigerants that are blends (e.g., R-407C) with high temperature glide can fractionate in the evaporator and condenser, creating significant performance issues. Accordingly, refrigerants with high temperature glide cannot be used in flooded or falling film evaporators. These types of evaporators can be used for larger chillers.

Water-cooled chillers use shell and tube heat exchangers, or brazed plate heat exchangers (in smaller chillers), as condensers. The condenser rejects heat to a cooling tower, evaporative condenser, or dry cooler. Air-cooled chillers employ finned tube or micro-channel coils and fans to reject heat directly to the ambient air.

To reduce power consumption and lessen the environmental impact, various energy efficiency features are available. Relatively recent features include high speed direct drive compressors using permanent magnetic motors, oil-free magnetic bearings in lieu of rolling element or journal bearings, wider use of variable speed drives and controls to optimize performance at part load, and heat recovery heat exchangers of various types.

Customers can make intelligent choices when system and product efficiency alternatives are explored, using building modelling and manufacturer product selection codes that are widely available. These tools include local weather data, the cost of energy, and other economic factors that govern a project. Manufacturers typically offer an array of efficiency choices for any application. High confidence in chiller selection is achieved through rating standards and certification programs that exist in most countries. AHRI Standard 550/590 (AHRI 2020) and EN 14825 (EN, 2018) are among the rating standards used by manufacturers and certification programs, when determining full and part-load performance. Chiller performance in many countries is verified by third party agencies who conduct performance tests to the appropriate rating test standards. Furthermore, the annual energy consumption can be calculated with computer simulation programs using the chiller(s) load profiles, building loads, and weather data. For large and complex chiller systems, extensive modelling can provide systems and chiller solutions that minimize total energy consumption. Though replacement chillers and smaller equipment are commonly sold on the basis of full and/or part load rating, performance certification programs are none-the-less available in many countries and give consumers confidence in their choice of system and product.

Several items seem to be frequently overlooked in the discussion of energy efficiency. First, correct chiller application, piping, unloading and staging controls will dramatically decrease the overall energy consumption of the installation. Accordingly, it is more important to pick the right chiller system and control strategy, than to pick the right efficiency level of chillers within that system. There is a great number of choices especially for large, multiple chiller systems, and a direct comparison of these systems involves extensive computer modelling. For small systems, such investigations are typically cost prohibitive.

Generally, water-cooled chillers are more energy efficient than air-cooled chillers for any geographic location (Sharma, 2017), notably so in larger capacities. However, air-cooled chillers are more dominant. Factors other than energy efficiency drive the choice towards air-cooled. These other factors include the building type and the need for a mechanical equipment room, simpler maintenance, the physical space around the building, the availability of water and water treatment, health concerns regarding Legionella in cooling towers, system complexity, budget and time considerations, new construction vs. replacement chillers, and the cost of energy.

Two other opportunities to reduce energy consumption are available with chiller systems. First is that of heat recovery or heat pump options that are available in some chillers. Any time waste heat is recovered or repurposed, it lowers the load on boilers or other items that may be used for space or water heating. In turn, this reduces the overall energy consumption of an installation. Thermal storage is a popular method used with chillers to take advantage of off-peak electricity costs while making ice or slurries used during the daytime. This cooling method also takes advantage of cooler temperatures in the night hours to reduce the energy consumption versus that of daytime cooling.

A recent trend is the use of chillers as the primary source of heat or pre-heating of boiler water. In this case, the chilled water is incidental and typically returned to a lake or other large water source. This particular application depends on the economics of the water supply, and space heating through electricity or natural gas, although the use of natural gas is restricted in some regions by government regulation. Dedicated heating machines are trending upward in the market as a result. In order to achieve high temperatures needed to replace boilers, the compressor and heat exchangers must be designed for this purpose.

8.2.3.2 Chillers with evaporative condensers

An air-cooled chiller can use an evaporative condenser with a spray tree and bare copper coil to replace a normal aluminium fin and tube coil. This is one way of achieving higher efficiency at the cost of copper coil and a water system for the evaporative condenser. In the evaporative cooled condensing process, water is continuously sprayed over the condenser tubes as the condenser fans draw air upward across the tubes to evaporate the spray and cool the condenser toward the ambient wet bulb temperature. Unlike an air-cooled condenser that rejects heat from the refrigerant to the air at the ambient dry bulb temperature using a fin and tube coil, an evaporative cooled condenser rejects heat from the refrigerant to the water at the wet bulb temperature. The wet bulb temperature can be 8 to 14 °C lower than the dry bulb temperature in hot, dry climates. The lower condensing temperature means that the evaporative cooled condenser can reject more heat than an air-cooled condenser, while requiring less compressor work and consuming less energy.

An alternative to the evaporative condenser is the hybrid chiller, an air-cooled chiller with both a conventional fin and tube coil, and a spray tree pre-cooler coil on the incoming air. Hybrid chillers with both evaporator and air-cooled condensers can be an attractive option where there is a big swing in temperature between day and night and in mild seasons. When air conditioning is required during the medium and low temperature times, and water is not widely available, the chillers can work in the air-cooled condenser mode. The evaporator condenser is employed during periods of higher temperatures. The hybrid design, using both the evaporator condenser and air-cooled condenser with an appropriate control scheme, can reduce the water consumption. At the same time, the hybrid design can keep the higher energy efficiency levels for all operating modes of the chiller.

8.2.3.3 Design considerations for high ambient temperatures

There are a number of regions which have a relatively high population density and are subject to high ambient temperatures (HAT) exceeding 46 °C (see Table 8-2 below). Among them are Eritrea, central India, southern Iran, Iraq, Oman, Pakistan, Kuwait, parts of Saudi Arabia, and southwestern USA. There are other regions that experience HAT conditions, but those regions are sparsely populated. Considering the populated HAT regions, the demand for all refrigeration, air conditioning, and heat pump products is small with less than 4 % of global demand. When considering indirect systems and the chillers used in commercial buildings, the global demand is even less.

Table 8-2: High Ambient Rating Conditions

T1	In non-HAT countries, systems are normally rated for 35 °C (T1 in ISO 5151:2014) with operation and performance ratings up to 46 °C
T3	High ambient temperature (HAT) conditions require a design at 46 °C (T3 in ISO 5151:2014) with operation and performance ratings up to 52 °C

Commercial building customers in HAT regions want full capacity products, not products that are designed for other regions and derated for use in HAT countries. This means that a 600-kW rated air-cooled chiller delivers 600 kW of cooling operating at T3 conditions. Customers want the product to be optimized at T3 conditions to keep energy cost as low as possible. The product must be reliable in harsh conditions to avoid purchasing redundant equipment. And in time, products must also transition to a refrigerant with lower GWP (other than R-410A or HFC-134a currently in use) and meet local minimum energy performance standards (MEPS). While there are a few case studies using full capacity products using low-GWP fluids operating at T3 conditions and meet MEPS, these are rarely available. MEPS are mandatory in some Article 5 parties like Saudi Arabia.

Air-cooled chillers are the product of choice and are widely used in HAT countries. The refrigerants commonly used are R-410A (with scroll compressors) and HFC-134a (with screw compressors). Some products are said to be optimized for HAT conditions, albeit these are somewhat limited. The reality is that major manufacturers focus on high volume products optimized at lower ambient (T1) temperatures. As the ambient temperature increases to T3 conditions, the building heat load naturally increases. The refrigeration system capacity and efficiency decrease due to higher condensing temperatures and higher thermal lift. This is normal, and unavoidable; it is just thermodynamics. It has little to do with the refrigerant and nothing to do with the specific design point of the compressor. As the condensing pressure increases, the compressor discharge temperature also increases. At higher ambient temperatures, if no mitigation measures are taken, some refrigerants will be operating too close to their critical pressure and the high-pressure limit for proper operation. Compressor motors can also be overloaded or run too hot. In order to keep the condensing temperature, the motor temperature and compressor discharge temperature within the allowable operating range, larger condensers, capacity control through compressor unloading, and liquid injection are used. These are undesirable effects ultimately affecting the size and cost of the equipment, as well as the power used and operating cost. Extra or oversized equipment is needed to compensate for the capacity shortfall at T3 conditions.

There are other negative factors too, such as the need to purchase redundant equipment due to reliability concerns, and increased maintenance due to the harsh and changing conditions. These are all economic issues in the end. To further complicate matters, refrigerants with lower GWP are needed to comply with the Kigali Amendment to the Montreal Protocol. And every new product must meet local MEPS. MEPS are developed to assure better utilization of energy and protection of consumer by supporting efficient products. MEPS vary from one country to another.

It should be noted that in some HAT regions, water is available. When water is available, there are several choices including water-cooled chillers, air-cooled chillers with evaporative condensers, and evaporative coolers. For example, Muscat, Oman is located on the seacoast. Intermediate heat exchangers or sea water suitable condensers can be employed to use water-cooled chillers.

8.2.3.4 Absorption Chillers

Absorption chillers do not use a compressor with an electric motor to drive a vapour compression cycle. Instead, they use a chemical cycle and produce cooling using heat instead of electricity as its motive force. Sometimes referred to as a “Not-in-Kind” (NIK) technology, absorption chillers do not use vapour compression technology like other compressor bearing chillers. There are many different types of absorption chillers (1, 2, and 3 effects), heat sources and capacities. A single effect absorption chiller is shown in Figure 8-5. Common absorption solutions are water-lithium bromide (H_2O-LiBr), and ammonia-water (NH_3-H_2O). Among the more common sources of heat are hot water, natural gas, steam, and recovered waste heat.

It is important to note that the COP of an absorption chiller is a ratio of cooling output divided by heat input and cannot be compared directly with that of a vapour compression chiller. This is because a vapour compression chiller’s COP is a ratio of useful refrigeration effect divided by the input energy to an electric motor-driven compressor. In order to compare both COPs, it is necessary to reduce that of a vapour compression chiller by the inefficiencies of producing electric power. The inefficiencies include the electric power plant efficiency, transformers efficiencies, and transmission efficiencies. Reducing the COP of vapour compression chillers by approximately 35 % provides a meaningful comparison of the two types. None the less, vapour compression chillers are typically more efficient than absorption chillers.

The economics of the cost of the absorption chiller versus a chiller using vapour compression, and the availability and cost of the heat source versus the cost of electricity typically drives the purchasing decision by the customer. However, there is uniqueness of absorption systems in utilizing a basic, direct form of energy together with their low electric power requirement (for a small fluid pump and controls). This makes absorption chillers an important element in the mix of available products for commercial comfort cooling and heating, as well as other industrial uses.

Absorption systems using ammonia-water as the working fluid pair are used for low temperature refrigeration applications. They are also used for comfort air conditioning since ammonia can operate at low evaporation temperatures.

Water-lithium bromide working solutions operate at above freezing temperatures; water is the refrigerant. They are used in air conditioning applications only. Absorption chillers using water-lithium bromide has an important role to play as an alternative technology to vapour compression because they can operate using rejected waste heat from other sources. In addition, absorption refrigeration is used regularly during peak hours for reducing peak electrical power consumption, and in summer seasons for increasing gas turbine performance of power stations through cooling of the turbine’s inlet air flow.

Figure 8-5: Single effect absorption chiller

8.2.4 Special commercial and industrial applications

Some applications of commercial and industrial air conditioning products fall in an unclear divide between “commercial” buildings and “industrial” uses. Industrial applications are covered in Chapter 10, Industrial Refrigeration and Heat Pumps and Heat Engines. While Chapter 10 focuses on primary usage for manufacturing and other process cooling and heating, some of the applications involve worker spaces requiring comfort conditioning covered in this chapter. The difference is serving thermal loads for production (Industrial) along with special ‘industrial’ features versus those for occupant comfort (commercial) with an array of ‘standard commercial’ features. Many of these commercial systems are huge and complex, which distinguishes them for normal applied building cooling applications.

Such large complexes include central chiller or less commonly, heat pump systems. These systems typically use multiple chillers to achieve the necessary capacity, and varying redundancy for reliability. This duplication by design enables maintenance, including overhauls as the systems involved often operate nearly continuously on both diurnal and or year-around basis. Furthermore, it allows for reliability when the applications are critical in function and worker life-threatening situations if disrupted.

8.3 Refrigerant **options** for **new equipment**

Table 8-3 shows the new refrigerant options available in the market today.

Table 8-3: New refrigerant options for air- and water-cooled chillers

	Low Pressure			Medium Pressure					High Pressure					
Refrigerant	**HCFC-123**	HFO-1233zd	R-514A	**HFC-134a**	R-513A	R-515B	HFO-1234ze(E)	HFO-1234yf	**HCFC-22**	**R-410A**	R-466A	R-452B	R-454B	HFC-32
Flammability Class	**1**	1	1	**1**	1	1	2L	2L	**1**	**1**	1	2L	2L	2L
Toxicity Class	**B**	A	B	**A**	A	A	A	A	**A**	**A**	A	A	A	A
GWP classification	**Very low**	Ultralow	Ultralow	**High**	Medium	Low	Ultralow	Ultralow	**High**	**High**	Medium	Medium	Medium	Medium

Notes:

- Low-, medium-, and high-pressure refrigerants are used in centrifugal, centrifugal and screw, and scroll and positive displacement compressor chillers, respectively
- HCFC-22 is only available in Article 5 parties

- Bolded columns are considered as the baseline widely available refrigerant options for the different categories

Not shown in Table 8-3 are chillers using R-717 (Ammonia, Safety Group B2L), R-718 (Water, Safety Group A1), and HC-290 (Propane, Safety Group A3). R-717 and HC-290 have a GWP < 1. Also not shown in the table are replacements for HFC-245fa, a minimally used refrigerant for chillers and for Organic Rankine cycle (ORC) machines. HFO1224yd(Z) has a similar capacity to HFC-245fa, a near zero ODP (0.00023) and a GWP <1 (Ultralow). It is considered to be design compatible as a replacement refrigerant in chillers, as well as ORC machines.

It is important to note that there is no single refrigerant replacement for any of the dominant refrigerants in use today shown in Table 8-1. There are multiple replacement refrigerants, creating complexity for the manufacturers and customer. While it is desirable to have consolidation to a single refrigerant in each category, it is impossible to say if consolidation will occur over time. However, there is information suggesting that use of HFO-1233zd(E) may be more widely adopted and replace products that use medium pressure refrigerants. This is because it has an A1 safety classification, high efficiency and because it is single-working fluid, not a blend. These factors lead to lower application costs and ease of service.

In addition, all the high-pressure refrigerants (replacing R-410A) and one medium pressure refrigerant (replacing HFC-134a) have a GWP greater than 300 (low GWP). Since there is no consensus on what final GWP level will be acceptable, the pressure to investigate new alternatives will continue. Accordingly, low GWP refrigerants are getting some attention including R-516A and R-515B for medium pressure applications. There is no report of future investigations for low GWP refrigerants that would replace high pressure refrigerants. HC-290 is a known low GWP solution, albeit it has a safety classification of (flammable).

8.3.1 HAT considerations

Several important factors must be taken into consideration when designing for HAT conditions including the refrigerant critical temperature, the application range of the compressor (which depends on the compressor and refrigerant used), and the refrigerant discharge gas temperature. These criteria are relevant for all types of refrigerants but will be more critical for some types of refrigerants that have a low critical temperature like HFC-32, a refrigerant option currently used in air-cooled chillers that use positive displacement compressors.

A demonstration project in Saudi Arabia responded to Decision 76/46 of the Multilateral Fund Executive Committee (World Bank, 2019). It was shown that showed that the chiller cooling capacity and energy efficiency using refrigerants HFC-32 and HC-290, is better than with R-410A at both T1 and T3 conditions. However, both alternatives can be applied in air-cooled chillers, with appropriate attention to local building codes. Given the opportunity to purchase new equipment, owners should continue to push manufacturers to offer products that use low GWP fluids, with full capacity at T3 conditions and meet local MEPS.

8.3.2 Barriers to change to refrigerants with lower GWP

Global markets for products used in applied building cooling systems are not homogeneous. As suggested earlier, the pace and intensity of the change to refrigerants with lower GWP is determined by market forces and government regulations and financial incentives. The latter two factors are covered above but building safety codes are an additional form of regulation worth discussion. Safety codes affect the potential use of flammable refrigerants, including those shown in Table 8-3. The safety codes must be changed in each region, legally adopted, and enforced. IEC 60332-2-40 (IEC, 2022) provides a safety framework for the use of flammable, refrigerants with lower GWP that can be adopted directly or adopted in modified form to suit specific country requirements. The U.S., for example, has used this standard as a basis for development of its own standards, namely UL 60335-2-40 (UL, 2019) and others. These standards go through continuous changes as research gives a technical basis for changes. A risk assessment may provide a path forward in some regions for use of new refrigerants where safety codes are not yet available. See chapter 3 for further discussion.

Three other related items are noteworthy. First, for new construction, a transition to refrigerants with lower GWP should be a primary customer consideration. But at this moment in time (especially for large, multiple-chiller installations), higher performance systems and the chillers used in those systems are typically higher on the list of customer requirements. For the ultimate customer, this relates to operating costs, i.e., the energy consumed and its cost over the life of the product. Therefore, offering correct products for a high-performance system, while using refrigerants with lower GWP than their predecessors is key going forward.

Second, the markets for existing buildings are far larger than those of new construction. Existing chillers are typically replaced using the same refrigerants as other machines in the building, on a rapid ship-cycle basis, assuming the refrigerant is still permitted. This is because the time that a system can be shut down is usually short, over a few winter months or less for applications requiring cooling year-long. Customers cannot normally change their system in any substantive way without revisiting building safety codes especially for mechanical equipment rooms. Due to building safety codes, this would occur when a new chiller is added, and the equipment contains a refrigerant with a different safety class. Large chillers located in mechanical equipment rooms contain large amounts of refrigerants. In the case of a catastrophic release of a flammable or toxic refrigerant, the danger to human occupants and property is real. The cost and complexity of conformance to the new requirements for the mechanical equipment room are typically costly and time consuming, typically an unacceptable issue for existing building changes. But regulations and enforcement can vary significantly by region or locality. As long as the jurisdiction having authority is involved early in a renovation project, there can be a successful outcome.

The third issue that can slow the introduction of refrigerants with lower GWP is system component availability. Most manufacturers do not design and manufacture their own compressors or other major components. These manufacturers are dependent on the supplier for these components. The supplier must not only supply the product, but also qualify it for use with the new refrigerant and its required lubricant (for reliability), as well as supplying certified performance and other technical information. Component availability and access to technical information and certified performance data in some regions is a challenge, notably for scroll compressors using HC-290 used in small, air-cooled chillers.

8.4 Refrigerant options for existing equipment

As the transition to refrigerants with lower GWP proceeds in new equipment, there remains a need to service the large, installed population of products until the end of their useful lives. Centrifugal chillers have a long useful life of 20 years or more, with proper maintenance. These products may contain CFC, HCFC and HFC refrigerants. The direct effects of refrigerant released to the environment is minimized when highly qualified service personnel using rigorous service and maintenance procedures are in place. This is especially true when the product is removed from service at the end of its useful life.

At the end of life of a product, or a change of refrigerant, recovery of the full charge of refrigerant is critical to environmental impact. For products like chillers, with very large refrigerant charges, the environmental impact is not negligible. Apart from a catastrophic failure causing a complete loss of refrigerant, full refrigerant reclaim at the end of life is perhaps the major source of lost refrigerant over the life of the equipment. Use of qualified service technicians who use special procedures are extremely important. Delivery of the recovered refrigerant to a qualified company who can either recycle the refrigerant, or destroy it properly is the last step. Globally, this is a significant challenge because of shortages in qualified technicians in regions where labour shortages exist, but especially in areas with low technical capability. Article 5 parties and remote locations are among these areas. This is exacerbated by the use of refrigerant blends introduced on the market, which makes it harder for operators to recover, recycle, and reuse the refrigerant.

8.4.1 Option 1: service and maintenance

Servicing and maintaining the equipment with the existing refrigerant is the most common option. Chillers are typically overhauled or repaired several times in order to achieve or even extend their useful life. This minimizes refrigerant losses due to small leaks. Experience suggests that a complete, rapid loss of refrigerant is actually quite rare during operating. Still there are other sources of released refrigerant that are known to occur as a result of the following:

- Shipping and Handling Damage. It is not uncommon to see a complete loss of charge during shipment and handling of products that are fully charged, a common practice for small factory packaged equipment. The loss of charge is typically caused by physical damage to piping and other small lines. The best method of avoiding leaked refrigerant during shipping is to ship the equipment uncharged and charge it in the field after installation.
- Leaking Gaskets, Seals and Joints. This occurs on semi-hermetic compressors and piping joints. Experience has shown that exposure to periods of hot and cold, along with changes in physical properties due to contact with lubricants and refrigerants, will ultimately cause gasket leaks almost without exception. Gaskets and seals must be periodically replaced every 8 to 10 years, as recommended by the manufacturer. Testing has also shown that certain types of piping joints are more prone to leaks and should be eliminated by design where possible. Flared joints are particularly prone to failure and leaks.
- Failure of Open Compressor Shaft Seals. Hermetic compressors and semi-hermetic compressors are the dominant compressor types, but open compressors are still available. Shaft seals do not have an infinite life and are prone to failure and loss of charge unless they are periodically maintained or replaced.
- Service of Equipment. Poor service practices lead to a loss of some, but not all, of the charge. For example, it is common to overlook the refrigerant that is dissolved in the lubricating oil before performing certain service or maintenance procedures that open the interior of the machine. When the chiller is opened, the dissolved refrigerant comes out of solution and is lost.

For more details, see Chapter 13, Servicing and Refrigerant Conservation for additional information.

8.4.2 Option 2: refrigerant change

This option changes the existing refrigerant with a blended refrigerant that has the same refrigerant safety classification. Blended refrigerants, so called “service blends” or “drop-ins,” are used so that the capacity and performance are minimally affected. In this case, the refrigerant and lubricant are changed, with minimal other modification to the equipment. System controls may need to be adjusted due to refrigerant property changes, e.g., the low-pressure cut-out setting.

Some compressor and manufacturers of larger systems carry out evaluations of selected refrigerant options and provide recommendations as to which they believe are suitable for use in existing installed equipment. In some cases, manufacturers explicitly warn against such replacements. Information on the application of these blends can be obtained from manufacturers.

Option 2 has been mostly used on equipment that uses HCFC-22 with positive displacement scroll or reciprocating compressors. There are several refrigerants available to replace HCFC-22 and they have been commercially available for over 10 years. They generally combine two or more HFC refrigerants with a small amount of HC (or certain HFC refrigerants, such as HFC- 227ea), which are added to the blend to enable the refrigerant to work with the naphthenic mineral-oil-based and alkyl benzene lubricants. These lubricants were historically used in nearly all HCFC-22 air conditioning systems. Suitable retrofit refrigerants for HCFC-22 chillers include R-407A, R-407B, R-407C, R-407D, R-407E, R-421A, R-421B, and R-427A. These blended refrigerants attempt to mimic HCFC-22. However, they seldom perform as well as HCFC- 22. Many have lower capacity, lower efficiency, or both, and have been rarely if ever been used. Also, many of them many have medium to high glide leading to relatively poor performance. Another disadvantage of using moderate and high glide blends is the need to remove and replace the entire charge during servicing to avoid substantial composition shift. R-407C has a moderate glide and laboratory and field experience indicates R-407C can be serviced without replacing the entire refrigerant charge with minimal impact on performance. In the majority of cases, the drop-in blends have been found to exhibit worse performance. Various studies reporting on comparative measurements with HCFC-22 and retrofit refrigerants (mainly R- 407C) were summarized in RTOC (2014), all of which found a reduction in COP and cooling capacity, typically in the order of 5 to 10 %.

The search for a “drop-in’ replacement for R-410A has gone on for several years. One candidate, R-470A, was announced in early 2020. It is a patented HFO blend that has similar energy efficiency and cooling capacity as R-410A, along with similar discharge pressures and volumetric flow rates. However, it has a significant temperature glide which requires appropriate heat exchanger designs to minimize any loss of performance. It has an A1 safety classification, the same as R-410A. It remains to be seen if this blend will be broadly used for R-410A replacement on existing equipment.

8.4.3 Option 3: retrofit

This option requires a change of the refrigerant, lubricant, and system components as opposed to a simple refrigerant change described in Option 2 above. Some general comments are appropriate. First, the customer must accept any change in capacity or performance and understand any potential reliability implications. Single component replacement refrigerants that are commercially available are not “drop-in” and usually have thermodynamic or physical property differences. This means that the capacity and efficiency will be affected. There are also possible reliability issues related to refrigerant, lubricant, and material interactions. Second, large chillers that are located indoors in mechanical equipment rooms contain large charges of refrigerant. Retrofit/conversion using a flammable refrigerant is a complex process and can lead to unforeseen safety issues.

Equipment installed indoors that uses a safety class A1 refrigerant should not be retrofitted or converted to use a toxic or flammable refrigerant without consultation with the manufacturer and consideration of the following:

- Applicable safety codes or standards that apply to the product changes. This typically involves addressing potential ignition sources. When the changes are accomplished, they must be verified by a certified testing lab field evaluation.
- Applicable safety codes or standards that apply to the installation location, including the mechanical equipment room if appropriate. This typically involves methods for refrigerant detection and exhaust of leaking refrigerant. Changes to the installation must be verified by the local jurisdiction having authority. The importance of consultation with the original equipment manufacturer and compliance with the building and product safety codes and standards cannot be overstated. Consultation with the original equipment manufacturer can address performance and reliability issues, as well as providing technical guidance. While safety codes and standards that

apply to retrofit/conversions must be used, they may not be available or legally adopted and enforced in specific locations.

There is at least one report of a retrofit reported in China that resulted in a catastrophe. There was an explosion of a chiller that was converted from HFC-134a (A1 refrigerant) to a blend of 95 % propane and 5 % butane (A3 refrigerant). One person was killed, and four others injured. Information is incomplete, but an investigation revealed that there was no refrigerant detection or emergency ventilation in the mechanical equipment room, and the equipment in the room was not explosion proof. Inclusion of this incident in this report is only meant to underscore the need for rigorous evaluation of all factors before performing a retrofit involving a flammable refrigerant (Investigation Unit, 2021).

Similarly, equipment located outdoors may be converted to a flammable refrigerant provided: 1) the original equipment manufacturer is consulted, and 2) the local authorities having jurisdiction are involved, approve the changes, and verify that the changes meet all safety requirements. Also, external aspects of the equipment location, such as natural air movement around the equipment and potential sources of ignition, must be addressed.

Retrofit refers to not only changing the refrigerant, but also some of the system components. For example, component changes could include the replacement of the compressor, refrigerant, lubricant, dryer, expansion device, and purging and flushing the system to remove all residual lubricant from the system. Retrofitting can be substantially more costly than using existing refrigerant. Retrofitting is generally not economically justified if either the compressor or heat exchangers have to be replaced, or if the efficiency is substantially reduced and negatively affects operating costs. Positive displacement scrolls, screw, and reciprocating compressors inherently work acceptably with a number of different refrigerants and pressure ratios if: 1) the compressor motor has adequate power, 2) the compressor casing or shell, tubing, heat exchangers, and other components can meet safety and pressure codes, and 3) the system materials and lubricant are compatible with the refrigerant. Despite this flexibility, there remain a number of issues in retrofitting or converting positive displacement chillers to operate with new refrigerants.

HCFC-22 Scroll and Reciprocating Compressors: There are a number of the HFC blends proposed as alternatives to HCFC-22 in existing chillers, as discussed in Option 2 above. While many of the proposed blends are seldom used, R-407C has been demonstrated to be an acceptable retrofit refrigerant and has seen widespread use in some regions. Provided that the compressor already uses a mineral oil, a change from HCFC-22 to R-407C requires replacement of the existing naphthenic mineral oil or alkyl benzene synthetic oil lubricant. Filter driers that are able to absorb breakdown products from synthetic lubricants should also be installed. At this time there are no retrofit refrigerants in widespread use for chillers using R-410A.

HFC-134a Screw Compressors: Several manufactures are offering retrofit programs that replace HFC-134a in screw compressor products using a refrigerant with lower GWP, namely R-450A or R-513A.

HCFC-123 and HFC-134a Centrifugal Compressors: By contrast to positive displacement compressors, centrifugal and axial-turbo are not very flexible regarding refrigerant changes. These compressors must be designed specifically for a particular refrigerant and a particular set of operating conditions for the refrigerant cycle in which they are used. Direct refrigerant substitution in these chillers can be made only in cases where the properties of the substitute refrigerant are nearly the same as those of the refrigerant for which the equipment was designed, or when the impeller speed and/or impeller geometry can be changed through cut-back or new impellers. In the past speed has been accomplished by gear changes for gear driven compressor or use of variable speed drives for both open and hermetic centrifugal compressor chillers. The compressor surge margin must be checked using the properties of the substitute refrigerant.

Centrifugal and axial-turbo chiller installations can represent a very large capital investment for the owner. Potential difficulties were reported in the 2014 RTOC report. So, despite the possible technical difficulties, several manufacturers are offering chiller retrofits using refrigerants with lower GWP, namely R-450A, and R-513A (for HFC-134a) and R-514A (for HCFC-123).

When a retrofit or conversion is performed for equipment located indoors, it is recommended that the machinery room be upgraded to the requirements of the latest edition of safety standards such as ASHRAE 15 (ASHRAE, 2019), EN 378 (EN 378-1, 2016 + A1 2020), or international standards such as ISO 5149 (ISO, 2014). In the case of refrigerant replacement and retrofit in HCFC systems, the GWP of the replacement refrigerant should be considered, as many blends have a GWP higher than HCFC. In all cases, before changing the refrigerant the original equipment manufacturer should be consulted and the local authorities having jurisdiction are involved and approve the change.

8.4.4 Option 4: Replacement

Replacement means that the equipment is completely replaced with new equipment that uses a zero ODP and refrigerant with lower GWP, before or at the end of its useful life. Normally the new product will have a higher efficiency than the product it replaced, providing an economic motivation through lowering operating costs. In non-Article 5 parties, equipment replacement is more common because the costs associated with performing a major retrofit or conversion discussed in Option 3 above are close to the cost of a new product.

8.5 Concluding Remarks

After years of research and product development, there are complete lines of all chiller types and sizes that use refrigerants with lower GWP. Additionally, there are non-fluorinated refrigerants available in some chiller types, especially noting absorption chillers, which have been available in the market for many years. Overall, the choices may be limited in some regions, but expansion of choices is expected. Existing products using higher GWP refrigerants have not been discontinued and are still the dominant products being sold in most markets. Normal market forces usually cause the mix of new and existing products to change over time. However, government regulations will force a more rapid change.

The chiller refrigerant options include flammable and toxic refrigerants, notably R-717 and HC-290. Also, refrigerants with lower GWP as replacements for HFC-134a and R-410A include flammable refrigerants primarily limited to safety class A2L. Safety regulations that allow use of these refrigerants exist, or are being written, but are not uniform nor adopted in all regions. Flammable or toxic refrigerants can cause significant health issues for humans and property damage. Building safety codes must be adopted and enforced and are crucial to the safe use of these refrigerants.

LCCP analysis shows that the environmental impact from chillers is dominated by their energy use over the lifetime of the equipment, rather than the direct emissions from released refrigerants. Customers and regulators alike are interested in less energy consumption while moving to even lower GWP than the products that are currently available.

Recovery of the entire charge of refrigerant in chillers, where charge quantities are typically large, is essential to minimize the environmental impact. Globally, this is a significant challenge because of shortages in qualified technicians in any region where labour shortages exist, but especially in areas with low technical capability, notably Article 5 parties and remote locations.

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Chapter 9

Mobile AC/HP

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9 Mobile AC/HP

9.1 Introduction

Since the mid-1990's, refrigerant alternatives to HFC-134a have been developed and deployed for mobile air conditioners (MACs). Today, nearly all light duty vehicles in Europe, Japan, North America, and in some other countries use the zero ODP ultralow-GWP HFO-1234yf as refrigerant in mobile AC applications. Sharing a common platform, as of 2020 four European brands introduced R-744 based heat pumps in some of their high-volume electric vehicle models (heat pump 2020). SAE International's Interior Climate Control Committee also updated its standards to allow HFC-152a in secondary loop mobile air conditioners (SL-MACs) (SAE, 2020b).

The increasing road transport electrification and awareness of environmental issues (energy efficiency and sustainability) is opening the door to a new generation of MACs that has to ensure passenger comfort (cooling and heating) and system (battery, motor, and inverter) thermal management. In this framework, the use of non-fluorinated refrigerants (R-744 or HC-290) or mixtures is under assessment to either improve the system's efficiency or reduce the use of synthetic refrigerants. Therefore, other options, such as R-744 and HC-290 and new refrigerant blends, are gaining renewed attention.

This chapter covers the new developments since the RTOC 2018 report; details on system design and history of refrigerant system development are included in preceding RTOC reports (UNEP, 2019).

The vapour compression cycle is the current technology used for Mobile Air Conditioning. Several alternatives have been unsuccessfully evaluated, while several other technologies are under assessment (see Chapter 12).

Light and heavy-duty vehicles use from 0.3 to 1.4 kg refrigerant charge, varying based on the system design and refrigerant selected, while for buses the charge could be from 8 up to 16 kg depending on the vehicle category (e.g., simple bus, articulated bus).

Considering that there are about 1.3 billion road vehicles in the global fleet with an average renewal rate of 7.7 % (i.e., 13 years average vehicle age), there are approximately 1 million tonnes of refrigerant in vehicles (OICA, 2017).

According to IEA (IEA, 2019) MAC installation rate in the global fleet is close to 100 % in advanced economies, and around 60 % in emerging countries ranging to 100 % for new vehicles. Assuming that 80 % of current circulating vehicles (i.e., approximately 1.3 billion units) are equipped with a MAC, with a yearly renewal rate of 8 % (e.g., approximately 100 million units), and that an additional 5 % of the installed quantity is required for service, the worldwide refrigerant demand is about 130 ktonnes/year. Considering the forecasted increase of circulating vehicles up to about 2 billion by 2040 (WEF, 2016), the amount of required refrigerants will increase similarly up to approximately 210 ktonnes/year, not considering the potential effect of progressive electrification of vehicles that may require slightly higher refrigerant charge.

In 2013 the transition to lower GWP refrigerants started. The European Union mandated the transition under the MAC Directive, while the United States Environmental Protection Agency (US EPA) encouraged the transition through regulations and incentives. This transition is progressively extending worldwide. In the meantime, the desire to reduce Greenhouse Gases (GHG) emissions is influencing vehicle efficiency regulations and this may consequently influence MAC technologies (see section 9.6 on regulatory frameworks).

Meanwhile, MAC systems tightness has improved mainly in Europe, US, and Japan, by adopting new hose materials, seals, and other technologies along with more effective coupling designs. In addition, system energy efficiency has increased owing to the development of better heat exchangers, compressors, and control strategies.

The transition to lower GWP refrigerants that generally have higher cost along with increased prices for regulatory controlled HFCs opened the door for counterfeiting, which has become an issue (Velders, 2009). Hence, counterfeit HFC-134a is infiltrating the refrigerant bank, particularly in Asia, but increasing illegal streams are also seen in Europe and North America.

Currently, even though the cost of HFC-134a is relatively low, counterfeit HFC-134a is still appearing in the automotive market, often in small service cans. Counterfeit HFC-134a can contain multiple hydrochlorocarbons (e.g., HCC-40), chlorofluorocarbons and hydrofluorocarbons, among which there are toxic or corrosive components. Counterfeits are a serious threat because they can destroy equipment and potentially injure vehicle owners and service technicians during repair. The use of counterfeits also increases the opportunity to enter the supply chain. The issue is even more relevant in countries where the refrigerant supply is not well regulated (EPA 2020) or where regulations have created a supply imbalance and enhanced by the cost differentials between substances.

Furthermore, there is an environmental risk that unethical vehicle owners and unprincipled technicians will recharge HFO-1234yf MAC with HFC-134a if there is a significant price difference, which drastically increases the MAC life cycle carbon footprint. In countries with HFC restrictions (e.g., EU and US), this practice fuelled illegal trade of HFC-134a that was illegally imported and sold to service MAC systems at a lower cost. As the price of HFC-134a increases due to restrictions, this practice is expected to decline.

This indicates that cost and availability are crucial elements in identifying refrigerant replacement(s) and in monitoring the achievement of HFC restrictions.

9.2 Refrigerant options for new equipment

The vapour compression cycle in combination with a ventilation system is generally used to provide the passenger compartment cooling by means of a coolant circuit and specific heat exchanger. Engine waste heat ensures the passenger cabin heating usually by means of a specific circuit. Both susbsystems are integrated in the vehicle heating, ventilation, and air conditioning (HVAC) system.

The combination of cooling and heating functions ensures air dehumidification that enhances the fogging prevention function.

Electrified vehicles (battery or fuel cells electric vehicle and plug in hybrid vehicles) lack the advantage of thermal engine waste heat. Therefore, electrified vehicles require new solutions to ensure the passenger thermal comfort and ensure safety functions such as defogging and de-icing.

For this reason, in an initial phase, PTC (Positive Temperature Coefficient) electric heaters have been used and are still in use, but they are progressively being replaced by heat pumps that ensure higher energy efficiency and good performance. PTC heaters will remain in use in cold countries in combination with heat pumps that in cold weather conditions are less performant.

The use of PTC heaters is of utmost relevance for battery electric vehicle considering that thermal management (i.e., passenger comfort) can reduce the range of electric vehicles by up to 30 % (Kang, 2021).

The refrigerants used for the most relevant applications are listed in Table 9-1 while the type of vehicle equipped with a MAC system and their evolution is detailed in the following paragraphs.

Internal combustion engine (ICE) Vehicle: The MAC is based on a mechanical belt-driven compressor while engine waste-heat is directed into the passenger compartment for comfort and safety (i.e., heating, de-icing, and defogging) purposes. In highly efficient and hence low heat generating vehicles, and for operations in very cold ambient conditions, additional heat is typically provided by an electric heater e.g., PTC heater and/or a fuel burner. Such additional heating systems come at a low capital cost but are not very efficient.

Hybrid Electric Vehicle (HEV): The internal combustion engine is combined with an electric motor that recuperates the vehicle kinetic energy, integrates the engine power, and enables the vehicle to travel short distances (e.g., 3 to 5 km) in pure electric mode. The electric recuperated energy is stored in a battery, typically located in the back end of the vehicle (i.e., boot). An electric hermetic compressor replaces the belt driven one; the rest of the system remains unchanged.

Plug-in Hybrid Electric Vehicle (PHEV) is a Hybrid Electric Vehicle with large battery capacity (e.g., 10 kWh) with the possibility to recharge the battery from an external source (plug-in) and allowing one to drive up to 100 km in pure electric mode. The MAC is part of the vehicle thermal system that must also serve the battery, motor, and thermal control. A hermetic electric compressor is generally used in a system that can have direct or indirect expansion and condensation. In case of a liquid cooled evaporator, the system integrates a chiller (refrigerant to coolant) or a direct expansion evaporator, either conventional for air-cooling or plate coupled to the battery array for battery thermal management. An electric resistance heater or a heat pump ensures the heating when the engine waste heat is not available or not sufficient.

Battery Electric Vehicles (BEV): The system is very similar to the one used for PHEV. For BEVs the thermal management is of paramount importance because heating and cooling is vital for battery performance and lifetime. If solid-state batteries will be deployed as next generation batteries, energy efficient heating will become even more important due to the higher operation temperatures of solid-state batteries (Zhang et al. 2020, Hughes and Vagg 2022). The heat pump function is becoming the preferred solution to ensure heating thanks to its higher efficiency with respect to a simple electric heater. The refrigerant charge is usually about 30 to 50 % higher than that in a conventional system due to function of the technology selected to cool the battery (indirect or direct expansion). Indirect expansion and condensation (i.e., liquid cooled condensers and liquid heated evaporators) is a solution enabling the reduction of the refrigerant charge and higher system flexibility. Secondary loop systems have started to be applied on some premium cars in addition to be presented as a viable technology option (Menken, 2016).

Heavy-Duty trucks: The heavy-duty trucks adopt a main system based on the same concept which is used in light duty vehicles but with a slightly higher refrigerant charge due to the longer distance from compressor to cabin. Quite often, to ensure comfort while parked, an auxiliary air conditioning system is adopted. This system is usually quite similar to domestic systems with an external condenser, an internal cooling and ventilation unit and an auxiliary electric compressor. Currently heavy-duty truck MAC systems use HFC-134a. In the US, HFO-1234yf is allowed on some classes of heavy-duty pickup trucks as well as medium-duty passenger vehicles and complete heavy-duty vans (e.g., EPA, 2016). There is an effort sponsored by Association of Equipment Manufacturers (AEM) in the US to apply for US EPA approval of HFO-1234yf in all Heavy-Duty on road vehicles.

Off road vehicles: In response to a 2019 application by the AEM, the US EPA in 2022 listed HFO-1234yf as an acceptable replacement for HFC-134a in the agricultural, building and construction, forestry, and mining vehicles (EPA, 2022a, SNAP Rule 24). Off-Road (also called nonroad) equipment can be grouped into five categories: Agricultural tractors > 40 HP; Self-propelled agricultural machinery; Compact construction equipment; Construction, forestry and mining equipment, compact utility, and turf equipment. The AEM developed a risk assessment for each category with a structure similar to previous SAE Cooperative Research Programme (CRP) risk assessments for the use of HFO-1234yf in light duty vehicle applications. The risk assessments found that HFO-1234yf can be used safely in off road equipment, due to the use characteristics (off-road vs on-road), increased construction (more robust design) and ventilation requirements (higher air exchange rates for off road equipment). In other world regions similar regulations for off-road vehicles have been issued or are expected to be issued.

Buses and coaches: Buses and coaches are mass transit vehicles that have air-conditioning systems that are larger in size and have higher cooling capacity and larger refrigerant charges than passenger cars. They also operate at ambient temperatures ranging from -30ºC to 50ºC.

These systems are typically packaged on the roof or rear mounted with the compressor belt driven by the vehicle engine. With the phaseout of HCFC-22, the most used refrigerant is HFC-134a, while R-407C is used in some cases for high ambient temperature applications (ASHRAE, 2019). The typical refrigerant (HFC-134a; R-407C) charge is about 5 to 6 kg, due to the use of microchannel condensers which lowers the refrigerant charge by 50 % than in previous systems.

Reversible heat pumps using R-744 have been implemented recently in Europe (Konvekta, 2022) and both R-449A and HFO-1234yf have been introduced.

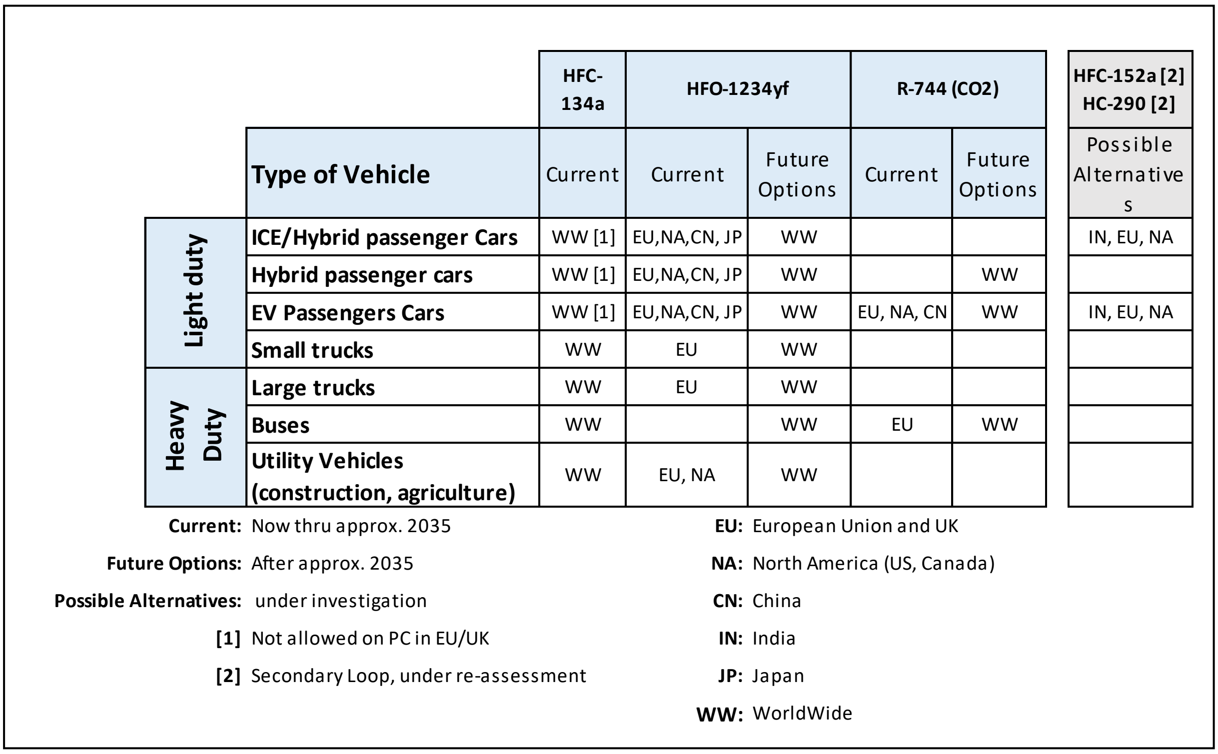
Fuel cell electric vehicles usually use polymer electrolyte membrane fuel cells (PEMFCs) to convert the chemical energy stored in hydrogen to electric energy. Due to the relatively low operating temperature of PEMFCs of approximately 70-90 °C most of their waste heat has to be rejected by a cooling system at low temperature differences between the ambient and the cooling system. Even a state-of-the-art liquid cooling system can limit the available fuel cell power due to insufficient cooling capacity, especially at high ambient temperatures. A high-temperature refrigeration system (HTRS), similar to a conventional MAC system, can be used to decouple the fuel cell operating temperature from the heat rejection temperature and thus provide additional cooling capacity. The HTRS works between the temperature levels of approximately 50 to 60 °C for evaporation and 100 to 120 °C for condensation and can either replace the liquid cooling system or can be used as a supplementary system (Reichler, 2009, Heinke, 2022). Possible low GWP refrigerants for such applications are HC-600 (n-butane) and HFO-1234ze(Z), with HC-600 showing slightly better energy efficiencies (Heinke, 2022).

Other related items: Hydrogen (H_2) fuel stations for fuel cell vehicles and high-performance fast charging stations for battery-driven electric vehicles need significant active cooling. State-of-the-art fuel cell electric vehicles store gaseous hydrogen at 350 bar or 700 bar nominal pressure in composite storage tanks. During the filling of these tanks, they heat up. The temperature rise depends, among other things, on the filling speed. In order not to exceed the tank materials temperature limit of 85 °C while maintaining a sufficient refuelling speed, a precooling of the hydrogen at the refuelling station is needed. For example, for passenger vehicles precooling temperatures down to -40 °C are common (SAE, 2020a) while for heavy-duty vehicles usually less precooling is sufficient. Due to this low temperature usually two-stage vapour compression cycles, either with one single refrigerant or as a cascade with two different refrigerants, are used. Promising fluid candidates for this application are R-717 or R-744 (see e.g., Elgowainy et al., 2017, Orion, 2021; Energie-Forschungszentrum Niedersachsen, 2021) but also fluorinated refrigerants are feasible.

9.3 Refrigerant options for existing equipment

Table 9-1 reports the most-used refrigerants for the existing equipment. As shown in Table 9-1 HFC-134a is widely used worldwide for existing equipment. Due to the regulatory framework in EU, US, and Japan, it is progressively replaced by HFO-1234yf. In addition, in the EU, R-744 is an emerging option based on improved heat pump performance.

Table 9-1: Refrigerant per application



		HFC-134a	HFO-1234yf		R-744 (CO2)		HFC-152a [2] HC-290 [2]
	Type of Vehicle	Current	Current	Future Options	Current	Future Options	Possible Alternatives
Light duty	**ICE/Hybrid passenger Cars**	WW [1]	EU,NA,CN, JP	WW			IN, EU, NA
	Hybrid passenger cars	WW [1]	EU,NA,CN, JP	WW		WW	
	EV Passengers Cars	WW [1]	EU,NA,CN, JP	WW	EU, NA, CN	WW	IN, EU, NA
	Small trucks	WW	EU	WW			
Heavy Duty	**Large trucks**	WW	EU	WW			
	Buses	WW		WW	EU	WW	
	Utility Vehicles (construction, agriculture)	WW	EU, NA	WW			

Current: Now thru approx. 2035

Future Options: After approx. 2035

Possible Alternatives: under investigation

[1] Not allowed on PC in EU/UK

[2] Secondary Loop, under re-assessment

EU: European Union and UK

NA: North America (US, Canada)

CN: China

IN: India

JP: Japan

WW: WorldWide

Other options are being explored. For instance, R-444A, R-445A, R-513A, and other blends have been proposed. Some of these with GWPs greater than 150 are proposed only for retrofitting or servicing existing HFC-134a systems. Some lower-GWP options are classified as A2 or A3 refrigerants (e.g., HFC-152a and HC-290, respectively). These are being investigated primarily for use in secondary loop systems, cooling a different fluid that could be used for passenger cooling or heating as well as cooling electronics/batteries in electric vehicles.

9.4 Energy consumption and efficiency considerations

The MAC system could increase the annual average vehicle energy demand up to the 20 % (IEA, 2019) increasing the fuel consumption or reducing the electric range of electric vehicles. The impact of mobile air conditioning on light duty vehicle's energy demand is higher than most other auxiliary systems. The MAC energy demand is a function of the vehicle's interiors dimensions and of the ambient conditions (Westerloh, 2019). In some conditions, e.g., urban driving at low speed, heating and cooling of electric vehicles can reduce the driving range by 40 to 50 % (Koehler, 2022).

Currently HFO-1234yf as well as R-744 based systems have efficiencies comparable with HFC-134a for cooling and heating (Koehler et al., 2018; Westerloh, 2019).

To achieve these performance levels for HFO-1234yf, manufacturers use either an internal heat exchanger (IHX) or larger degree of subcooling, while for R-744 appropriate system design (e.g., IHX) and controls are required (Koehler et al., 2018; Westerloh, 2019).

The mobile air conditioning yearly fuel consumption has been estimated of about 1.8 million barrels of oil equivalent per day (Mboe/d) in 2015, i.e., 370 TWh assuming an efficiency of the internal combustion engine of 33 % (IEA, 2019). This results in MAC indirect emissions of approximately 280 million tonnes CO_2–eq. per year.

The progressive electrification could reduce this amount to 180 million tonnes CO_2-eq per year when vehicles will be fully electric, assuming the current energy mix of electric energy production, i.e., 475 g CO_2/kWh (IEA,2018), and this figure is expected to continually decrease thanks to the transition to lower-carbon or renewable energy sources.

So, despite the progressive road transport electrification that will lower the CO_2, the mobile air conditioning system energy demand and consequent equivalent CO_2 emissions will remain relevant. Hence, it will continue in importance to further improve the energy efficiency of MAC systems. As a matter of fact, considering that the number of circulating vehicles is expected to increase by 50 % by 2040 (WEF, 2016), to not keep the global MAC CO_2 equivalent emissions at the same level of 2015, it would be required to increase the MAC efficiency by a similar percentage, i.e., 50 %, while continuing the transition to low-GWP alternatives.

The energy efficiency of MAC systems for mobile applications is usually measured in terms of the Coefficient of Performance (COP), the ratio of heating or cooling power to electric power input. The energy consumption of MAC systems for electric vehicles usually is expressed in terms of the reduction of the driving range due to the energy consumption of the MAC system.

Since COP as well as range depend on many parameters, a comparison between the energy efficiency and consumption of different system layouts and control strategies and especially different refrigerants is a challenge and is always open for debate. Especially the vehicle range, which depends on the features of the vehicle itself, is hard to compare.

However, looking at several recent papers, certain trends can be described comparing on one hand HFC-134a and HFO-1234yf (almost identical vapour pressure curve and energy efficiency) and on the other hand the refrigerant R-744. Together the three refrigerants represent the most widely used in cars, light trucks, and buses.

In the air conditioning mode, the cooling COP decreases with increasing ambient temperatures; however, the COPs of the different refrigerants are very similar up to an ambient temperature of about 30 °C. Above this temperature the energy efficiencies of HFC-134a and HFO-1234yf refrigerant are better than that of R-744 (Junqi, 2021).

In the heating mode, COPs decrease with decreasing ambient temperatures becoming very similar near freezing and above. Around 0 °C, heating COPs in the range of 2.0 to 2.5 can be expected with HFC-134a, HFO-1234yf or R-744.

Below 0 °C the energy efficiency of R-744 is superior to HFC-134a and HFO-1234yf refrigerants. For example, at very low ambient temperatures of about -20 °C, HFO-1234yf has a heating COP equal to that of an electric PTC heater of 1.0, due to sub-atmospheric evaporation pressures. At such conditions, R-744 still has a COP of about 1.5 or higher because its evaporation pressure is significantly higher (Wang et al., 2018, Wang et al., 2019, Chen et al., 2021, Junqi et al., 2021, Peteranderl, 2021, and Song, 2021).

Recently, a global chemical and air conditioning company introduced a new blend (R-474A), which was designed to be especially suitable for BEV heat pump applications. Compared to HFO-1234yf, the blend has a slightly higher vapour pressure curve and shows equal energy efficiency but higher cooling and heating capacity (Rydkin et al., 2021, Kumakura et al., 2019), however the blend exhibits glide.

Most of recent battery-driven electric cars are equipped with reversible heat pumps to limit the energy demand in winter climate which could be relevant in case of use of PTC (Positive Thermal Coefficient) heaters.

With the exception of operation at very low ambient temperatures (e.g., < -15 °C), the range reduction of a heat pump is significantly less and similar for the different refrigerants if compared to a PTC heater.

When most of the MAC operation takes place at ambient temperatures near freezing or above, the annual energy consumption is similar for all refrigerants (Westerloh, 2019, Peteranderl, 2021, Koehler, 2020). However, there is still room for improving the heat pumps: by limiting the flash fogging, and improving efficiency, noise, and de-icing strategies (Westhaeuser, 2022).

Further study of new refrigerants for more efficient operation over the full temperature range of the vehicle fleet is underway as part of a CRP managed under SAE International. In addition to new fluids, new system architectures with some existing refrigerants, including secondary loops, are being investigated (Patti, 2020).

9.5 Safety considerations

With reference to other aspects, the mostly diffused and currently used refrigerants (see table 9.1) do not have any specific safety issue and they are commonly used in direct expansion systems, even in the case of the lower flammability (A2L) refrigerant HFO-1234yf, (SAE , 2020b).

In case the use of higher flammability refrigerants, such as HC-290, ISO 817 class 3, or HFC-152a, ISO 817 class 2, there is a need to decouple the refrigerant from the passenger compartment and this will be ensured by a secondary-loop system.

For all alternative refrigerants, safety considerations should be evaluated which include the flammability, toxicity, and particular system operating pressures.

9.6 Regional regulations, influencing factors and scenarios

All of the following countries/regions are signatories to the Kigali Amendment, which will have an effect on the supply and price of HFC-134a and the transition to lower GWP refrigerants. Some specific conditions are highlighted below.

United States: US EPA promoted the use of low GWP refrigerants by means of an “off-cycle” mechanism awarding the low leakage rate system or the use of low GWP refrigerants with GHG credits to be used to mitigate the stringency of the overall GHG regulation. The GHG regulation sets targets of GHG emission at a manufacturer fleet level (EPA, 2022b).

Under the American Innovation and Manufacturing (AIM) Act of 2020, and as a signatory to the Kigali Amendment, the US EPA is implementing a phasedown in HFC production and consumption. The phasedown began in 2022 and is consistent with the Kigali Amendment (e.g., same formula to calculate a baseline, 90 % start; 60 % level in 2024, etc.). Unlike HFC-134a, HFO-1234yf is not on the AIM Act’s list of controlled substances, nor is it listed in the Kigali Amendment, and is not included in the phasedown with its GWP < 1.

A separate section of the AIM Act allows the public to petition US EPA to restrict substances by end-use. To date, US EPA has received 17 petitions covering a wide range of end-uses in the refrigeration, air conditioning, foams, and aerosols sectors. US EPA granted a petition that requested US EPA to ban the use of HFC-134a in light duty vehicles as of January 1, 2023 (EPA, 2021b). Granting a petition does not mean this is a requirement; instead, US EPA is required to issue a proposed rule and take comment from the public. If finalized, any ban would take effect no sooner than one year after publication of the final rule

On 15 December 2022, the US EPA issued a proposed rule responding to this petition, proposing to ban the use of HFC-134a, and any HFC refrigerant or HFC-containing blend with a GWP above 150, in new light duty mobile air conditioning systems beginning in Model Year 2025. US EPA also proposed the same GWP < 150 restriction for medium-duty passenger vehicles, heavy-duty pickup trucks, complete heavy-duty vans, and nonroad vehicles, beginning with MY 2026 (EPA, 2022c).

To introduce alternative refrigerants, systems in the US must be designed in accordance with SAE standard J639*, Safety and Design Standards for Motor Vehicle Refrigerant Vapor Compression Systems.* This standard was updated in 2020 to include HFC-152a used in a secondary loop (SAE 2020b).

European Union (EU27), European Free Trade Area (EFTA), and UK: The MAC (EU 2006/40/EC) directive in place since 2006 gradually banned from 2011 to 2017 the use of refrigerant with GWP higher than 150 (i.e., HFC-134a) on passenger cars and light duty vans whereas all other road transport vehicles are excluded. In the meantime, the F-Gas Regulation (EU 517/2014) set progressively decreasing "Quota" for manufacturing, import and use of HFCs and other high GWP fluids in the European Union territory having the effect of progressively eliminating the use of the high GWP HFCs.

To promote the MAC energy efficiency increase, the European Commission included it (EU 631/2019) in the list of technologies/functions eligible for the Eco-Innovation scheme in the next CO_2 reduction regulation framework for light duty vehicles, opening the door for a further technology evolution.

The automotive MAC industry started to react to the TFA/PFAS issues and potential impact (see Chapter 3) intensifying the research and development activities to re-assess the possible alternatives, i.e., R-744, HC-290, HFC-152a, and HFC-32 (Saurabh, 2022).

Japan: By 2023, Japanese regulations are expected to limit higher GWP refrigerants (HFC-134a with GWP 1310) to less than GWP < 150 for use in passenger vehicles. It should be noted that in Japan, passenger vehicles are noted as those vehicles that are less than 11 passengers (METI/MOE). For trucks and buses, Japan is seeking to transition to such refrigerants by 2029. Currently, in the Japan domestic market, nearly 100 % of sold vehicles is equipped with HFC-134a while for few and for exported vehicles to US or Europe, HFO-1234yf is the primary choice.

NEDO (New Energy and Industrial Technology Development Organization) in Japan conducted a risk assessment of the application of HFO-1234yf to truck and bus air conditioning systems and reported that the risk of fire is less than 1/1000 of those of air and/or rail accidents. Based on these results, Japan METI/MOE are expected to replace HFC-134a with HFO-1234yf or other low GWP (< 150) refrigerants for these systems by 2029 (NEDO, 2021).

China: China has not updated any new regulations regarding future refrigerant for vehicles. In the present Chinese regulations, HFC-134a is the only indicated refrigerant for vehicles. The current scenario shows that almost 100 % of sold vehicles are equipped with HFC-134a and few models use HFO-1234yf.

In some newly developed electric vehicles, R-410A has been adopted as the refrigerant for the heat pump system. A German car manufacturer is selling electric cars with R-744 (CO_2) heat pumps in volumes (> 100,000 units per year).

Canada: Canada has laws or regulations encouraging the use of refrigerants with GWP < 150 in MAC. Canada enacted the Ozone-depleting Substances and Halocarbon Alternatives Regulations in 2016. In 2017 these regulations were amended to include a requirement that any MAC system on vehicles imported into or manufactured in Canada from model year 2021 must contain and be designed for a refrigerant with GWP of 150 or less (Government of Canada, 2017).

Mexico: In 2012, Mexico's Secretary of Environment and Natural Resources (SEMARNAT), the Secretary of Economy, and the Secretary of Energy jointly adopted fuel economy and CO_2 standards for new light-duty passenger vehicles. Credits are offered for manufacturers who reduce CO_2-eq emissions from MAC systems.

To get this credit, manufacturers must demonstrate that 80 % or more of their vehicles sold: 1) reduce CO_2 equivalent emissions of refrigerants, either through substitution of refrigerants or through low-leak systems; and 2) are equipped with more efficient technologies relating to the MAC system (SEMARNAT, 2013).

South Korea: South Korea's Ministry of Environment and Ministry of Commerce, Industry, and Energy offers credits for transitioning to low-GWP refrigerants and improved AC efficiency as part of the GHG and energy-efficiency standards for new light duty vehicles.

Credits for model years 2016–2020 were capped at 10 g CO_2/km total for air conditioning refrigerant and performance improvement and three other defined technologies. (Ministry of Environment, 2014).

9.7 Concluding remarks

More than one refrigerant is used for passenger vehicles, buses, light duty truck and off-road vehicles air conditioning: HFC-134a is largely adopted worldwide until pressured by the phasedown under the Kigali Amendment to the Montreal Protocol. Where regulations require low GWP refrigerants, HFO-1234yf and R-744 provide market options. HFO-1234yf is widely adopted, especially for passenger vehicles. Vehicle refrigerant use is shifting from being an optional feature for passenger cooling to a requirement for total vehicle thermal management.

The deployment of highly electrified vehicles (PHEV and BEV) in Europe, China, North America, and Japan will lead to the implementation of heat pumps for passenger and battery heating and cooling; manufacturers and suppliers are working on the improvement of this feature.

R-744 is increasingly applied in fully electrified vehicles due to its good performance when operating as a reversible heat pump. However, R-744 is less suitable in hot and humid climates where energy efficiency is somewhat lower than that of HFC-134a and HFO-1234yf systems. Some European OEMs introduced reversible R-744 heat pumps for their high-volume BEV models, which they currently sell in the EU, North America (Canada), and China.

One car manufacturer has expressed interest for the Indian market by adopting HFC-152a in secondary loop systems. Other low GWP refrigerant and refrigerant blends (e.g., R-444A, R-445A, and R-474A) are under investigation.

The automotive MAC industry started to react to the TFA/PFAS issues and potential impact (see Chapter 3) intensifying the research and development activities to re-assess the possible alternatives. The low-GWP refrigerant cost is higher than HFCs, which represents a relevant barrier to a wider deployment and favours counterfeiting and illegal importing.

It cannot be foreseen whether currently used refrigerants will remain in the market for a longer period of time. It is also unclear whether the bus sector (where currently HCFC-22, HFC-134a, R-407C, R-744, and R-449A are used) will follow these trends. HFO-1234yf has been introduced and is expected to be used in the heavy-duty truck and off-road sectors. In existing systems primarily designed for CFC-12 or HFC-134a, hydrocarbons (e.g., HC-290) are reported to be used in some regions (e.g., Australia).

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Chapter 10

Industrial refrigeration, heat pumps and heat engines

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10 Industrial refrigeration, heat pumps and heat engines

10.1 Introduction

Industrial refrigeration and heat pump systems are an integrated part of the global food cold chain from harvest to table. But industrial refrigeration is also used in a range of other industries such as fishing ships with large processing plants, pharmaceuticals, petrochemicals, etc. The majority of large industrial systems in most parts of the world use R-717 as the refrigerant, and thus also used in all climate zones for many years including High Ambient Temperature (HAT) climate zones. R-717 plants are seen with capacities from about 300 kW to over 100 MW cooling capacity. Recent developments have shown that also R-744 trans-critical systems are entering the industrial markets, especially in advanced countries where plants with a few MW cooling capacity is seen.

Industrial systems are normally designed for the purpose of the customer considering the ambient and other conditions to fulfil the local regulations. Currently also a growing number of systems apply cascades with R-717 and R-744 that are used in a variety of low temperature systems worldwide. Existing HCFC-22 systems are substituted with R-717/R-744 cascade systems, particularly in warm climates where the latter have a better efficiency and durability than most competing technologies such as R-744 only or HFC solutions. Many fishing vessels have been converted from HCFC-22 to either R-507A/R-744 or R-717/R-744, the first mainly when the system was converted from HCFC or HFC where copper and other incompatible components remain.

Industrial heat pumps are gaining popularity because they can produce hot process water, cleaning water, pasteurization, or hot water for other purposes. R-717 is used for high temperature heat pumps (up to 95 °C). HFOs, like HFO-1234ze(E), are also a possible low-GWP alternative to HFC-134a for district heating systems but also in process heating. For high temperature heat pumps, e.g., for steam production above 100 °C, R-718 and HCs are also viable and commercially available options, often to avoid use of fossil fuel heating. Some HFOs, HFO-1233zd(E) or HFO-1336mzz(Z), are also designated for use in Organic Rankine Cycle (ORC) for generating electricity from waste heat and for high temperature heat pumps (Wilk, 2020), as well as natural refrigerants, such as R-744 and HCs (Andresen, 2022).

Since the 2018 RTOC Assessment Report, some developments have emerged. There has been a lot of focus on charge reduction but also the number of systems using R-744 as refrigerant has been making some inroads to industrial systems mainly in capacities below 5 MW. However, R-744 has also been used in cascade system in significantly larger sizes. In the EU it has not been allowed to install new systems with refrigerants with a GWP over 2500 since January 1st, 2015. The mission-critical applications are transitioning towards long-term solutions including R-744, R-717, or fluorinated gases. HFO blends are also adopted for cold stores applications, particularly across Europe. These blends are used only in single stage systems.

In China, R-717, as an example, is perceived as dangerous in parts because the cities have grown up around food processing plants and cold stores, which traditionally used large volumes of R-717. The Chinese market is currently using cascade systems with R-507A on the high temperature stage with R-744 in the cold areas. Cascade systems reduce the charge of the high temperature stage by about 90 %. The 2018 RTOC report described means to handle R-717 leakages using a scrubber and ventilation in machine rooms.

The main barrier for R-717 seems to be the perceived risk rather than searching for a solution. According to (Lindborg, 2009) “The incidence of accidents and fatalities involving ammonia refrigeration is extraordinarily rare compared to other risks in society. There is a general unawareness of this, with society pronouncing ammonia, with its heavy, pungent smell, as both dangerous and frightening.”

Transcritical R-744 systems are currently being used in small cold stores and processing plants in South America. Lund, 2019 demonstrated that R-744 systems result in lower efficiency compared to other alternative solutions in in warmer climates. The performance gap in warm climates may be reduced by introducing work recovery options.

10.2 Applications

This section highlights some of the most common refrigeration systems and their solutions.

10.2.1 Food processing

Refrigeration and freezing are used to extend the shelf life of food beyond what would otherwise be possible by storing the food at ambient temperatures. During the processing, heat may be recovered from the refrigeration systems using a heat pump and used for heat treatment or bacteria kill in other parts of the processing plant. One example could be in the dairy sector where milk is kept at 2 to 5 °C upon arrival to the dairy and again after processing. During the processing, the milk is pasteurized at about 82 °C, for ultra-high-temperature (UHT) milk at about 110 °C, for which a heat pump can provide the heat, as the heat source it can be using the condenser heat from the refrigeration systems on site. In a slaughterhouse a lot of heat is used for cleaning after working hours or every night. The heat can be recovered from the refrigeration systems using de-superheaters or heat pumps. Only if the temperature is over 90 °C the water is considered warm enough to provide a bacteria kill, at lower temperatures you must use chemicals added to the cleaning water. In some cases, steam is used for cleaning, which is an emerging possibility for heat pumps producing temperature up to 160 °C hot water or steam (Arpagaus, 2018).

In the larger food processing industry R-717 has been used as the refrigerant of choice mainly driven by the energy efficiency but also because experienced personnel have been available. The systems have been providing hot water using de-superheater as a standard.

HFCs and blends using HFOs are seen in smaller industrial systems, but to a lesser extent, mainly due to problems with temperature glide, which can be handled by design in DX systems. At low temperatures in pumped systems the zeotropic fluids can cause problems with fractionation of the blends. The glide will also give problems in a plate freezer which is a very common application within many types of frozen food products e.g., fish, packaged food products, or ready meals.

10.2.2 Cold storage

When the food is processed and frozen, they are kept in large cold stores until they are distributed to the customers or shipped to different parts of the world, where they are again stocked on cold stores until they are sent to the distribution centres or directly to the supermarket. The distribution centres are also a cold storage but here they often have two or even three temperature levels for storage of different products – low temperatures are stored at -30 to -20 °C a little depending on the products, fresh produce is kept at 0 to +5 °C, although fruit, bakery products and vegetables are stored between 8 and 12 °C, and finally distribution centres have space for less sensitive product kept at about 20 to 24 °C.

Distribution centres often have relatively large refrigeration systems. In cold and mild climates R-744 trans-critical systems have been used with some success. In warmer and warm climates R-717 still has a fairly large proportion of the market. Modern cascade systems using a combination of R-717/R-744 has also been used in this application. Cascade systems reduce the R-717 to about 10 % compared to direct R-717 system. Thereby alleviating issues related to risks by implementing a scrubber system. In Lund, 2019, it is shown that cascades are very close in efficiency compared to the R-717 solutions in terms of efficiency. It is important not to focus on the risk of R-717 alone.

For pharmaceutical storage of temperature sensitive products some cold stores have been built using HFC-23 and HFC-508A but due to the high GWP this is not perceived as being sustainable. In the latest move to get new blends to the market, three suppliers have proposed the following solutions: high-GWP R-469A, medium-GWP R-472A and high-GWP R-473A.

In some installation alternatives to HFC-23 has been HC-170 using either R-717 or HC-290 in a cascade combination. Some smaller systems have been using a special blend with several pressures on the liquid side but only one compressor, also referred to as auto-cascade systems. This solution is for small freezer types and the blends are a propriety and confidential blend (not published). Also, large systems used in the petrochemical industry use the auto-cascade technology with propriety blends. The traditional HCFC-22/23 cascade has been analysed in Yingbai Xie (2008), comparing a HC-290/HC-170 solution. The two solutions are found to be very close in performance and the latter solution is suggested for the future due to a better climate performance. Due to small charges of 150 grams, the flammability issue has been minimized. The solution has been used for some vaccine storage and freezers used for research. Cold storage facilities have been built using the combination of HC-170 and R-717 as well.

10.2.3 Leisure applications

Indoor skating and skiing have become very popular and even in Norway, which has a cold climate, there is now a year-long indoor ski-dome reported by Williams, 2019. The cooling is provided by R-744 trans-critical systems. In warmer countries like in the United Arab Emirates you can find both ski resort and ice-skating rinks as part of the entertainment options in the big shopping malls based on R-717. The options of using R-744 is also being exploited for the activities during the Olympic Winter Games reports Yoshimoto, 2020. For the ice rink R-744 was selected and for the bobsled rinks R-717 was selected. In North America there has been a steady conversion of ice rinks from HCFC-22 to R-717 or R-717/R-744 cascade. System retrofit to R-744 is also reported by Bolteau (2019) for ice rinks. In 2018 a sponsorship deal between Chemours and NHL set out to speed up the phaseout of HCFC-22 and to promote Chemours' new refrigerant. This has resulted in several ice rinks now being converted from HCFC-22 to high-GWP R-449A or medium-GWP R-513A.

The more specialized outdoor activities using refrigeration systems are speed skating and bobsled rinks. These systems are often built with several circuits because a single circuit will not suffice and give a uniform surface temperature as required for a successful competition.

Outdoor snow production is being promoted but this is for extending the season of current natural ski slopes. Normal snow guns have their highest capacity at temperatures from -10 to -5 °C, however, snow can be produced by evaporating water at a very low pressure and then be distributed over the night. If the snow is sufficiently dry the ice can stay for an extended time on the hills for a month or two after the normal season has come to an end. Snow produced by temperature independent ice-making machines are also installed, though the heat from the plant preferably should be used for useful heating due to the higher power demand introduced.

A specialty leisure application is cooling systems for arctic and cold loving animals like penguins, polar bears, and other animals. These animals cannot live at temperatures as high as 30 or 40 °C and therefore it is required to cool down their areas and water. These systems have also been made with R-717 and other fluids including HFCs in the past.

10.2.4 Process refrigeration

Cooling is used in a wide variety of process applications. The cooling can be applied by a direct refrigeration system with a coil in the process tank, or a jacket around the outside of a chemical reactor vessel or storage tank.

Alternatively, a secondary fluid such as water, brine solution or glycol may be used. In these cases, standard chillers as described in Chapter 8 might be used, although there may still be other reasons for requiring the chiller to be specially designed for the project, for example location of the equipment within a hazardous area.

In refineries, refrigeration is used to remove light hydrocarbons from the process stream. Such systems can be extremely large and may use HCFC or HFC in centrifugal chillers. It is also possible to use the feedstock, particularly ethylene (HC-1150) or propylene (HC-1270) as the refrigerant, either in a closed-loop system or as part of the process flow. In very large systems the use of HFC-134a enables centrifugal compressors to be used whereas ethylene typically requires screw compressors which at that size are significantly more expensive.

A highly specialized and very critical application is the pharmaceutical industry where the precise and reliable systems is the difference between success and loss of products. There are very strict regulations in place for monitoring every part of the production process and the transport of these products. The highest demands are given by the US FDA, but also other rules say that if one product unit in a batch is temperature damaged all the batch is discarded. This may result in significant capital loss for minor operation disturbances. Hence many of these systems are provided with n + 1 systems so the second one system fails another can take over. Some storage facilities are kept at -80 °C now using HC-170 on the low stage and R-717 on the high stage but in other cases other solutions are used. The latest alternatives to HFC-23 comprise the newer blends high-GWP R-469A, medium-GWP R-472A and high-GWP R-473A.

Some specialist processes including plastic forming, paper milling, and precision machining require multiple small capacity systems and are typically constructed on site using HCFC or HFC. The use of multiple flexible hoses to connect to the moving parts of these machines presents a particular challenge due to high refrigerant leak rates.

Where processes produce high grade waste heat, for example flue gases from glass production, power stations, steel mills, incinerators, or cement factories, the heat can be used to drive absorption chillers, either directly or by feeding steam to the chiller. Such systems are tailor made to the application to ensure that the heat production and cooling demand are well matched.

The cooling of deep mines presents another challenge because the operating conditions are arduous, and the available space is severely constrained. Typical systems use centrifugal chillers above and underground. An alternative to the use of HFC-134a or HCFC-123 in centrifugal chillers was to produce cooling at the surface, either as cooled ventilation air or as chilled water or ice-slurry. However, the depth to which surface cooling is effective is limited and for mines deeper than about 2,000 m, some form of underground cooling is required to counter the effects of geothermal heat, air compression, and the power required to transport the cooling effect from the surface to the workface. HCFO-1233zd(E) is replacing HCFC-123 as the preferred refrigerant in some brands. Ice slurry is used as well.

HFC-134a is widely used in South African mines. However, esters can be degraded by water to free acid and alcohol hydrolysis. Thermal decomposition generally gives alkenes, water, CO, and CO_2 (Kramers, 2002). HFC-134a is not flammable at ambient temperatures and atmospheric pressure. However, this material will become combustible when mixed with air under pressure and exposed to strong ignition sources and elevated pressure levels (Global Refrigerants, 2017). This has been reported as having caused an accident in South Africa. Some of the new fluid blends currently under development for other applications.

10.2.5 Gas liquefaction

Liquified Natural Gas (LNG) is a growing market and involves industrial refrigeration equipment. The temperature levels reach down to -160 °C by using auto cascade systems with different numbers of components in the blend. These temperature levels can be reached either by using three or four stage cascade systems or by using propriety blends (not published) using different compositions of gases to adapt the temperature profiles to the cooling curve of the gas to be liquefied. These plants are used at the production fields or on ships used for transporting LNG. In the past some of the gas was burned off in the engines of the ship, keeping the remainder of the gas in the tanks cold. To reduce these losses as well as the CO_2 emissions the refrigeration system condenses the boil-off gas developed during the transport and the liquid is re-injected to the vessel.

For special processes systems are built to work at temperatures down to -270 °C, e.g., CERN (European Organization for Nuclear Research), in four or five cascaded systems using helium and other noble gases in the lower stages and other gases on the higher stages. There is also a considerable activity on developing more efficient liquefaction plants for hydrogen, due to the emerging market of using hydrogen as an energy carrier. Future transport of liquid hydrogen as todays LNG transport, as well as using liquid hydrogen as a means of fuel storage for energy demanding applications such as long-distance transport and aviation, is envisioned. (Saif et al., 2022)

10.2.6 Industrial heat pumps and heat recovery

Heat pumps are often associated with space heating in households and offices. But heat pumps are much more than just space heating and district heating. Heat pumps are used for industrial processes to recover surplus heat or waste heat for heating a process or preheating process fluids.

Industrial heat pump systems have heat delivery from 100 kW to over 100 MW, with the heat source usually at ambient temperature or the waste heat temperature from a variety of source e.g., industrial process, wastewater, cooling towers, etc... These systems are usually required to deliver higher temperatures than domestic or commercial heat pumps used for space or water heating. Typical heating temperatures are in the range 60 to 90 °C, although, if the recovered heat is to be used for steam heating, then it needs to be at least 130 °C level. Research on systems producing heating at more than 180 °C is ongoing with working fluids, such as HCs and HFOs but also using water in Mechanical Vapour Recompression (MVR) systems.

Heat recovered from large industrial systems is usually transferred to water or a heat transfer fluid and used for heating hot tap water and process heating and cleaning processes or for supply to district heating systems. Quite several projects are using the exhaust in chimneys e.g., from electricity production or industrial process boilers, as a heat source, to recover as much energy as possible from the process.

There is no real definition of what industrial refrigeration or heat pumps is. The industrial compressor is often based on open-type compressors or the semi-hermetic compressors which are using suction gas cooled motors. The internally cooled motor to some degree limits how high the suction gas temperature can be, where the open type compressors are less sensitive. High suction gas temperatures to some degree affects the efficiency of the built-in electrical motor and sets the limit for its use.

Also, thermally driven heat pumps are attracting renewed attention. They are available in capacities from about 10 kW to several MW. The system is driven by heat that can come from both direct burning fossil fuel or indirectly using waste heat or renewable heat sources.

10.2.7 Heat-to-power systems for heat recovery

Heat-to-power systems, often also referred to as Organic Rankine Cycle (ORC), can be used to recover energy from various industrial processes at different temperature levels. The heat sources range from geothermal heat, solar heat, and biomass combustion. Also heat from industrial process and heat recovery from flue gas and hot excess process air can come into the picture for high temperature systems and in some cases a two-stage cycle can be used.

It is estimated that the global population of heat-to-power systems is 1754 with a total energy output of 2700 MW of electricity (Tartiére, 2017). The simple heat-to-power system consists of a pump, an evaporator, an expander which is connected to a generator and a condenser. For higher temperatures a cascade solution can be used to increase the overall heat recovery and electrical output (Novotny, 2020).

Astolfi (2017) describes the technical options for ORC systems providing a good overview for those interested in the technology and for further studies. A combination of a heat pump and heat-to-power heat recovery system has also been suggested and has been studied, see Figure 10-2. In this case HC-600a outperformed HFC-245fa until it reached the critical temperature. The paper does not disclose why other hydrocarbons were not studied such as pentane and heptane. Several working fluids can be used for this kind of system.

Nemati, 2017, discussed different types of cycles including ORC, Trilateral Rankine Cycle (TLC) and Kalina cycle. The aim of cycles is to recover waste heat and generate electric energy. The technology is still developing, and the efficiency is increasing. The paper also reports that different working fluids are being studied e.g., a blend of HC-290/R-717 with 84 % of R-717.

For high temperature heat sources, typically above 250 °C and high capacities, above 1 MW, Rankine systems applying steam R-718 or R-744 dominates, much because the molecules have a superior chemical stability at high temperatures. For lower temperature heat sources, the working fluids used in the past has often been HFC-245fa, but this is now being phased out and new fluids are entering the market e.g., HFO-1233zd(E) which has a much lower GWP. Considerable work is also done for systems using different hydrocarbons, R-717, and R-744 as working fluids, as well blends of R-717/R-718.

Kwakye-Boateng (2014) presented different hydrocarbon refrigerant blends in ORC systems. The blends studies are pentane/hexane (90/10), pentane/hexane (10/90), pentane/isobutane (90/10) and pentane/isobutane (10/90). In this study the pentane/isobutane (10/90) came out as the best solution.

Oyekale (2022) concluded in a review that “The conventionally life cycle analysis (LCA) of ORC plants equally revealed that the choice of organic working fluid has a significant effect on the environmental impact of the system. Although many authors don't consider leakage of working fluid in ORC environmental impact assessment, results from a few studies that considered leakages showed that the effects are not negligible.”

Andresen (2022) presented results on development of systems using natural refrigerants, typically R-744 and HCs. The systems may operate in a sub-critical cycle, trans-critical or even super-critical cycle.

For energy recovery applications, where the pressure difference is higher than for traditional refrigeration systems, the option of expanding the vapour through a reverse cycle compressor (Brayton cycle) and recovering the energy for other processes is economically viable. There are examples with transcritical R-744 systems where up to 15 % of the compression energy can be recovered.

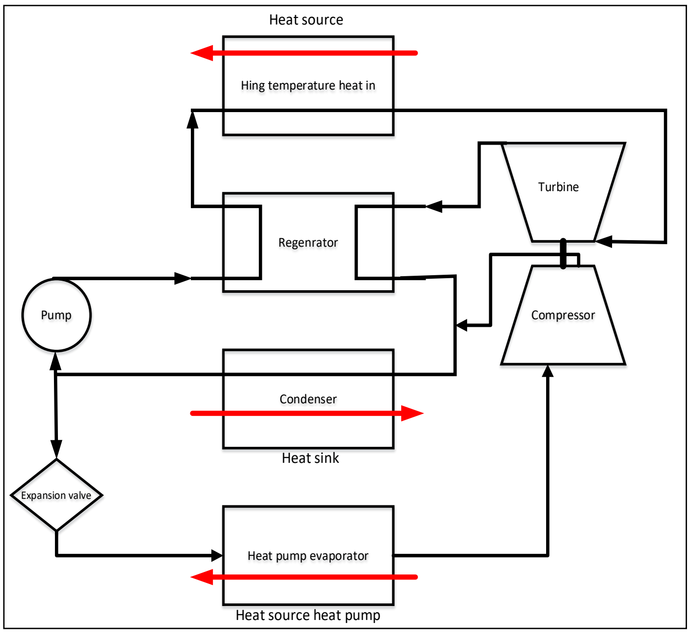

Figure 10-1: Combined ORC and heat pump cycle. The recovered energy is used for driving the heat pump

Table 10-1 shows the pure working fluids that have been investigated in different papers/projects (references included) for heat recovery systems.

Table 10-1: Potential working fluids for heat recovery systems

Working fluids	Critical temperature (°C)	Critical pressure (Bar)	Critical density (kg/m^3)	Heat of vaporization (kJ/kg)	Work range	Reference
R-245fa	124,90	32,00	551,30	145,31	50 to 100 °C	Darvish 2015
R-134a	101,06	40,59	511,90	177,78	50 to 100 °C	Thurairaja 2018
R-1233zd(E)	165,60	35,77	476,31	191,76	45 to 60°C	Jacob 2020, Spencer 2020
R-1336mzz(Z)	171,35	29,03	499,39	168,48	up to 160°C	Juhasz 2017
R-227ea	101,95	29,25	594,25	111,60		Darvish 2015
R-236ea	139,29	34,02	565,00	155,68		Thurairaja 2018
R-365mfc	186,85	32,66	473,84	195,30		Thurairaja 2018
R-123	183,68	36,62	550,00	171,37	250 to 500°C	Darvish 2015
R-600	151,98	37,96	228,00	361,48		Darvish 2015
R-600a	134,66	36,29	225,50	328,92		Darvish 2015
Ethanol	241,56	62,68	273,19	920,67	150 to 200°C	Thurairaja 2018
Toluene	318,60	41,26	291,99	412,85	250 to 500°C	Darvish 2015, Thurairaja 2018
Iso-pentane	187,20	33,78	236,00	345,46		Darvish 2015
n-pentane	196,55	33,68	231,60	366,41		Darvish 2015, Thurairaja 2018
Iso-heptane	187,20	33,78	236,00	346,46		Feng 2017
n-heptane	267,05	27,36	233,47	365,01		Feng 2017
Hexane	234,67	30,44	233,19	366,19	50 to 100 °C	Thurairaja 2018
Iso-hexane	224,55	30,40	233,97	347,08	250 to 500°C	Thurairaja 2018
Benzene	288,87	49,07	304,71	433,55	150 to 200°C	Thurairaja 2018
Butylbenzene					200 to 300°C	Thurairaja 2018
n-dodecane	389,95	18,17	226,55	361,45	250 to 500°C	Thurairaja 2018
R-717	132,41	113,63	233,25	1165,83		Nemati 2017
R-744	30,98	73,77	467,60	119,65	450 to 750°C	Liu 2019, Zühlsdorf 2019
R-718	373,95	220,64	322,00	2441,67		Nemati 2017, Zühlsdorf 2019

Table 10-1 can be extended very much by adding both official blends and proprietary blends which represent more than hundred different fluids. Heat of vaporization at +25 °C and saturation pressure. More is reported in (Lin, 2021).

10.2.8 Deep mine cooling using ice slurry

Bellas & Tassou (2004) describe how ice slurry created by a vacuum system has been used in a South African gold mine. Ice slurry has some advantages over flake ice as the centre temperature of the pumped fluid tends to be more uniform than with flake ice. The ice slurry also tends to be easier to pump than the flake ice. The cooling capacity in the actual system was 3 MW. The chillers are described in Chapter 8 in more details.

Water has been used as working fluid with different grades of success. In the past, vacuum ice has been used in the South African deep mines for cooling the supply air. Water has also been used in vacuum ice for fish cooling and other quick cooling purposes, but it has not really become a mainstream technology so far in industrial cooling systems. Water is also considered in large heat pump systems but until now in research systems only.

Water with ice is researched as ice-slurry with small ice particles and with crushed ice. The binary/small particle ice is faster in cooling by melting than the crushed ice which tends to be larger ice particle and slower in melting.

10.2.9 Absorption systems, chillers, heat pumps and heat recovery

Absorption systems using ammonia-water solutions can be used for low temperature applications, reaching temperatures as low as -60 °C (Colibri, 2017). This is because the ammonia is used as the refrigerant, with water as the absorbent. Absorption systems can be provided from 10 kW to 10 MW or more for process systems. Water-lithium bromide (LiBr) systems can only be used to a few degrees below the freezing point, about -8 to -5 °C.

Absorption systems are effective if there is an abundant source of heat at high temperature to drive the system. It is not normally economic to burn fossil fuel for the sole purpose of driving the regenerator of an absorption system, particularly in low temperature systems, because the heat rejection plant is significantly larger than for an equivalent duty, electrically driven vapour compression system.

Absorption systems are primarily used for process cooling in food, beverage, chemical and pharmaceutical plants where waste heat to drive the system is readily available. There is an increase in the food industry, where local on-site power generation is used, and provides a source of waste heat. This has been particularly noted in developing countries such as India and China, where increased food production is being achieved but the electrical infrastructure is under construction. In these cases, chilling is normally achieved with vapour compression plant, but with some absorption cooling available to increase the cooling capacity when the generator is running. In many other Article 5 parties where the electrical grid is not robust enough for a large capacity refrigeration system, it makes sense to use absorption systems. In countries where natural gas downstream piping infrastructure exist and where gas prices are reasonable compared to electricity, direct fired chillers are used to produce chilled water for industrial applications. Those are normally double effect units. Countries with a shortage or unreliable electric supply use direct fired chillers in industrial cooling. Examples are in India, Pakistan, Bangladesh, and China. Those units are generally fuel-oil fired or gas fired. Indirect fired absorption units are used primarily in applications where excess boiler capacity is available in summer months and where steam or hot water are generated by a co-generation application. Those units are normally single effect and are fired by water or steam temperatures of 90 to 120 °C. The efficiency of those units is compared to those of vapour absorption in Chapter 8. The lithium bromide-water chillers are all water cooled.

10.2.10 District heating

One of the fastest developing areas is the heat pump sector. Heat pumps based on ammonia are used for district heating systems. The systems have a reduced charge, which can be managed. Heat pumps with capacities from about 500 kW up to about 60 MW have been installed in Europe using different technologies and refrigerants.

The latest development is a 50 MW heat pump to be installed in Denmark using the North Sea water has heat source and CO_2 as a transcritical working fluid. In Europe many heat pumps using R-717 has been installed in both district heating systems but also for other sorts of heat recovery in industrial applications. Several manufacturers have also launched large heat pumps using HFO-1234ze(E) for district heating application. The lower efficiency at high temperature of these solutions have limited their impact on the market so far, but as all heat pump sales will grow steeply over the coming years, there will also be more industrial heat pumps with HFO-1234ze(E) installed.

The growing concerns about the use of ammonia can be mitigated by using wet scrubbers in which ammonia vapours are absorbed in the water and disposed of in a safe way. On sites with a flare, one will send leaked ammonia vapour to the flare where it is disposed-off in a safe manner.

10.2.11 Data Centres

With the growing electronic communication and storage of information there is a growing need for cooling the heat generated in the data centres. These can have a need for cooling away massive amounts of heat which can be done in different ways. Traditional chiller solutions can be used, but also water from nearby lakes or rivers or even the open sea can provide the cooling. Experiments with under-water data centres have been carried out successfully.

In mild and cold climates, the heat from the chillers provides an excellent heat source for heat pumps which can turn the condenser heat into heat which can be used for district heating or industrial processes. The trend is that the electronic chips are growing to be more tolerant to higher temperatures. In the early days the temperatures were kept at about 20 °C, but today it is normal to have a significant higher temperature. This makes the use of a heat pump more interesting because it allows a higher suction temperature and hence higher efficiency.

10.3 Refrigerant options for new equipment

It is important to keep in mind that when a new potential customer asks for a new refrigeration system then it is because he/she needs it for a specific purpose. There are many options and many things to consider before you come to the choice of refrigerant. Some customers may receive advice about using a certain refrigerant, but many times the customer has no specific opinion on which refrigerant to select and the choice is left to the engineering, procurement, and construction contractor.

10.3.1 Low-GWP HCs and HCs mixtures

The main hydrocarbon used for typical refrigeration and chiller applications is HC-290. HC-290 chillers are available from several suppliers, mainly in the European markets. Restrictions on the use of flammable refrigerants holds back the implementation in some regions, e.g., China where high-GWP R-507A.

For low and very low temperatures systems using HC-1270 (propene, also known as propylene) is used in system from -10 °C down to -100 °C which is deep vacuum which requires a double shaft seal as an additional safety measure. These systems are mainly used in chemical plants in particular chemical cooling other fluids in tanks that can hold 50,000 m^3 or more of products.

For low temperature storage in e.g., pharmaceutical production HC-170 (ethane) is sometimes used for freezers down to -80 °C with evaporation of the refrigerant just over normal boiling point.

For special purpose cold rooms and in chemical process system some systems are using HC-1150 (ethylene or ethene) for temperature down to about -110 °C, or sometimes even lower.

In the gas industry where you wish to liquefy gases you sometimes build systems for what is called auto cascade system or single mixed refrigerant processes, in which you only use one compressor but a refrigerant blend consisting of five or more components depending on the temperature level (Omar, 2014). Each component evaporates at different temperatures helping to condense other components of the blend during the process. The complete blend of gases is then returned to the compressor which compresses the blend at a normal pressure. This kind of systems can reach temperature of -200 to -150 °C. These blends consist of both noble gases and hydrocarbons.

10.3.2 Low-GWP R-717 and R-744

The major hazard presented by R-717 is its acute toxicity, although its pungent odour ensures that low, relatively harmless concentrations are obvious and provide an early warning of danger.

R-717 is flammable in relatively high concentrations, but it is difficult to ignite and as a result R-717 conflagrations are extremely rare. The products of combustion are nitrogen oxides and water, so there are no toxic consequences. The lower flammable limit is 16 %; about 5,000 times higher than the short-term exposure limit, and almost 50,000 times higher than the lowest level which can be detected by smell.

R-717 systems can be designed for very high efficiency, particularly with higher condensing temperatures, so in recent years it has been used more often in smaller systems with air cooled condensers, condensing at about 50 °C (IIR, 2008). Compression of R-717 produces relatively high compressor discharge temperatures compared with most fluorocarbons, but if oil injected screw compressors are used then the heat of compression can be removed by oil cooling. R-717 also produces relatively high heat transfer coefficients and requires a low mass flow due to its high latent heat. The high critical temperature of 133 °C makes R-717 very suitable for high temperature heat pumps. Ammonia has a normal boiling point of -33 °C, a relatively high temperature for industrial freezers. This means that many freezers operate at sub-atmospheric pressure, so air and moisture are drawn into the system if it is not pressure-tight on the low-pressure side. This unfortunate consequence is generally tolerated because the moisture is soluble in ammonia liquid; it does not immediately cause unreliability and both air and water can be relatively easily removed from the system while in operation. However excessive water build up will eventually impair operating efficiency and therefore increase electrical consumption, so system contamination should not be left uncorrected.

In an effort to address safety concerns, there is a current focus on R-717 charge sizes. Statistics available from ESH in the UK show that 60 % or more of all accidents related to refrigeration happen during service and maintenance. Similarly, in the USA accidents and fatalities occur during service and maintenance. This points to lack of education and training. In Europe, the new drafted standard EN ISO 22712 which will substitute EN 13313 deals with education and training, from design to disassembling of the system, and to the level of educational knowledge given.

Definition of the lower charge has different perspective. For a chiller, where the entire refrigerant charge is always contained in the chiller, one can reduce the charge greatly by using different heat exchangers and technologies. When talking about larger systems with ammonia in the air coolers or freezers, it is more complex. One way to go is to use rooftop units with a limited charge on each unit. Normally one does not assume that all units start leaking at the same time.

Because long liquid lines carry a large quantity of refrigerant, one can use rooftop units with a water-cooled condenser, where the gas from the evaporator goes to the central compressor plant room at a low pressure and then back to the unit and the condenser at a higher pressure.

Here the gas is then condensed before it is again injected to the evaporator. In this way one avoids having long liquid going from the machine room to the evaporators. In this way most of the charge is then concentrated around the evaporator and the rooftop unit. The amount of gas represents a relatively small part of the total volume of refrigerant.

A third way to reduce the ammonia charge is to use cascade systems. Here one can reduce the ammonia charge to about 10 % of the original design and substitute it with R-744. This method has been used in all parts of the world for a variety of applications mainly within food and beverage (F&B). The low stage is most often working at about -50 to -45 °C and the medium temperatures are between -20 to -10 °C. The ammonia charge is then limited to work from about -15 °C on the evaporator and condenser to the ambient.

The results achieved in commercial systems are 18 g/kW, which is very low compared to many other systems. How big a system can be managed using the same technology is difficult to say at this moment. In most parts of the world one can use water in the evaporative condenser or cooling tower. What is not so often used is seawater-based cooling towers, but they are and have been available in the market for several years.

In future, condenser heat will be an energy source that can be circulated in district heating and cooling systems. This may support the carbon free future that is being envisioned in many parts of the world.

10.4 Refrigerant options for existing equipment

Industrial refrigeration and heat pump systems are often optimized for a specific refrigerant and the best way to approach a conversion project is to evaluate the system from the start with the new refrigerant and then identify the main differences from the existing equipment and the new project.

It is a legal requirement in most countries that the materials (pipes, vessels, valves, and compressors) are documented and compatible with the fluids. The alternative is testing the material and that can include new pressure tests of the system. In some countries with strict rules pressure tests need witness from a third party.

O-rings and sealing material will absorb the blend of refrigerant and lubricant/oil present over time. It is therefore necessary to change them to avoid failure when the new refrigerant or/and oil is introduced to the system.

The required motor power needs to be checked, but in many cases, this is not a problem. If it is about an open type of compressor also the shaft seal needs to be checked and best changed. In addition, compressor manufacturers should be consulted whether the valves need upgrade when operating with different refrigerants.

10.5 Standards and safety standards

When working with refrigeration systems and especially with large systems and with R-717 it is required that you have the skills to do it safely. The ISO-5149 and ISO-22712 is a good place to start. According to the safety standard ISO-5149 you must be competent to do your job whatever that might be from design to scrapping the plant at the end of practical service life of the system. To elaborate on the competence matter you are advised to consult ISO-22712 in which you find different activities as one axis and the skills on the other. The competence levels are graduated depending on job function topic. If your job is leak-detection you do not need to be highly skilled in designing the system, to take an example.

Other standards apply when it comes to personal safety and equipment. Not everybody is aware of these standards, but as value of human life increases world-wide, these standards will come into common use especially detectors that can warn you in case of a refrigerant leak.

10.6 Concluding remarks

Industrial refrigeration and heat pump systems are optimized and often customized for the site and process in which they are part in order to yield the highest possible efficiency. Energy is one of the most important parameters and highest cost in many applications, hence the attention of the topic. If the industry is to meet the expectations of reduction of CO_2 emissions even more focus on energy efficiency is required.

R-717 is the most commonly used refrigerant in large industrial systems. Currently also a growing number of R-717/R-744 cascade systems are installed for low temperature application, as well as systems using R-744 as the only refrigerant. Low-GWP and some high-GWP fluorinated refrigerants are also gaining market in some applications.

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Chapter 11

Heating only heat pumps

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11 Heating only heat pumps

11.1 Introduction

Heat pumps upgrade (“pump”) heat from a lower temperature to a useful higher temperature level. The heat is then used for space heating, service (including domestic) water heating, or process heating. The heat sources generally used are ambient air, water, ground, or waste-source heat. The heat sink can be air, water, or a process fluid. This chapter only covers systems where water is the sink (the coloured zone indicated in Table 11-1). The equipment types for industrial process heating and, in general, large capacity heating systems (typically in the order of several MW capacity), are covered in chapter 10 (“Large refrigeration, heat pumps and heat engines”). All air-to-air heat pumps are covered in chapter 7.

The temperature difference between the source and sink has a direct impact on the pressure difference the compressor has to deal with, which will also depend on the characteristics of the refrigerant applied. In general, heat pump systems will be less efficient under higher temperature difference (temperature lift) conditions. The required compressor power input is a fraction of the total useful energy (heat) delivered. The required input power to the heat pump is mainly dictated by the heating capacity required, the temperature difference between the source and sink, the effectiveness of the heat exchangers and the compressor/driver efficiency. The required power input to water pumps, fans, controls, and also the power input during the standby period need to be included to determine the power consumption of the total heat pump system. The heat pump overall coefficient of performance (COP) is defined as the useful heat delivered divided by the total power input. The European standard EN14825 and the EU regulation 813/2013 are referring to a seasonal coefficient of performance (SCOP), which is the energy weighted average of the heat delivered and the corresponding energy input at temperature conditions in steps of 1 K to simulate the typical ratio of annual useful heat delivered divided by the corresponding energy input.

In most applications, heat pumps are an alternative to gas or oil combustion boilers or direct electrical heating, in general resulting in a significant reduction of primary energy consumption and resulting CO_2 emissions. The cost of the equipment and the COP/SCOP, combined with the minimum outdoor ambient temperature and the maximum water supply temperature, are the most important factors in the competition with gas- and oil-based heating systems. The use of hybrid systems, where the part determined as the “lower temperature-lift” of the heat demand (i.e., the operation at high COP) is supplied by the heat pump, has become an attractive option in certain countries in Europe. Heat pumps are also used at the end-user level in low-temperature district heating systems and are also used in total energy systems.

In 2020, the global air-to-water heat pump market increased to 3.28 million units. According to Energy Technology Perspectives by the International Energy Agency (IEA, 2021) the proportion of heating equipment sales accounted for by heat pumps will almost triple by 2030 and is expected to continue to grow thereafter. It is forecast that the number of heat pumps sold in the residential sector over the next 20 years will be roughly equivalent to the number of gas boilers sold in the same sector over the last 20 years (JARN, 2021). While almost all heat pumps are electrically driven, gas engine driven heat pumps are still being placed on the market.

11.2 Types of equipment and their applications

Heat pumps can be classified by heat source/heat sink, application, and design. In case they are classified by heat source (air, water, and ground) and heat sink (air, water), definitions for the type of heat pumps used in this chapter are therefore given in Table 11-1.

For air to water heat pumps, the ambient air is used as heat source. For water-to-water heat pumps, a water source is used as heat source. This can be done by directly using the water of the source or via a secondary circuit using brine or pure water as the heat exchange fluid.

When ground is used as the heat source, heat pumps are usually referred to as geothermal heat pumps. There are two basic types of ground loop systems: horizontal where pipes are buried approximately two meters below the surface and vertical where boreholes are drilled typically one hundred meters deep. In most of the cases these ground loop heat pumps utilise indirect expansion systems with a secondary fluid in the ground loop but there are also examples of applications using direct expansion. Although they are more energy efficient, direct expansion systems have a relatively large refrigerant charge and their use may be prohibited in some locations due to environmental regulations.

It is also possible to classify heat pumps by types, depending on their application – as shown in Table 11-1:

1) Heat pump water heaters (HPWH)

2) Space heating heat pumps

3) Combined water and space heating heat pumps

4) Decentralized micro-booster district heating systems

- heat pumps for water and/or space heating,
- reversible heat pumps for water heating, space heating and space cooling

5) Integrated energy system heat pumps for simultaneous water heating, space heating and cooling/refrigeration purposes

Table 11-1: Heat pump classification by heat source and heat sink

			Heat source	
		Air	***Water***	***Ground***
Heat sink	***Air***	Air-to-air	Water-to-air	Ground-to-air
	Water	Air-to-water application (1, 2, 3, 5)	Water-to-water application (1, 2, 3, 4, 5)	Ground-to-water application (1, 2, 3)

Note 1: This chapter covers only systems where water is the sink (green zone indicated in Table 11-1
Note 2: Heat pumps may utilise either direct expansion or indirect expansion systems (applying a secondary fluid circuit) at the evaporator side (heat source).

Apart from the classification by heat source (air, water, and ground) HPWHs can be further divided by design into mono-block (integrated units, see Figure 11-1, Figure 11-2, and Figure 11-3) and split systems (see Figure 11-4), and also via the refrigerant circuit design for single stage and cascade systems.

Figure 11-1: Example of a heat pump water heater

Figure 11-2: Example of an air-to-water mono-block - space heating heat pump

Figure 11-3: Example of a water-to-water heat pump

Figure 11-4: Example of a split air-to-water combined water and space heating heat pump

11.2.1 Heat pump water heaters

HPWHs are a category of heat pumps designed to heat domestic hot water (DHW) and other service (hot) water to temperatures between 50 and 90 °C.

In most of the developed world, the heating of water for domestic use (DHW) is one of the largest consumers of energy in the household sector (10 to 20 % share of total heat consumed). With 'nearly Zero Energy Buildings' (nZEBs) building codes in place in Europe and added to this the amount of existing buildings being renovated, the share of DHW production in the total heat consumption of the building has increased. DHW production has become a dominant factor in the total use of heating systems for new buildings.

When selecting the refrigerant to be applied for HPWHs, the hot water temperature levels during operation have to be considered. For DHW production, HPWHs must be designed in such a way that they enable a periodical increase of the water temperature above 60 °C to suppress growth of legionella bacteria in the system without significant deterioration of the heat pump efficiency.

11.2.2 Space heating heat pumps

A space heating heat pump is normally optimised for comfort heating. Comfort heating heats a room or any space by heating water for distribution to an under-floor panel, an air handling unit, or a radiator.

The required water temperature depends on the type of heat emitter:

- for under-floor heating the temperature is typically 25-35 °C (up to 45 °C in some regions);
- for air handling units the temperature is typically around 45 °C;
- for radiator heating the temperature is typically ranging from 50 to 65 °C;

- for high temperature radiators the temperature ranges normally from 65 to 80 °C.

Heat pumps used for operating temperatures below 65 °C are designed as single stage equipment while for higher temperatures they are designed as dual stage or cascade systems. Based on product information, single stage heat pumps able to deliver hot water at 70 °C that use HFC-32 or HC-290 are available on the market.

11.2.3 Combined space and hot water heat pumps

Combined water heating and space heating heat pumps have two functions: (1) supplying domestic hot water as well as (2) providing space heating. Several configurations of combined water and space heating heat pumps exist in order to optimise the seasonal energy efficiency for a specific application.

11.2.4 Heat pumps in district heating systems.

Through the installing of district heating, it is possible to cover up to 50 % of the heating demand in Europe. Heat pumps can deliver around 25 % of the energy required to the district heating grid and CO_2 emissions can be reduced by more than 70 % compared to the current situation (IEA, 2019). Because of high system temperatures prevailing in many of the heating networks, adapted concepts are needed in order to be able to guarantee cost-effective operation of the systems. Heat pumps make it possible to use very low (below 60 °C) and ultra-low (below 45 °C) temperatures in the district heating grid which make it possible to minimize the grid losses. Studies have shown that supply temperatures at the 40 to 45 °C level are sufficient for covering the heating demand during 80 % of the “heating”-year; this implies that the grid losses can be reduced by 25 % on an annual basis. Nevertheless, a circulation loop temperature of 45 °C will still lead to about 50 % heat losses. (IEA, 2019)

In a district heating system heat pumps are used as:

- centralized heat pumps, and
- decentralized, micro-booster heat pumps for:
    - DHW production,
    - space heating and DHW production or
    - space heating, DHW production, and space cooling (reversible heat pumps).

According to the IEA heat pump technology Annex 47-2019 report (IEA,2019) there are many possibilities for the integration of heat pumps into district heating systems.

In this chapter decentralized, micro-booster heat pumps are covered, while centralized heat pumps are addressed in chapter 10 (“Large refrigeration, heat pumps and heat engines”).

Very low (VLT), ultra-low (ULT) temperature and thermal district heating grids (TG) are also known as “5th generation district energy networks” and a lot of literature is being published on their account (Revesz, 2020; Buffa, 2019)

In case very low (VLT), ultra-low (ULT) temperature and thermal district heating grids (TG) are used as a heat source application of micro-booster heat pumps, it is relevant to keep the sink temperature above 50 °C, which is related to requirements for space heating of buildings and DHW preparation. In order to ensure safe water supplies without the risk of legionella bacteria, many countries regulate both the minimum DHW supply temperature and the recirculation temperature. The risk from legionella bacteria is increased if water temperatures in (all or some parts of) the system are maintained between 20 and 45 °C, an appropriate temperature range for bacteria growth. To ensure that risks from legionella exposure are minimised or reduced as far as practicable, the hot water should be stored at least at a 60 °C level and distributed. In this way, it would not reach lower temperatures than 50 °C (55 °C in healthcare premises) during maximum one minute at the water outlets (Health and Safety Executive 2014: Legionnaires’ disease technical guidance Part 2: The control of legionella bacteria in hot- and cold-water systems).

Table 11-2: Heat pump integration in the district heating system

District heating system type	High temperature (HT)	Low temperature (LT)	Very low temperature (VLT)	Ultra-low temperatures (ULT)	Thermal grids (TG)
Typical supply/return temperature	100/50 °C	80/40 °C	60/30 °C	45/30 °C	28/8 °C
DHW production	Storage tank/ Instantaneous heat exchanger unit	Storage tank/ Instantaneous heat exchanger unit	Storage tank/ Instantaneous heat exchanger unit	Micro-booster heat pump/electrical heater/gas or oil boiler	Micro-booster heat pump/decentral heat pump
Space heating type	Radiator/ under-floor	Radiator/ under-floor	Radiator/ under-floor	Radiator/ under-floor/air handling units	Under-floor
Heat pump integration	Central	Central	Central/ decentral	Central/decentral	Decentral

A typical lay-out of a micro-booster heat pump for DHW production integrated in VLT and ULT district heating networks is shown in Figure 11-5.

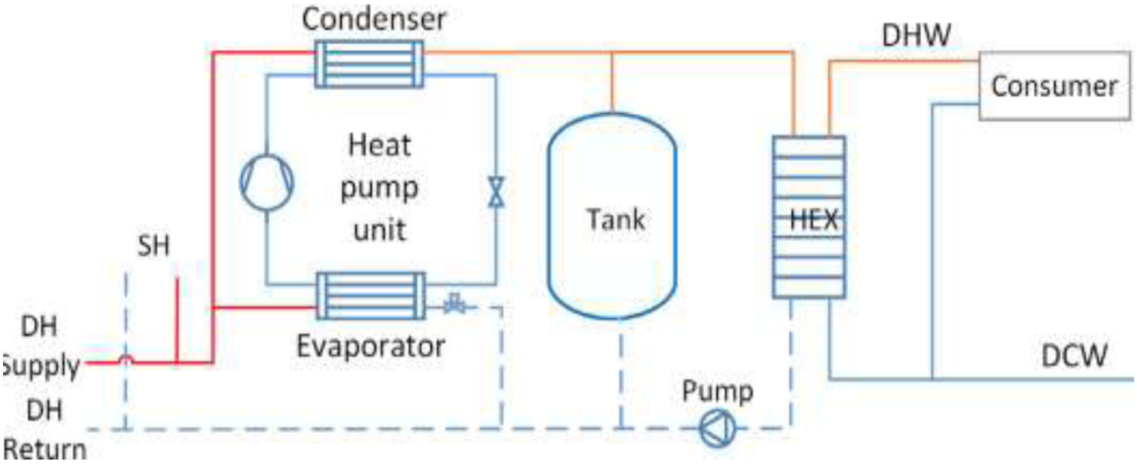

Figure 11-5: Integration of micro-booster heat pump for DHW production in VLT and ULT district heating networks (IEA, 2019)

If a district heating network with a 25 °C supply temperature is used (a so-called TG grid), a heat pump has to be used in each dwelling to provide domestic hot water and space heating. In this case the locally installed heat pump can be of a reversible type and should also be able to provide space cooling. An example of a TG grid is shown in Figure11-6.

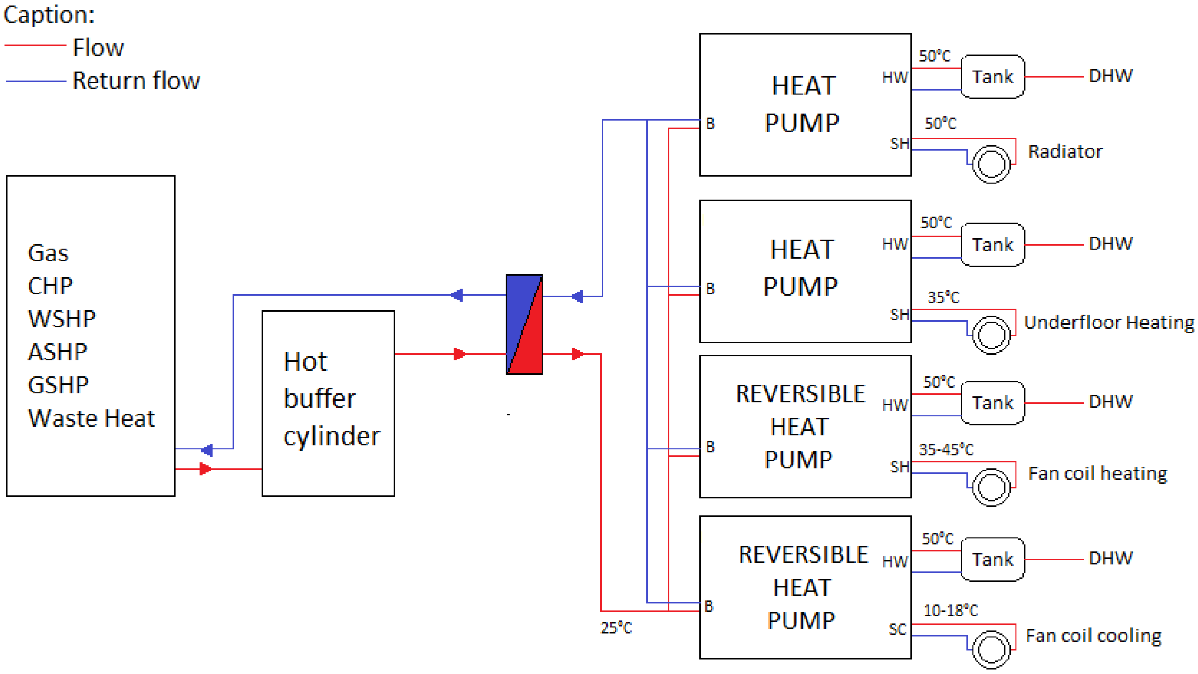

Figure11-6: Example of integration of heat pump for DHW and space heating and cooling in thermal district heating grids (TGs)

(Note: DHW = Domestic Hot Water; CHP = Combined Heat and Power; WSHP = Water Source Heat Pump; ASHP = Air source Heat Pump; GSHP = Ground Source Heat Pump)

11.2.5 Heat pumps for energy systems

In situations where a simultaneous need for heating and cooling energy exists, as in the case of combined DHW heating, ventilation and space heating, ventilation, and space cooling, and/or refrigeration applications in supermarkets, residential buildings, and commercial buildings (hotels, hospitals, schools, etc.), the use of heat pumps as part of integrated energy systems will be advantageous. This approach can be particularly prominent in achieving the targets as given in the nearly Zero Energy Buildings (nZEBs) building code in Europe. Buildings with an improved envelope, with large, glazed surfaces as a part of modern architecture while having increased internal heat gains from electrical equipment and occupants show a significant increase in air conditioning needs, this even in colder seasons. Unlike a reversible heat pump that either works in a heating or cooling mode, a heat pump for simultaneous heating and cooling can operate in three distinct modes: heating, cooling, and simultaneous mode.

The importance of simultaneous needs for heating, cooling and domestic hot water is a decisive factor when choosing a technical heat pump solution together with a certain refrigerant. Moreover, the right choice has a big impact on the heat pump seasonal efficiency. The past refrigerants of choice were mainly HCFC-22 and R-407C, while R-410A, HFC-32, R-454C and HC-290 are mainly used at present.

Reported system SCOPs (mainly for hotels in the Nordic countries) are 3.0 (determined in field measurements on integrated R-744 systems, (Smitt, 2020)) and 3.6 (theoretical study on a heat pump and chiller system for hotels using R-407A (Byrne, 2009)).

A case study of one nZEB concerns a heating system for a school in southern Norway with a CO_2 based heat pump and an adjusted heat emission system to allow low return temperatures (low temperature radiators 45/40 °C, under-floor heating 35/30 °C, and ventilation air heating 30/18 °C connected in series) shows an average measured COP of 3.0 with the potential for an improvement of the design to achieve a COP of 3.4 (see Fig. 11-7). (Heat pumping Technologies, 2022)

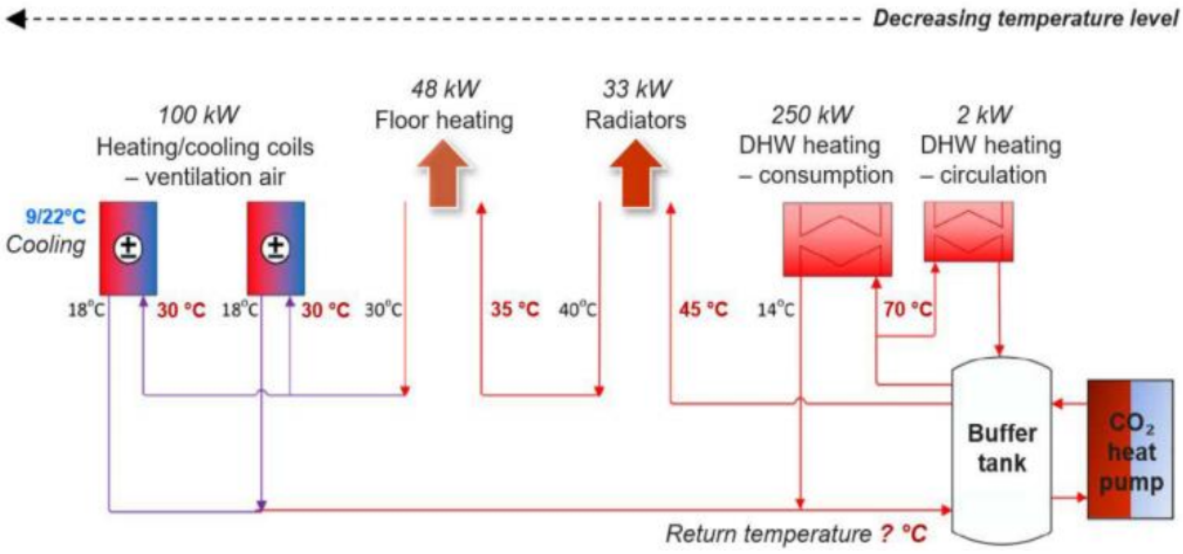

Figure11-7: Layout of the heating system of Justvik Skole in Kristiansand with R-744 heat pump and adapted heat emission system

11.2.6 Capacity ranges of water and space heating heat pumps

Table 11-3 shows the most common heating capacity ranges as (commercial) offered for single units of water and space heating heat pump types described above.

Table 11-3: Water and space heating heat pump capacity ranges

Heat pump type	Capacity range (kW)
Heat pump water heater	1 - 50
Space heating heat pump	4 - 400
Combined water and space heating pump	6 - 45
Micro-booster heat pumps in district heating systems - DHW heat pumps - combined water and space heating heat pump - reversible heat pump	 1.5 - 50 4 - 400 4 - 400
Heat pumps as a part of integrated energy systems	5 kW to a few 100 kW

11.3 Refrigerant options for new equipment

Transfer to non-ODS refrigerants has been completed in non-Article 5 parties, but HCFC-22 is still in use for high and moderate temperature water and space heating applications in Article 5 parties. The phasedown of the use of high-GWP refrigerants following the Kigali Amendment and the expected growth in the heat pump market will advance the development and use of medium and low-GWP refrigerant alternatives.

11.3.1 Important parameters influencing the choice of refrigerants

The most important aspects to be considered in selecting a refrigerant are environmental aspects, overall system costs, size, weight, sound level, efficiency, safety, and reliability. As for all refrigeration systems, there are many considerations that lead to the preferred choice, which are listed in Chapter 3. Specific issues to be taken into account for heat pumps are the relatively high temperatures at heat rejection and the potential temperature glide of the heat sink, as for heat pump water heaters.

The adoption of heat pumps for new dwellings is and will continue to be rapid due to the lower incremental installed cost difference over time and to the improved carbon footprint requirements if compared to fossil fuel operated system. Further, the space heating demand in newer dwellings is currently much reduced, while the cooling load is increasing. For these systems, it is easier to implement (refrigerant) mitigation alternatives that have high pressure, toxicity, or flammability. The argument is that the heat pump and its refrigerant charge is smaller and mitigation solutions are more reasonable from a technical and cost point of view. On the other hand, adopting a retrofit for existing installations, even when it is supposed to be a good solution, will take far more time than installing a new construction, therefore incentives will have to play a key role in driving the transition.

The low-GWP (GWP < 300) refrigerants options considered as long-term alternatives for heating only heat pumps are R-744, R-717, HC-290, HC-600a, and HFO-1234yf. Further, some new HFC/HFO blends are proposed, however, their potential use for water and space heating heat pumps has not yet been clarified. Medium-GWP (GWP: 300 to 1000) refrigerant options are HFC-32 and some new HFC/HFO blends. High-GWP (GWP > 1000) refrigerant options are HFC-134a, R-407C, and R-410A. The high-GWP options are already "under pressure" in well-regulated regions (e.g., Europe), and it will eventually be a global challenge to comply with the Kigali phasedown requirements. The different options are described more in detail in subsection 11.3.3, "Refrigerant options".

Developments are underway to broaden the use of R-744 and HC-refrigerant based water and space heating heat pumps. R-744 heat pump water heaters are already established products on the Japanese market, with growing market shares in different parts of the world, including Europe, China, Australia, and North America. HC-290 heat pump water heaters are already established products in Europe.

In Europe, there is a strong need to apply refrigerants that yield lower system charges, resulting in a reduction in CO_2 equivalents of a given refrigerant charge (the value obtained by multiplying the charge and the GWP of the refrigerant applied). Due to the quota limitations in the EU, based on CO_2 equivalents, both the price and the availability of high-GWP refrigerants become important selection criteria. On the other hand, the change-over to medium- or low-GWP refrigerants generally requires a redesign of the equipment including the major components such as the compressor. Generally speaking, the following items make it a difficult and time-consuming task to switch over to medium- or low-GWP substances:

- mitigation of flammability risks, as most medium and low-GWP refrigerants are flammable,
- design changes required to maintain the same operating range and performance,
- availability of components at a competitive price level,
- for air source systems, obligations regarding the sound level in combination with the efficiency requirements,
- the length of time necessary for the large number of tests (conditions) for each iteration in the re-development of the heat pump, and
- the total size and weight of the equipment.

11.3.2 Safety considerations

Except for R-744, the most efficient medium- and low-GWP refrigerants tend to be flammable. Therefore, safety standards receive increased attention, particularly also the development of them. The latter is related to including mitigation of flammability risks associated with use of refrigerant options according to the ISO 817 classifications A2L, A3 and B2L, as valid for HFC-32, HCs, and R-717, respectively. Nevertheless, the toxicity characteristics and application limits have to be taken into account.

An important distinction deserves emphasis between mono-block and split system solutions. Outdoor installed mono-blocks pose fewer challenges related to the application of flammable or high-pressure refrigerant alternatives due to the fact that the refrigerant is contained outdoors (in comparison to indoor mono-blocks). Because of this, one may see a faster adoption of alternatives consisting of HC-290, R-744, HFC-32 or HFC/HFO blends. Split system solutions are more challenging in terms of safety mitigation; they may lead to the adoption of mainly A2L alternatives such as HFC-32 or HFC/HFO blends, or the A1 refrigerant R-744. However, new IEC standards open up the potential for A3 refrigerants to be used in small single split systems.

11.3.3 Refrigerant options

Table 11-4 gives an overview of the presently used as well as the emerging refrigerants. Both categories are commercially available. The refrigerants used at present have matured in the market. Table 11-4 gives an overview of currently used refrigerants that are mature in the market (defined as 'baseline refrigerants') as well as emerging refrigerants. Both categories are commercially available. Emerging refrigerants are defined as refrigerants that are already used in certain full range product ranges at the moment and that show a clear potential for further growth in the coming years.

Table 11-4: Baseline and emerging refrigerants used in heat pumps

Product	Baseline refrigerants	Emerging refrigerants
Heat pump water heaters (HPWH)	HCFC-22[1] HFC-134a R-407C R-410A	HC-290 R-744 HFC-32 R-454B R-454C
Space heating heat pumps	HCFC-22[1] HFC-134a R-407C R-410A	HC-290 HFC-32 R-454B R-454C
Combined water and space heating heat pumps	HCFC-22[1] HFC-134a R-407C R-410A	R-744 HC-290 HFC-32 R-454B R-454C
Micro booster heat pump for District heating and cooling	HCFC-22 HFC-134a	R-744 HFC-32

[1] Still in use in Article 5 parties

11.3.3.1 High-GWP HFCs and HFC blends, HCFC-22

High-GWP HFCs and HFC blends, as well as HCFC-22, are still used in new equipment, but their numbers are decreasing. HFC-134a, R-407C, and R-410A are well commercialised for use in water and space heating heat pump systems globally.

In countries where HCFC-22 consumption reductions were implemented in advance of the Montreal Protocol requirements (i.e., mainly in Europe), high-GWP refrigerants are being used in water and space heating heat pumps with high to low sink temperatures. In Japan, R-410A is used; HFC-134a and R-410A are used in Canada and USA, and to a lesser extent in Mexico and the Caribbean countries. R-407C has been mainly used to replace HCFC-22 in existing product designs because of the minimal design changes required. However, the use of R-407C is declining in favour of the higher efficiency and lower system cost in case R-410A is applied (UNIDO, 2016). To adequately use R-410A, design changes are necessary to address its higher operating pressures and to optimise the system taking into account the refrigerant properties, thereby achieving the higher performance.

Air-to-water cascade systems are on the market using R-410A for the low temperature circuit and HFC-134a for the high temperature part. They both guarantee high seasonal COP in colder climates, even at high water sink temperatures around 80 °C, while delivering the required heating capacity without any auxiliary electrical heaters. Both refrigerants are mostly used for combined space and hot water heating, in order to replace existing boiler systems (Long et al., 2018; Dong et al., 2013).

The energy efficiency of R-407C systems is typically lower than the ones operated on HCFC-22, although similar COPs can be achieved with a careful system design. In practice, R-407C shows a pronounced temperature glide during both evaporation and condensation, which may lead to operational difficulties.

Compared to small systems, the design pressure has a larger impact on the cost for larger systems. For small and medium size systems, R-410A is the most cost-effective refrigerant, while HFC-134a tends to be more cost-effective for large systems.

Now that systems with high-GWP refrigerants are being considered for phaseout, the conversion to medium- or low-GWP fluids has started. In some Article 5 parties, one has the possibility to leapfrog from HCFC-22 to medium- or low-GWP refrigerants.

11.3.3.2 Medium-GWP HFC-32 and HFC/HFO blends

Water and space heating heat pumps have already been commercialised on a large scale. Moreover, in the case of the application of HFC-32, similar units may operate at a higher COP than in case they would use HCFC-22 or R-410A.

HFC-32 has saturation pressures slightly higher than the ones of R-410A, which is approximately 60 % higher than the one of HCFC-22. System refrigerant charges can be up to 43 % lower than for HCFC-22, while the energy efficiency is the same or higher (Yajima, 2000). HFC-32 has a better heat transfer performance than R-410A. However, since HFC-32 has higher compressor discharge temperatures than R-410A, a more accurate temperature control is necessary, particularly for high temperature water and space heating heat pumps and low temperature heat sources (Konghuayrob and Khositkullaporn, 2016).

The direct cost of the pure HFC-32 refrigerant chemical is lower than R-410A, but this has limited impact on the system cost. HFC-32 based space heating, as well as HFC-32 combined water and space heating heat pumps have been introduced on the market. They had the same performance as R-410A units, however, delivered a 5 K higher temperature, up to 65 °C. Recently, hybrid versions of HFC-32 based water and space heating heat pumps (a heat pump combined with a natural gas supplementary heater) have been placed on the market.

The main restrictions for using HFC-32 are related to the safe use of lower flammability refrigerants (class 2L as defined by ISO 817); see Chapter 3. The ISO-5149 standard was updated in 2014 and IEC 60335-2-40 was updated in 2017 to accommodate this new class 2L. However, some building codes do not allow the use of flammable refrigerants in certain types of buildings. If the refrigerant to water heat exchanger is placed outside, the safety issue is easier to resolve, however, in that case frost prevention becomes an issue.

Among the HFC/HFO blends, R-454B (preferred over R-452B) has been introduced by some manufacturers as a medium GWP alternative to R-410A, mainly due to the similarity in system and component design as applied for R-410A systems.

11.3.3.3 Low-GWP HFOs and HFC/HFO blends

HFO-1234yf is comparable to HFC-134a where it concerns thermophysical properties. It therefore yields comparable performance and there is no need for substantial system modifications compared to an original HFC-134a system (Nawaz et al., 2017).

A number of other HFOs have been studied and identified as possible low-GWP refrigerants for heat pumps (Arpagaus et al., 2018). Here, special attention has been paid to HFO-

1234ze(E) and HFO-1234ze(Z) (Fukuda et al, 2014) for high temperature applications. The latter is related to the favourable heat transfer coefficients of these HFO refrigerants in comparison to other refrigerants used so far in heat pumps (Longo et al, 2014).

For water heating and space heating heat pumps that currently use HCFC-22, R-410A, or R-407C, significant design changes would be required to optimise the system for HFO-1234yf or HFO-1234ze(E). The heat transfer is expected to be lower than for R-410A systems because of the lower saturation pressure. The relatively higher pressure drop in the refrigerant pipes and heat exchangers will result in lower efficiency at the temperatures that are typical for heat pump water heaters. Thus, some of the changes required for HFO application include larger displacement compressors, larger connecting tubes' diameters, larger heat exchanger tubing, as well as additional heat exchanger surface in order to offset both lower heat transfer and higher flow resistance. Component cost will be even larger than the one for an HFC-134a system, but the flammability will specifically affect larger systems, due to the pressure vessel codes that need to be taken into account.

Blends of HFOs with HFC-32 or HFC-125 may result in more or less the same properties of HCFC-22, but the "blending" results in higher refrigerant GWPs than for pure HFOs. It is too early to judge whether any of these blends will be commercialised in water and space heating heat pump systems, since issues of acceptable performance and competitiveness so far remain. The same A2L restrictions as for HFC-32 apply for these blend refrigerants (see section 3.3). Furthermore, R-454C is also being applied, see Table 11-4 (the azeotropic R-513A is only used for larger equipment (see Chapter 10)).

11.3.3.4 Low-GWP R-744 (carbon dioxide)

R-744 is one of the few low-GWP refrigerants classified in the safety category A1, as defined by ISO 817. Development of R-744 water heating heat pumps started around 1990 (Nekså, 1998). R-744 heat pump water heaters were introduced to the Japanese market in 2001 (JARN, 2018), with heat pumps for heating of bath or sanitary water as the main application. Space heating heat pumps that operate at lower water temperatures in combination with hot water heating have also been developed (JARN, 2018). R-744 operates at high pressures; they are approximately 5 times higher than HCFC-22 operating pressures and 3.5 times higher than the ones of R-410A. Actually, this is an advantage that may enable more compact system designs. The low critical temperature of R-744 implies that the system has to operate trans-critically. R-744 as a refrigerant has been primarily used in water storage type heat pump water heater applications.

Continued market growth for domestic hot water heat pumps is expected in Japan, Asia, and to some extent in Europe. Recently, R-744 heat pumps for domestic space heating applications have also been developed in Europe. For commercial buildings with combined radiator and air heating systems, R-744 is a very promising refrigerant (Smitt and Hafner, 2018). This also holds for new low-energy buildings with a large domestic hot water demand compared to their space heating requirement (Nekså, 2016). It is not known which level of market penetration R-744 space heating heat pumps will experience (Pardiñas et al., 2016). The ultimate market acceptance will be determined by system economics, energy labelling, minimum energy efficiency requirements, and sustainable environmental requirements.

Application of R-744 as a refrigerant enables heating of domestic hot water up to temperatures as high as 90 ºC without the use of auxiliary electrical heaters. R-744 may give a high performance if used at low temperature source and high temperature sink conditions (greater than 65 °C), together with a low return inlet water temperature (less than 35 °C) and a high temperature difference between the inlet and outlet (greater than 40 K). This makes it well suited for use in hot water storage type heat pump water heaters, in which low temperature inlet water is heated to a high temperature, i.e., for the thermal storage of domestic hot water.

Compared to HFC refrigerants, design modifications are required to achieve an equivalent performance of R-744 if applied only for space heating (Nekså, 2010). It is challenging to achieve high efficiency for domestic space heating applications once there is a low temperature difference between the high and low water temperature of the heat sink. In that case, system designs are required that result in a low water return temperature (Nekså, 2010). Otherwise, work recovery components, e.g., ejectors or expanders, would have to be applied to overcome energy efficiency barriers. However, their costs may make the product less competitive.

The cost of R-744 is low. However, because of its high pressure, certain types of systems will require more robust designs for pressure safety, which adds cost, but the specific tube dimensions to be applied are much smaller compared to the practices currently applied, which yields the advantage of compact tubing and insulation material. The main barriers are the cost of the system and how to achieve comparable energy efficiency in some applications.

Manufacturers catalogue data show that R-744 has been introduced in Europe for medium sized water heating heat pumps. Air source and ground source water heating heat pumps are available up to around 50 kW. In Japan, R-744 water heating heat pumps were already introduced on the market in 2001. Their market volume has expanded steadily, and cumulative shipments are now at 5.8 million units, as of January 2018 (JARN, 2018). Since the Great Earthquake in eastern Japan in 2011, the annual sales volume has remained more or less stable, however, a continuing increase is expected in order to reduce future global warming impact.

11.3.3.5 Low-GWP hydrocarbons

Hydrocarbons (HCs) include three refrigerants for use in water and space heating heat pumps, i.e., HC-290 (propane), HC-1270 (propene) and HC-600a (iso-butane). All are classified as low-GWP refrigerants and are classified in the ISO 817 safety category A3. According to many of the standards, there are restrictions in relation to the charge amounts applied.

At present, a number of low charge level heat pump water heater installations are sold in Europe that use HC-290. However, for water and space heating systems with a ventilated enclosures configuration, larger refrigerant charges are allowed and have been introduced on the market.

In the 2000s, their use declined due to introduction of the Pressure Equipment Directive in Europe (Palm, 2008), but compressor manufacturers are now offering a wide variety of compressors for HC-290 applications. In Europe, some heat pump manufacturers have one or more water and space heating heat pumps in their product range that use HC-290 as a refrigerant.

The efficiency of HC-290 and HC-1270 in water and space heating heat pumps is known to be good (Palm, 2008), and the cost of the refrigerant itself is relatively low. Based on the HC refrigerant properties, the equipment cost is comparable to the one of HCFC-22; devices to mitigate safety issues are supposed to add certain costs.

The main barriers to mass commercialization are related to safety. For systems with parts located in occupied spaces, the allowable charge quantity is limited, whereas for systems located outside, there are no major restrictions. Recent development work has been done on charge minimization in order to increase system capacity for a given refrigerant charge (Andersson, 2018). The necessity to ensure that technicians are appropriately trained to handle hydrocarbon flammability forms a part of the constant training technicians need to take in light of the wider uptake of flammable working fluids. For equipment manufacturers, the liability for safety aspects during the total life cycle of the equipment including transport, storage, service, and end of life disposal phase, combined with costs for safety measures are the main barriers to extend the use of hydrocarbons. Mono-block equipment installed outdoors has reduced safety risks during the operation stage and consequently, a smaller number of barriers exist.

11.3.3.6 Low-GWP R-717 (ammonia)

R-717 has a GWP of zero and is classified in the ISO-817 safety category B2L. R-717 is mainly used for large capacity systems, such as large buildings and airports. It has also been used in a small number of reversible water and space heating heat pumps, including sorption systems. It is not expected to be used in small capacity water and space heating heat pumps. The energy efficiency of R-717 when applied in water and space heating heat pumps is known to be very good.

The main restrictions are related to safety aspects imposed by the safety category B2L (see Chapter 3). It has been shown that small capacity water and space heating heat pump systems can be designed to operate with a very low ammonia charge (100 g of ammonia for 9 kW heating capacity (Palm, 2008)), but market introduction has been limited by measures required during the life cycle of the equipment with ammonia, the minimum capacity required for cost-effectiveness and certain national regulations that apply to installation procedures.

Another obstacle for the commercialization of small capacity R-717 water and space heating heat pump systems is the limited supply of components. Nevertheless, hermetic, and semi-hermetic compressors are available for medium and larger size water and space heating heat pumps based on the scroll compressor typology, a unit with 15 kW input for water and space heating is now commercially available in Japan.

11.4 Refrigerant options for existing equipment

The most important parameter is the limitation, restriction of refrigerant options for existing equipment. The parameters include the ones for new equipment, but with existing equipment there are several extra constraints (whether a safe retrofit can be carried out). The liability and warranty aspects are important issues that should be thoroughly considered when modifying existing equipment. In most countries, liability and warranty issues do not anymore fall under the responsibility of the original equipment manufacturer, but they belong to the party that carries out the modification of the equipment and the change of refrigerant. In many countries, the replacement of the refrigerant by something different from the original one is considered a new design and a new piece of equipment. As a result, one does not see offers in practice for a change of the refrigerant in an existing system. The effort and cost for changing the refrigerant is normally not competitive with replacing the equipment with a new and more efficient one. As mentioned in chapter 13, the use of a reclaimed refrigerant which is the same as the original refrigerant in the equipment can be considered as the best technical option for existing equipment. When doing so, special attention will be required regarding the quality of the reclaimed refrigerant and more specifically to the composition of the refrigerant in case refrigerant blends are used.

11.5 Resource efficiency and circular economy issues in relation to refrigerants and energy efficiency

11.5.1 Resource efficiency and circular economy

The topics that deserve most attention, are listed below:

- Heat pumps are material-intensive products when compared to oil or gas boilers or direct electrical heating systems. For the heat pump industry, resource efficient, material conscious designs and manufacturing of components and products are essential to cost-efficient production. A direct comparison of these technologies that is only based on heating capacity and materials used for manufacturing cannot be valid. Instead, Life Cycle Climate Performance (LCCP) should be taken as the method for comparisons since it measures direct and indirect global warming impact of equipment based on (1) the total related emissions of greenhouse gases associated with manufacturing, (2) the emissions of greenhouse gases due to energy consumption during the lifetime, (3) emissions due to leakage and during disposal of the refrigerant, and (4) other factors such as the energy consumed to obtain raw materials.

- Most important for the resource efficiency is the circular economy of the total heating system. Water and space heating heat pumps require specific handling during recycling for refrigerant and lubricants, which is, of course, not needed in the case of other (fossil-fuel based) heating equipment.
- The circular economy of refrigerants is not at all unique for water and space heating heat pumps in comparison to other refrigerant containing applications. Resource efficiency of refrigerants can be enhanced through refrigerant recovery, reclamation, and reuse as well as through the reduction of the amount of refrigerant charge and the reduction of leakage. In order to compare material resource efficiency, one has to evaluate the system based on the same performance characteristics such as heating capacity at the design point, energy consumptions during the total year, sound levels, as well as the operation range of the equipment.
- The material usage is influenced by several parameters such as pressure, heat transfer characteristics, minimum material thickness for the production process, etc. Generally, the material usage in equipment is smaller the higher the pressure of the refrigerant. Systems that use R-744 do not always follow this logic due to the fact that they operate with a trans-critical cycle, where material usage depends on the total system concept.
- The selection of refrigerants with their individual and favourable thermophysical properties have a strong impact on resource and material efficiency. These properties include thermodynamic properties (pressure-temperature relation, density, volumetric capacity, specific heat capacity, viscosity, surface tension, temperature glide), the compatibility with building materials, ease of use (system complexity), availability of refrigerant and associated cost, safety, and environmental properties:
    - high pressure refrigerants require thicker walls for piping, compressor casings, vessels, and heat exchangers, but, on the other hand, low pressure refrigerants require compressors with higher displacement volume (swept volume), larger pipe sizes, larger vessels, and larger heat exchangers.
    - lower pressure ratio (condensing to evaporation pressure) means higher compressor volumetric efficiency and consequently smaller compressor swept volume (smaller compressor) and lower energy consumption.
    - of all flammable refrigerants, refrigerants with low liquid density and a high Lower Flammability Limit (LFL) have a positive influence on the various safety aspects.
    - refrigerants with higher vapour density at the compressor inlet, such as R-744 in comparison to R-410A or HFC-32 have a higher volumetric cooling capacity, i.e., a lower refrigerant mass flow rate for the same capacity, hence smaller compressor, and reduced diameter of suction and liquid lines.
    - a higher pressure drop at disposal for a same change in saturation temperature of 1K in suction lines allows the use of smaller diameter pipes (R-744 in comparison to HFCs and to R-717).
    - a small ratio of vapour to liquid density will cause homogeneous flow in narrow channels which is a basic reason for the 60 to 70 % higher heat transfer coefficient for R-744 in comparison to HFC and HC refrigerants which results in smaller and/or more energy efficient heat exchangers.
    - a low surface tension leads to better pipe wetting, which again leads to higher heat transfer and consequently smaller heat exchangers.
    - because of the high-pressure, special materials such as copper-iron alloys (K65) or steel pipe work, are often used in R-744 systems, especially in discharge lines and headers. Steel can become brittle at low temperatures. In the event of a leak the temperature can reduce to near -78 °C, so low temperature steel must be used.

- the incompatibility of R-717 and copper leads to the necessity to use steel. This adds cost to the system in terms of material quantity (and qualified workforce-welders) due to the low thermal conductivity of steel.

11.5.2 Energy efficiency considerations

Heat pumps are often considered as an energy-efficient heating technology which makes use of renewable energy form the air, ground, or water. In Europe, Japan and the US, governments have been promoting them in various applications. The performance of air-source water heating heat pumps depends on incoming water temperature, outgoing water temperature, ambient temperature around outdoor units, heat transfer characteristics, and various heat losses. A lower ambient temperature leads to lower energy efficiency and lower heating capacity. Heat pumps for supplying domestic hot water are required to heat water to high temperatures to compact hot water storage tanks. Therefore, water heating heat pumps intended for cold climate regions tend to have a larger outdoor unit, a two-stage or variable speed compressor or a cascade refrigerating cycle. The evolution to variable speed in order to extend the operating range and retain high efficiency at low ambient is particularly evident in smaller heat pumps (less than 20 kW), where advanced compression technology (with dual/triple rotor, liquid injection etc.) is extending the operating envelop and improving efficiency at low ambient temperatures. Compression technology is also critical to extend the operating envelop upwardly, allowing heat pumps to achieve water temperatures of 90 °C or more while retaining reasonable efficiency levels. In terms of refrigerant properties, refrigerants with higher critical temperatures can transfer heat to water more efficiently owing to the use of condensation heat, even when temperature differences between incoming water and outgoing water are comparatively small in space heating. The optimization of the water flow rate is, however, imperative in heating water to temperatures above critical temperatures with condensation heat. In addition, refrigerants with too high critical temperatures tend to have low volumetric capacity, which leads to larger compressors. Since R-744 with its low critical temperature operates in trans-critical conditions it would be more suitable for producing high temperature water, as needed for water heating heat pumps. Although increases in incoming water temperatures can sometimes result in a lower energy efficiency.

Most of the water heating systems for space heating and domestic hot water still use fossil fuel. This is due mainly to the much higher initial cost of heat pumps including their installation cost. The effectiveness of water heating heat pumps is usually evaluated based on primary energy efficiency and CO_2 equivalents. Heat pumps are typically driven by electricity. It is reported that the efficiency of electricity production from conventional thermal power plants is between 40 % and 45 %, which decreases to roughly 35 % at end-users' homes due to transmission losses. As a result, when heat pump performance expressed in the form of seasonal coefficient of performance (SCOP) is around 3.0, its primary energy efficiency exceeds 100 %, which means that it can reduce primary energy consumption as opposed to fossil fuel combustion heating systems. This indicates higher electricity generation efficiency and higher SCOP which lead to less primary energy consumption, again resulting in less CO_2 emissions.

In the EU, air-to-water heat pumps and ground source heat pumps which have a primary energy efficiency of 115 to 125 % have been allowed to be sold from September 2017. This results in a seasonal coefficient of performance (SCOP) of respectively 2.875 and 3.125 in contrast to the SCOP of 3.8 for air-to-air heat pumps. The seasonal efficiency is based on a specific temperature pattern and includes standby energy losses. For the moment, this test method has no drastic impact on performance of equipment with refrigerants presently in use (Table 11-4). The impact on equipment performance for emerging refrigerants is unknown.

In Japan, a unique program called "top-runner approach" has been used for improving energy efficiency of water heating heat pump systems. In that program, mandate minimum energy efficiency is set based on the most energy-efficient products on the market. Currently the program is only applied to R-744 based heat pumps to supply domestic hot water. Owing to this program, R-744 heat pumps have achieved annual performance factors ranging from 3.6 to 4.0.

In the US, federal appliance efficiency standards that went into effect in 2015 require larger electric tank water heaters to use significantly less energy. Requirements go from about 90 percent efficiency to nearly 200 percent. Heat pump technology is in use to meet a 200 % efficiency standard.

In China the government is strongly promoting heat pumps in order to reduce the air pollution caused by fossil fuel heating under the Air Pollution Prevention and Control Action Plan. There is a strong demand for having heat pumps suitable for operation down to -20 °C ambient temperature while delivering space heating water higher than 60 °C with good energy efficiency.

11.6 Heat pump market growth considerations

Considering the phasedown scenario established by the Kigali Amendment to the Montreal Protocol and the decarbonization movement, the market growth rates for heat pumps will have an important impact on the consumption (and use) of HFCs. At present, the main markets for water heating heat pumps are China, the EU, and Japan. Recent figures show that China accounted for approximately 60 % of the global demand of roughly 3.4 million units in 2019. A close look at this situation indicates that the market sizes for water heating heat pumps in the EU and Japan are small during their baseline years, compared to air conditioners with a global demand of 100 million units. Considering that the global market for water heating heat pumps has shown a double-digit growth rate for four consecutive years, however, the water heating heat pump market has the potential for rapid growth throughout the world. This means that higher GWP refrigerants will get a greater pressure for phaseout in order to achieve the necessary reductions. The heat pump industry, therefore, may face future shortages of HFCs unless it continues developing equipment using low-GWP refrigerants.

In the EU, water heating heat pump installation has been fostered through several directives and market incentive programs. Now that the EU is the biggest driver for pushing heat pump technology, the water heating heat pump market in the EU is expected to continue to have double-digit growth rate of 20 % further down the line leading to potential tripling its size in ten years, i.e., by the year 2030. With approximately 224 million residential buildings in Europe, on the other hand, its current market share in building stocks is estimated to be about 5 %. This may defeat EU climate targets which will anticipate at least a 40 % reduction in fossil fuel demand in contrast to a 20 % increase in electricity demand compared to the 2015 levels in residential buildings by 2030. Therefore, a higher market growth rate, which leads to a higher market size will be required. There is a high chance that water heating heat pumps market will become as large as the air-to-air air conditioners global market. In the EU, there is a strong demand for combined space and hot water heating heat pumps, where the majority of these heat pumps are using HFC refrigerants. Water heating heat pumps, therefore, may put a considerable strain on the HFC phasedown and cause shortages of HFC refrigerants. Whatever the refrigerant choice may be at the short term, heat pump manufacturers will have to focus on marketing high energy-efficient products. In addition, there is a tendency that residential water heating heat pumps and residential/light commercial air conditioners share the same component technologies to optimize the cost of the components and equipment. Consequently, if certain refrigerants were only used in heating only heat pumps, increases in the initial cost would be unavoidable.

In Japan, almost all the water heating heat pumps for residential use are heat pump water heaters, which heat water to 65 °C or higher for the use of hot water in kitchens and bathrooms. The cumulative shipments of this type of heat pump equipment reached 5.8 million units in 2018 (JARN, 2018), whereas its market share is just over 10 % of the water heating equipment including water heating gas equipment. Although the Japanese government expects the cumulative shipments of heat pump water heaters to double by 2030, this type of heat pump will have no impact on Japan's HFC phasedown because the (non-HFC) refrigerants R-744 or HC-290 are the refrigerants used. Recently, however, one can observe that there is a slight indication of an increasing growth of a residential hybrid system. This consists of a water heating heat pump using an HFC refrigerant and a high-efficiency gas heating system, even when there is currently no financial support for any hybrid systems. Although there is no doubt that more heat pumps will be used than ever before, air-to-air heat pumps are already prevalent for space heating and cooling in residential buildings except in part of the cold regions in Japan. Therefore, as long as Japan is implementing a plan to reduce the use of HFCs every year with more than 20 % of HFC quotas stipulated by the Kigali Amendment as reserves for any eventuality, the spread of hybrid systems only through market mechanisms will not have a significant impact on the HFC phasedown or cause a market confusion.

In North America, the penetration of "heating only heat pumps" has been traditionally very limited. However, several states have de-carbonization plans that will increase heat pump adoption. In California, the "low NOx" regulation is making the initial cost of boilers higher due to the required mitigation, thus reducing the installed cost gap versus heat pumps, particularly for new installations. In addition, California has committed by law to carbon neutrality by 2045, and it is clear that the transition from boiler/furnaces to heat pumps will be necessary to achieve that goal. New York State has also committed to 40 % emission reduction by 2030. Some local governments in the US (e.g., New York City, California) will offer incentives or require the use of heating only heat pumps instead of boilers. (California-NY, 2022)

In Article 5 parties, pre-charged equipment from non-Article 5 parties will dominate the market. The Kigali Amendment does not cover the consumption (import) of HFC refrigerants in pre-charged equipment. However, as certain quantities of refrigerant are needed to maintain and service the equipment, similar situations to those in the EU and Japan may occur. The rapid growth of the water heating heat pump segment, on the other hand, will create a high demand for qualified installers and a proper electric power supply. Therefore, not only skilled workers shortage but also power supply shortage could stall the spread of heat pumps in those countries.

11.7 Concluding remarks

At present, most heating only heat pumps make use of non-ODS refrigerants, including R-410A, HFC-32, HFC-134a, R-407C, R-454C, HC-290, HC-600a, R-717, and R-744. Emerging refrigerants are R-744, HC-290, HFC-32, R-454C, and R-454B.

The main parameters to select the refrigerant are efficiency, cost effectiveness, economic impact, safe use, and ease of use. From the ones mentioned above HFC-134a, R-744 and the HFC blends R-410A, R-407C and R-454-C are commercially available alternatives that have the highest grade of safety and ease of use. There is a growing tendency to change from the use of high-GWP to medium- and low-GWP refrigerants HFC-32, R-454B, R-454C, HC-290 and R-744. HFC-32 is already commercialised on a larger scale while for refrigerating circuits that are completely installed outside a building the trend is to use HC-290, as safety limits allow a sufficiently flexible installation. There is a continuing growth of R-744 heat pumps for global commercial applications, and also a growth of residential applications in Japan.

In some Article 5 parties, HCFC-22 may still be used, however, also in Article 5 parties replacements are commercially available, technically proven, and energy efficient and have a similar or lower environmental impact.

Due to the HFC quota requirements the current trend is to go to low- and medium-GWP alternatives such as HC-290 and HFC-32 in most of Europe. The temperature ranges in which HC-290 and HFC-32 can be operated are better than those for R-410A, moreover, their efficiencies are generally better – or definitely similar. The application of R-410A, HFC-32 or HC-290 is most cost effective when used in small- to medium-sized systems.

Replacing the refrigerant in existing equipment by another type of refrigerant is no common practice for heating only heat pumps. The loss in energy efficiency combined with liability aspects are not in favour of a refrigerant change. Proper use of reclaimed refrigerant may be the best alternative.

Since heat pumps are more material intensive than fossil fuel combustion boilers or direct electric heating, the material resource efficiency has to be considered carefully as this will influence the affordability. The selection of the refrigerant for a certain water heating application will influence both the material resource and energy efficiency as well as the life cycle climate impact.

At present, the main markets for water heating heat pumps are China, the EU, and Japan. Recent figures show that China accounted for approximately 60 % of the global demand of roughly 3.4 million units in 2019. A close look at this situation indicates that the market sizes for water heating heat pumps in the EU and Japan have been small in comparison to air conditioners with a global demand of about 100 million units.

Based on the tendency to decarbonize the water heating sector it is expected that the use of water and space heating heat pumps will show a substantial growth in the coming decades. It is also expected that the total market size may soon become as large as the one of the air-to-air conditioners.

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Chapter 12

Not-In-Kind Technologies

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12 Not-In-Kind Technologies

12.1 Introduction

Vapour compression systems have been the dominant refrigeration and air conditioning systems since the mid-20th Century. Vapour compression systems use natural refrigerants as well as synthetic refrigerants such as CFCs, HCFCs, and HFCs.

This chapter will look into technologies that do not employ mechanical vapour compression (MVC), or in-kind, technology and will explore those Not-In-Kind Technologies (NIK) that offer energy savings compared to vapour compression as well as compare their attributes and properties in a tabulated form.

In the text, technologies are classified as follows:

- Widely commercially available; these are technologies produced by more than one company.
- Commercially available; these are technologies produced by at least one company.
- Emerging; these are technologies that have been demonstrated through rigorous research and development phase and awaits product commercialisation.
- Research and Development (R&D); these are technologies going through active R&D and have not been fully established.
- Other technologies; these are NIK that have very limited use or that have not seen any recent development or application

12.2 Widely Commercially Available NIK Technologies

12.2.1 Thermoelectric

Thermoelectric cooling technology is currently less efficient than mechanical vapour compression. However, thermoelectric systems are simple and have an economic advantage over vapour compression systems for capacities requiring less than 50 W cooling and relatively small temperature lifts. It is expected that nanomaterials research may deliver better thermoelectric materials in the future and provide system efficiencies comparable to vapour compression systems.

The technology is commercialised in rather small applications in low efficiency systems. An application example is in cars for temperature-controlled seats, especially for conditions in High Ambient Temperatures (HAT). Spot cooling for electronics equipment, portable refrigerators, wine cabinets, and subcoolers to improve the efficiency of vapour compression systems. Small water coolers, compact refrigerators and portable coolers are also commercially available applications.

12.2.2 Evaporative cooling (with DX or chilled water coil)

In chapter 8, Indirect Evaporative Cooling is described as a cooling option for air conditioning systems. Evaporative cooling (EC) systems employ the evaporation of water in an air stream to generate a cooling effect and can be used for air-conditioning application, especially in dry climate locations, such system typically use electricity for the air circulation fans and water pump.

Indirect evaporator cooling (IEC) systems can be combined with a vapour compression system (DX arrangement) or with water cooled coils. The combination is in particular relevant for higher humidity ambient as the IEC can deliver cooling without raising the indoor humidity. Depending on the season, the IEC delivers a smaller or larger part of the cooling capacity required, hereby increasing the overall efficiency of the system. As the IEC cooling capacity increases generally with high ambient temperatures it can also reduce the maximum load to the DX or cooling coil, hereby reducing overall installation costs.

Modern IEC units with hybrid arrangement IEC-H, utilise reduced water consumption rates compared to early models. This technology is applied in HAT countries specially where humidity ratios are low in summer. There are several ongoing projects to test the comparative EER and refrigeration capacity of IEC-H unit compared to DX units in HAT.

12.2.3 Absorption heat pump

Absorption chiller/heater incorporate an absorber and a generator instead of a compressor and a motor used in MVC systems. This allows operation of the unit by heat instead of electric or mechanical motive power, thus allowing several forms of firing to operate the unit instead of electric/mechanical motive power.

The units can be direct fired (natural gas, light oil, heavy oil burners, etc.) or indirect fires (steam, hot water, recovered reject heat, etc.). In chapter 8, Absorption heat pumps are suggested as a cooling option with available refrigeration capacity for a combination of absorber-refrigerant pairs. The difference between COP of an absorption unit (heat ratio) and that of a vapour compression system is also shown.

12.2.4 Adsorption heat Pump

A typical adsorption technology uses a hygroscopic salt with high affinity to water as an adsorption media and water as the refrigerant. Adsorption units can operate in cooling or heating modes and have reported COP efficiencies for cooling of 0.5 to 0.7 and for heating 1.15 to 1.4. Those values are lower than comparable MVC although their ability to utilise low temperature hot water (e.g., down to 80 °C) is unique and makes them important in waste heat or solar thermal application. Although this technology is not very recent, it is nevertheless moving steadily in new areas of use especially in the heat recovery applications. Current range is 35 kW to 1,170 kW (10 to 330 TR), a smaller range than that of absorption units.

12.2.6 Brayton-Cycle heat pump for transport, refrigeration, and process cooling

The reversed-Brayton cycle is based on a gas cycle where the gas is first compressed, then cooled down and expanded and finally passes through a heat exchanger in order to cool an object or space. When air is used as the working fluid, it can be directly supplied into the space being cooled (open cycle). The Brayton cycle is not new and has been commercialised for use in aircraft air conditioning systems, in the liquefaction of natural gas to transport from upstream liquefaction plants to degasify and pump downstream to consumers.

It has also been used in lower temperature refrigeration in applications such as batch blast freezing and freezing tunnels as well as low temperature cold storage and cryogenic cooling.

12.3 Commercially Available NIK Technologies

12.3.1 Ejector Heat Pump

The ejector heat pump uses an evaporator and condenser as in a regular MVC. but instead of a compressor uses an ejector to drive the refrigerant. The operation of the ejector is based on the venturi effect of a converging-diverging nozzle to convert pressure energy of a moving fluid into kinetic energy in order to entrain the suction gas leaving the evaporator. The mixed fluids are then recompressed by converting kinetic energy back into pressure in the diffuser part of the ejector and flows towards the condenser.

The COP of ejector heat pumps is generally lower than MVC or thermally activated systems, which makes it difficult for the technology to have market penetration. Nevertheless, the technology has undergone a transformation lately because of its ability to use heat recovery to drive the system. Effort is made to use ejector technology with CFD analysis and refrigerant optimization in prototype constructions. Although the ejector cycles use the same refrigerant for both primary and secondary flow, binary mixtures are being tested to improve cycle performance.

12.3.2 Stand Alone Solid Desiccant

Stand-alone solid desiccant is used as an alternative to absorption or adsorption units and employ a solid desiccant which absorbs moisture from an air stream, which is thereby dehumidified. The desiccant is subsequently regenerated applying heat from e.g., a warm air stream, this process is typically handled in a desiccant wheel. The dehumidified (dry) air is cooled in a series of heat exchangers and eventually led into the room.

Low-grade heat (temperature of about 60 to 95 °C) regenerates the desiccant. Renewable energies may be used for regeneration. Solar energy as well as geothermal energy are used as well as conventional fossil-fuel systems waste heat. When waste heat or solar energy are used for regeneration, COPs could be superior to those of MVC systems. With low grade energy the system's COP is comparable to those of vapour compression.

12.3.3 Stirling cooler

The Stirling cooling cycle alternately compresses and expands a fixed quantity of gas (usually helium) in a closed cycle. The compression takes place at a high temperature to facilitate the discharge of heat caused by compression, whereas the expansion is performed at the low temperature required by the application. The cycle typically employs a piston and a displacer with a phase shift between these two moving parts.

The Stirling cooling cycle has traditionally been used in low temperature applications as in liquid air production or niche applications, such as sensors cooling. To date also commercial applications have become available in ultra-low temperature freezers ranging from -160 to -80 °C where the technology can compete with cascaded vapour compression systems or auto-cascade systems.

12.4 Equipment in the emerging phase

12.4.1 Stand-alone liquid desiccant AC

Similar to Stand Alone Solid Desiccant AC except that the desiccant is liquid which provide more flexibility to the system. It has similar COPs to the solid variant. An advantage of liquid desiccant technology is that it can deliver drying without cooling which is, especially at moderate temperatures / high humidity conditions, more efficient as DX systems

12.4.2 Evaporative Liquid Desiccant Air Conditioner AC (development status: emerging)

Because indirect evaporative have limited dehumidification potential is humid areas, without a DX or chilled water coil in a hybrid arrangement, they are used primarily in lower humidity regions. This system uses evaporative cooling as well as liquid desiccant technologies. This technology combines the benefit of liquid desiccant and evaporative cooling technology. It has potential to achieve reduction in energy consumption of 39 to 84 % compared to MVC.

12.5 Equipment in the Research and Development phase

12.5.1 Magnetocaloric

The magnetocaloric effect is the basis of this technology, where paramagnetic materials show reversible temperature change if exposed to a changing magnetic field. This generally means that the material needs to be exposed to an alternating high or low temperature air or liquid stream which can be achieved by rotating devices or switching valves. This inherently reduces efficiency. Further the materials operate at a specific temperature difference making it less flexible to varying operating conditions. Better materials are being developed partly offsetting these effects [IIR 2022].

Magnetocaloric technology can be used for cooling, heat pumps as well as for air-conditioning applications. At least one manufacturer has the technology available. Magnetic cooling is further applied at extremely low temperatures (e.g., below 1 K). Magnetocaloric technology is reported to have the potential to reduce energy consumption of 20 % when compared to mechanical vapour compression.

12.5.2 Membrane Heat Pump

Membrane technology for air conditioning provides dehumidification of the space using a special polymer membrane to separate moisture from air. Dehumidification by an MVC is associated with cooling the air which can make the membrane technology more efficient if no sensible cooling is required. Polymer membranes were developed originally for the filtration and purification of sea and brackish water or for enthalpy, wheels for recovering exhaust air.

12.5.3 Thermoelastic

The technology uses Shape Memory Alloys (SMA), which are alloys such as nickel titanium alloys (NiTi) which when mechanically stressed will go into a solid-to-solid phase transformation and reject heat. The phenomena are reversible and SMA absorb heat as they return to their original shape [IIR 2022]. Plans are underway to develop a window air conditioner. A car air conditioning prototype based on thermoelastic technology is also planned . This p technology is in its early stages of research and development. It has a projected COP of 6 compared to COP of 3 for MVC.

12.5.4 Ground-Coupled Solid Desiccant AC

Ground coupled solid desiccant cooling technology is in its R&D stage. The operation is made by coupling an open cycle desiccant assisted air conditioning system with borehole heat exchangers.

Electricity demand of the system can be reduced to the consumption of the fans, wheels, and pumps. Electric energy efficiency ratio of 6.63 are reported, enabling electricity savings of more than 70 % compared to a conventional system and 54 % compared to a desiccant assisted hybrid system relying on an electric chiller. (Speefork et.al, 2016)

12.6 Other Technologies

12.6.1 Thermoacoustic

Thermoacoustic technology uses sound waves to cool or heat air. The sound waves have pressure oscillations, which causes gas to compress and expand. Compressed gas heats up while expanded gas cools down. There are two types of Thermoacoustic units: standing wave and travelling wave. A noble gas is used in those units.

Only one thermoacoustic product is commercially available; a cryogenic freezer. Thermoacoustic technology is better suited for refrigeration applications rather than air conditioning. Efficiency figures are not yet available.

12.6.2 Vuilleumier Heat Pump

In the duplex Stirling concepts, a Stirling engine drives a Stirling heat pump, which is similar to the Stirling cooler described before, in one assembly. It typically has 3 moving parts: one piston and two displacers. The system is typically heat driven.

The Vuilleumier heat pump can be seen as a variant of the duplex Stirling concept but has only two moving parts both usually called displacers.

This technology is reported to have a COP for heating of 1.6 to 2.2 and a COP for cooling of 0.8 to 1.2. The technology may provide primary energy saving of 26 % for heating over electrically driven MVC which of course depends on the local Primary Energy Factor

12.7 Special Applications

Deep Sea Cooling is a relatively new technology that uses the cold-water temperature of the seas, at great depths, to cool chilled water of a centralized or district cooling system. The main advantage of this technique is that may consume down to a tenth energy consumption compared to In-Kind technologies. Low temperature water is used for direct cooling applications. Ocean water can be tapped at 7 °C at a depth of 500 m as shown in Figure 12-1.

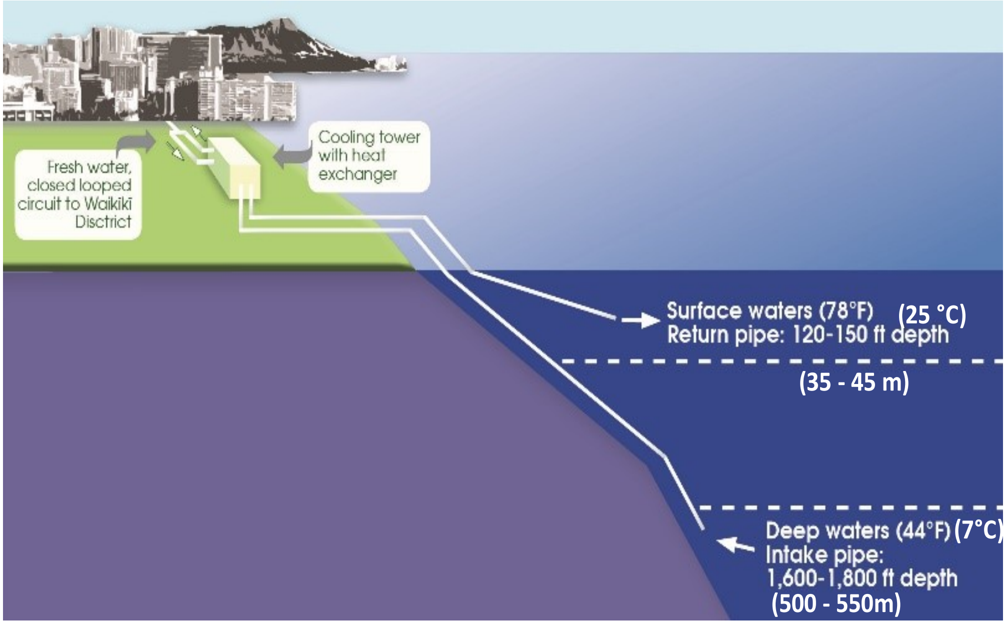

Figure 12-1: Typical DSC piping and DC station system schematic diagram

12.7.1 Oceans photical and aphotical depths

Oceanographers divide the ocean into categories by depth. The broadest category is the upper part of the ocean known as the photical zone. This is generally regarded as the upper 200 meters of the ocean where sun light penetrates, and photosynthesis takes place. The bottom part of the ocean is called the aphotical zone where sunlight does not add heat and cold temperatures are present. Bathymetry and oceanography studies suggest that at an ocean depth of at least 1000 meters, 4 °C water temperature is assured. It should be noted that 4 ºC temperature might also be available at depths of 500 to 900 meters depending on the deep-sea currents. Diligent temperature studies, by Remote Operated Vehicle (ROV) and shore seismic studies, need to be conducted as part of overall study preceding a proposed project.

12.7.2 Laying piping from shore to sea; horizontal directional drilling (HDD)

There are a number of problems associated with laying a pipe to access cold water from shore to the required depth. The tide action might dislodge anchoring blocks of the piping, especially with high seas. Coral Reefs and seabed marine life may also be affected.

Often Horizontal Directional Drilling techniques (HDD) are used from the shore with DSC in conjunction with laying pipes supported with anchoring blocks at certain depths. HDD is a mature technology used in the Oil and Gas field. This technique enables directional drilling under the surface from the shore to access deep cold water with a horizontal displacement of up to eleven kilometres from shore. A rig could also drill a diagonal tunnel of suitable diameter to bring cold seawater to the surface. Using heat exchangers between the cold seawater and a chilled water system, temperatures of 5.5 to 6.5 °C could be achieved at the fresh chilled water network. Similarly, the rig would also drill suitable tunnel to return heated water to a suitable depth.

12.7.3 Environmental Permits

Environmental permits may be difficult to obtain. This is because returning seawater to the sea must be at depth strata where the seawater temperature is the same as that of the returning water. The use of diffusers in the pipes to reduce speed of the water is important so that the plankton and other living organisms are not affected. This assures conservation of the sea microorganisms. Environmental studies are also concerned with the preservation of coral reefs and algae. Often environmental permits will suggest solution to the piping layout to help conserve the local ecosystem.

12.7.4 DSC systems in operation

Cornell University's Lake water cooling system is the largest and oldest in the United States.

Toronto city in Canada, launched its lake water cooled system in 2004. It now cools over 100 downtown buildings, ranging from City Hall and Toronto General Hospital to hotels and a brewery. Toronto's system utilizes three supply pipes of 5.5 km length south of the city and 100 m underwater, in the depths of Lake Ontario where the water remains cool year-round.

It should be noted that in the middle and the far east, where the sea is sometimes warmer compared to northern latitude, care should be given to conduct ROV studies to confirm depths at which water temperatures are within 6 to 8 °C therefore suitable for chilled water applications. It may be necessary when water is warmer to use in series chillers to get to the required design conditions. Capital costs of DSC system is often 1.5 to 2 times higher than that of conventional DC systems. However, the low operating costs are such that the difference in capital cost is recuperated in a short number of years, making the net present value of the system over its expected lifetime lower than that of conventional systems.

12.8 Reported efficiency of NIK technologies

Table 12-1 lists some of the reported COP of different NIK along with vapour compression systems COP.

Table 12-1: COP of some NIK technologies compared to IK technologies

Technology	**COP**	**Test or Operating Condition**	**Reference**
VCS R-410A Split A/C	4.11	AHRI B condition at 27.7 °C	U.S. EIA, 2019
Absorption LiBr/Water A/C	1.10	AHRI B condition at 27.7 °C	Ananthanarayanan, 2021
Thermoelectric A/C	0.86	Modelling for AHRI B condition 27.7 °C	ORNL, 2000
Stirling Cycle A/C	0.93	Modelling for AHRI B condition 27.7 °C	ORNL, 2000
Brayton Cycle A/C	0.98	Modelling for AHRI B condition 27.7 °C	ORNL, 2000
Transcritical CO_2 A/C	2.32	Data for AHRI A condition 35 °C	ORNL, 2000
VCS wine cooler R134a	0.70	Cabinet at 12 °C	Maleski et al 2021
Magnetocaloric wine cooler	0.40	Cabinet at 12 °C	Maleski et al 2021

It should be emphasized that the COPs reported are currently published figures at testing conditions that may or may not be at variance with established comparative data but are the nearest reported data to commercially established conditions.

The COP of absorption lithium bromide-water chillers are actually heat ratios. When compared to the COP of MVC, such as VCS R-410 A, which are net refrigeration capacity divided by the work exerted by the unit, one should take into consideration that the work exerted are attributed to its original state at the power station where it was produced.

Taking these factors into consideration, NIK technologies such as thermoelectric AC, Sterling cycle AC, Bryton cycle AC and magnetocaloric may have a lower COP compared to MVC. Nevertheless, they fill an important place in niche markets.

12.9 Concluding remarks

NIK technologies are classified in four stages of development: widely available (more than one manufacturer), available (one manufacturer only), emerging and promising – not yet ready for manufacturing and in the Research and Development (R&D) stage.

There are four widely available technologies, where three of those are for large and small applications- absorption, adsorption, and direct/indirect hybrid – and one for small application- cryogenic.

Operational Lifetime Cost (OLC) comparisons are shown for 17 widely available technologies. Twelve NIK combined technologies of these are compared with five MVC technologies. Of the twelve NIK technologies exhaust recovery evaporative cooling with desiccant medium and direct/ indirect evaporative cooling show the best OLCs, although the second is for central AC only.

Implications of NIK technologies on SDGs and the cold chain for the Kigali amendment, are shown. For the cold chain, the effect is not evident yet as refrigeration NIK technologies are not yet well established.

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Chapter 13

Servicing and refrigerant conservation

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13 Servicing and refrigerant conservation

13.1 Introduction

Past assessment reports have dealt with servicing and refrigerant conservation in a variety of ways. Refrigerant conservation had a chapter dedicated to the subject until 2014 when it became part of the sustainability chapter. Servicing, on the other hand, did not have a dedicated chapter and was viewed in light of reducing emissions as part of refrigerant conservation.

Under the Montreal Protocol, servicing is one of two sectors eligible for funding in phaseout plans, the other is manufacturing. Servicing was also introduced in reports on Decisions XXIX/10, XXX/5, and XXXI/7 as a factor affecting the energy efficiency of equipment and systems over their lifetime.

Refrigerant conservation was previously discussed through the concept of the three (R)s: reduce, recycle, and reuse. Recovery, recycling, and reclamation is an efficient way to reduce consumption of virgin refrigerants. HCFC-22 phaseout management plans mostly contained initiatives related to recovery, recycling, and even reclamation. As pointed out in MCTOC 2018 Assessment Report (MCTOC, 2018), destruction of recovered or impounded refrigerants is not a mandatory obligation under the MP except for purposes of claiming a benefit within the definition of production when reporting under Art. 7. It is rather limited to otherwise being just encouraged on a best-efforts basis and remains a challenge where a sustainable mechanism to collect, recycle, or destroy refrigerants is needed. The barriers are informational, financial, technological, and legal which can be overcome through the creation of a mechanism for ODS waste management with financial incentives as stated in section 13.3.3. For complementary information on end of life and destruction issues, refer to the MCTOC 2022 Assessment Report.

This chapter introduces aspects of safety and refrigerant conservation that were not fully discussed in previous reports and links those aspects to the sustainability development goals (SDG) adopted by the United Nations in 2015. Aspects like effect on energy consumption, probable impact on the environment, and gender issues in a socially balanced technicians' workforce are discussed for servicing. Refrigerant conservation introduces aspects on circular economy and market mechanism to enhance conservation, along with infrastructure and barriers to the implementation of initiatives. Some of these aspects are complimentary to those discussed in Chapter 2 on sustainability.

The chapter is in five sections dealing with servicing, refrigerant conservation, education, training & certification, links to SDGs, and high ambient temperature effects on service.

13.2 Servicing

Servicing, as defined by the Montreal Protocol, includes installation, maintenance, repair, and disposal /destruction at the end-of-life covering the life cycle of equipment. Proper servicing affects emissions of refrigerants with their impact on the ozone layer, which is the preoccupation of the Montreal Protocol, and on climate change due to their global warming potential. Servicing also affects the indirect CO_2 emissions from power needed for the operation of air conditioning and refrigeration products and systems. The effect of proper servicing on energy consumption is discussed in sub-section 13.2.3.

Servicing is the application of good practices in a safe and efficient manner using the proper tools for the issue at hand. To acquire good practices, a service technician should have the proper background technical education and adequate training on a continuous basis to absorb the knowledge of new refrigerants and technologies, enhance energy efficiency, and understand the emerging field of Internet of Things (IoT). This process is not static as technologies evolve and systems change, and technicians keep abreast by being aware of the technology evolution and by upgrading their knowledge and skills through additional training.

There is a need for additional qualification of personnel and guidelines for those aspects of the life cycle such as transport, warehousing, service, and end-of-life management that are not covered by product safety standard.

Not all technicians are capable of achieving this continuous upgrade of skills on their own or through their employers. A large portion of service technicians are employed in what is known as the informal sector which includes the transitory workforce who are only active during peak seasons, and those technicians who are employed by parallel trades such as car repair garages that double as AC repair shops when needed.

The market readiness to accept new products and technologies depends to a large extent on training and certification of the technicians who will install, maintain, and repair the new products. Market readiness affects the accessibility to new technologies and the ability of markets to introduce products that can meet higher energy efficiency standards.

Formalizing the workforce is an important aspect of a good service set-up especially in Article 5 parties. This acquires additional importance when the aspect of safety at the workplace, which is connected with the newer flammable refrigerants, is taken into consideration. The informal sector may pose a challenge both to the industry, through the propagation of uninformed practices, and to the environment, through the unnecessary emissions related to bad practices.

Regulating servicing through certification thus acquires an added importance. This is discussed under section 13.4 along with training and education.

13.2.1 Installation and commissioning practices

The first functional definition of air-conditioning, which was created in 1908 and is credited to G. B. Wilson (ASHRAE, 2022), reinforces the importance of good installation. The definition includes maintaining suitable humidity in all parts of a building and supplying a constant and adequate supply of ventilation to efficiently remove micro-organisms, dust, soot, and other foreign bodies from the air. These factors are all attributes of a good installation.

Proper installation and commissioning ensure the efficient operation of RACHP systems and reduces or delays the need for repairs and service. Trained technicians, following proper practices, are key for all applications, from small residential units to large central systems including district heating or cooling projects.

Safety precautions, as per standards, should be followed whenever activity related to servicing is carried out. For example, manufacturers' guidelines and standards should be followed during the process of site selection for equipment installation to prevent the possibility of refrigerant leakage. Manufacturers may further limit installation options beyond the safety standards requirement.

Improper installation will result in deviation from the design performance. Inadequate air flow over the condenser heat exchanger results in higher operating pressures and the stressing of joints leading to premature failure of the heat exchanger, compressor, or joints. Other problems include reduced system efficiency, a shortened system life span, and decreased indoor comfort through uneven heating or cooling in the conditioned spaces. Poor installation can cause even high-efficiency units to waste energy.

Air-conditioners are installed in various outdoor environments which can be challenging in corrosive environments like seashore applications where outdoor units are subject to saline atmosphere, or near chemical plants, animal farms, or even open sewage lines due to the presence of hydrogen sulphide H_2S (Tran, 2003). Corrosive environments impact the life of the heat exchangers requiring additional treatment to protect the coils. The normal fin and tube heat exchangers have aluminium fins and copper tubes which can corrode where the two metals are connected thus reducing heat transfer and impacting energy consumption. For these environments, proper measures should be taken to prevent corrosion.

To comply with city bylaws, split system air conditioners are sometimes installed in confined spaces such as inner light wells which are sheltered from wind to carry away the rejected heat. Studies have shown that the temperatures in the void space increased continuously along the height of the building by 10 –13 °C, showing a significant stack effect from the rejected heat from condensing units. A study has shown that temperatures of around 50 °C at the inlet of the condensing units for floors 10 and above are the combined result, reducing the unit efficiency by around 30 % compared to the undisturbed design case. This significant effect is completely neglected in building design and performance evaluation, and only with an integrated design process can truly efficient solutions be realised (Marcel Bruelisauer, 2014)

13.2.2 Refrigerant retrofit, drop-in and conversion

Switching to medium and low GWP refrigerants for new products is important for the reduction of HCFC consumption and HFC climate impact; however, that is not necessarily sufficient. It is also necessary to address refrigerant emissions due to the service of refrigeration and air conditioning equipment already installed in the market. One of the important means is retrofit; however, retrofitting cannot be performed for all refrigerants, and several factors must be taken into consideration including flammability, toxicity, and compatibility of the components. Pressure characteristics should also be considered when selecting a replacement refrigerant with a significantly different pressure than the original one to avoid loss of performance when the pressure is lower or excess stress with higher pressures. Those refrigerants that meet the criteria are recognized as retrofit candidate refrigerants.

It is recommended that retrofitting not be performed on units with burnt compressors as this presents different challenges for the equipment due to the residues from the burnout. If recovered refrigerant collected cannot be reclaimed to original conditions, it should be sent for destruction (Environment Canada, 2013).

There are also legal implications to retrofits. Some countries consider the entity performing a retrofit as having the same legal responsibility regarding warranty as the original equipment manufacturer as shown in the case study Case Study 13-1 below

Case Study 13-1: Legal Implications of refrigerant retrofit

CASE STUDY – Legal implications of refrigerant retrofit
Country - Japan
The law: In Japan, the High-Pressure Gas Safety Act is a law that guarantees the safety of refrigeration and air conditioning equipment mainly for commercial use. Based on this law, retrofitting is not always possible at present. A technician who replaces a refrigerant is by law considered having the same responsibilities and liabilities as the manufacturer of the equipment. The technician is required to comply with the obligations on safety and affixing new labels on the retrofitted unit.
Caveat: Japan is considering the relaxation of the law since technicians have become reluctant in performing this activity thus depriving the market of a means to reduce consumption of certain refrigerants.
Conclusion: It is necessary for technicians and service companies to thoroughly check the safety laws in each country and region, and for authorities to take measures or amend the law to ensure market compliance while preserving the accessibility of customers to this service.

Labels should be affixed on retrofitted units to reflect the changes to the unit, which brings out the question as who can issue the new label and whether a service company has the legal right to affix a label to a unit originally manufactured by another entity. Some countries have started adding the GWP of refrigerant labels which presents an opportunity for incorporation on retrofitted labels noting that the label design and information included is the responsibility of regulators and/or standards' bureaus.

Regarding energy efficiency, the use of reclaimed refrigerant, instead of using a drop-in one should be considered as an option to keep the energy efficiency of the product as designed.

Retrofitting equipment could, unwantedly, extend the life of old, inefficient equipment and can have a positive or negative impact; consequently, retrofitting should be considered carefully in policymaking.

13.2.3 Effect of service on energy consumption

The Energy Efficiency Task Force (EETF) on Decision XXIX/10 concluded that the impact of proper installation, maintenance, and servicing on the efficiency of equipment and systems is considerable over the lifetime of these systems while the additional cost is minimal (EETF, 2018). Actions such as optimization, monitoring, and regular maintenance can help in preventing the degradation of energy efficiency contributing to the savings in CO_2 emissions from the use of power to run these units.

The effect of fouling on heat exchangers has been documented since at least 1993 when a simulation on the effect of partially blocked condensers on a 10 kW vapour compression system was made and reported that the efficiency was predicted to decrease by 7.6 % when the air flow across the condenser was reduced by 40 % for a constant-speed fan (Bultman, 1993). A more recent study found that performance degradation of the evaporator often has a larger effect on compressor power requirement while that of the condenser has an overall larger effect on the efficiency (Qureshi, 2011). Generalized results showed that for the systems equipped with fixed orifice expansion valves, a 10 % reduction in condenser airflow caused a 0.8 % reduction in capacity and a 2 % reduction in efficiency, whereas a 50 % reduction in condenser airflow caused an 11 % reduction in capacity and a 25 % reduction in efficiency; however, a 2019 study found that fouling does not have a significant effect on coil's heat transfer capacity, hence system efficiency, even though it significantly decreases the coil's airside pressure drop (Mehrabi, 2019).

The drop in system efficiency will increase when adding other factors such as inadequate design and wrong installation to improper maintenance. Energy Star program (EPA, 2009) demonstrates the effect of bad design and installation on system efficiency for ducted residential applications. In the Figure 13-1, a duct air leakage (shown on the chart as system leakage) due to bad maintenance can affect the system performance by up to 15 %; however, if incorrect sizing is added, the effect goes up to 20 % and can reach 27 % when incorrect refrigerant charge and low airflow are added. A loss in performance is translated into efficiency loss as the system continues to draw full power.

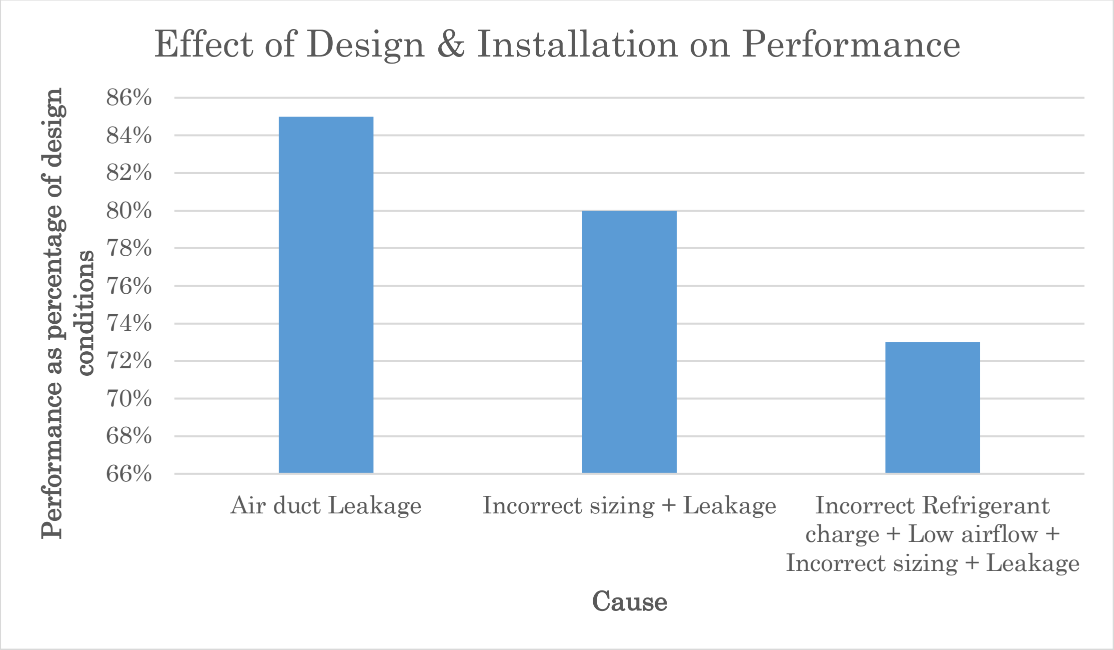

Figure 13-1: Reduction in performance due to bad design and installation techniques
(EEA, 2019)

Previous metrics developed for the US department of Energy had estimated an annual degradation rate of about 3 % for unmaintained systems (Hendron, 2006). Hendron developed an equation which was adopted as a benchmark:

$\mathrm{SEER}^{20}{}_{\mathrm{degrade}} = \mathrm{SEER}_{\mathrm{nominal}} * (1\text{-}M)^{\mathrm{Age}}$

Where SEER is seasonal energy efficiency ratios, M is the maintenance factor, 0.01 for expertly maintained equipment and 0.03 for unmaintained; and Age is equipment age in years.

A study of 56 homes in Florida found that equipment with higher SEERs have lower rates of degradation (Fenaughty & Parker, 2018).

In 2020, the EETF on Decision XXXI/7 added that there is a lot of advice on the effect of servicing on the degradation or maintenance of energy efficiency, but that there is little data or measurement of those effects. What is needed is a tool “to enable policymakers estimate the scale of energy losses as a result of poorly installed or maintained refrigeration and air conditioning equipment in order to assess the cost and benefits of mandating improved maintenance and installation of air conditioning equipment.” (EETF 2020).

In 2021 The Australian Department of Agriculture, Water, and the Environment commissioned a study on leaks, maintenance, and emissions in refrigeration and air conditioning equipment (Brodribb, 2021) to explore opportunities to reduce emissions from refrigerant leaks and unnecessary electricity consumption due to faults in the installation, operation, and maintenance of stationary refrigeration and air conditioning equipment. The study found that “losses of refrigerant from operating RAC equipment was responsible for approximately 1.2 % of national emissions in 2019. However, in that year RAC equipment was estimated to consume more than 24 % of all electricity generated in the economy, resulting in a combined total of direct and indirect emissions of 61.28 million tonnes carbon dioxide equivalent (Mt CO_2e) or approximately 11.5 % of national emissions.” The study concluded that, “there is significant potential to reduce the electricity consumption and leaks

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[20] SEER = Seasonal Energy Efficiency Ratio defined as the ratio of the cooling output of an air conditioner over a typical cooling season, divided by the energy it uses in Watt-Hours.

of refrigerant from large stocks of RAC equipment if that equipment was subject to more frequent maintenance.”

Document UNEP/OzL.Pro/ExCom/86/13 analysed activities related directly or indirectly to the improvement of energy efficiency of serviced RAC equipment and/or reduction of GHG emissions and concluded that the largest potential to improve energy efficiency comes from total system design and component improvement, which can improve efficiency up to 70 %. On the other hand, the proper installation, configuration, maintenance, and servicing of RAC equipment has a significant impact on the efficiency of equipment and systems over the lifetime of these systems with minimal additional cost. Appropriate maintenance and servicing practices can curtail up to a 50 % reduction in performance and maintain the rated performance of the equipment over its lifetime (UNEP, 2021b).

13.2.4 Safety during servicing

Irrespective of the type or refrigerant used, safety aspects such as frost bites, direct inhalation, etc. during service has always been a primary concern. Even class A1 refrigerants can be hazardous in a confined environment if they reach a certain concentration. With the introduction and increasing use of class A2L and A3 refrigerants, and the dominant position ammonia is having in the industrial refrigeration sub-sector, the focus on safety practices has also increased. Training of technicians in proper safety techniques is included in many HPMPs and will hopefully be continued in the HFC phasedown initiatives.

ISO 5149-4:2014 and EN 378-4 specify requirements for safety and environmental aspects in relation to operation, maintenance, and repair of refrigerating systems and the recovery, reuse, and disposal of all types of refrigerants and oils. These requirements are intended to minimize risks of injury to persons and damage to property and the environment resulting from improper handling of refrigerants or from contaminants leading to system breakdown and resultant emission of the refrigerant.

There is not much data published about the frequency of servicing and its impact on reducing risks of flammability during servicing or maintenance. GIZ issued guidelines on the safe use of hydrocarbon refrigerants (Croiset, 2012) which includes elements of a safety management system. Other GIZ guidelines are for safety in refrigeration and in production rooms. Refrigerants Australia is planning[21] to launch a project to analyse data from years of actual service visits by a nationwide company to study the effect of inspection visit frequency on leaks and other factors which can affect safety.

Quantitative risk analysis (QRA) associated with refrigerant handling during servicing and maintenance activities on systems using flammable refrigerants is based on identifying a set of standard tasks, for example area preparation, recovery, etc., and corrective actions, like evacuation, charging, testing, etc. to ensure that the system works in a normal and safe way. Event tree analysis (ETA) is used to identify the combinations of sequence of events that may lead to a release of refrigerant and an active source of ignition that could result in ignition and eventually the probability of ignition and severity of consequences. The three events that lead to the greatest flammability risk are opening/accessing the system, charging refrigerant, and closing/sealing the system. It is also crucial to have the requisite tools available for carrying out the higher-risk tasks correctly (Colbourne, 2011). It is important to conduct life-cycle risk assessment across the life cycle. i.e., use-phase, servicing, transportation, storage, disposal etc. For example, servicing is one of the riskiest phases in all life cycle when using flammable refrigerants. Risk mitigation varies from region to region with a need to conduct thorough risk assessment for servicing in each region

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[21] Information is based on discussions between authors and representatives of Refrigerants Australia

13.2.5 Tools and good practices

Good practices guides and codes are part of the initiatives that were started with the CFC phaseout and continued with the HPMP. The structure of these guides and codes needs to be revised to reflect the reality of dealing with flammable and toxic gases.

In 2016, OzonAction issued a quick pocket guide on "Good Servicing Practices for Flammable Refrigerants" (OzonAction, 2016). A mobile App (8017Smartapp2.pdf (unep.org)) is also available offering an easy reference to the key safety classification and technical properties of flammable refrigerants that are available in the market. It also provides important safety guidance for the installation and servicing of room air-conditioners designed to use flammable refrigerants.

Refrigerant-related servicing requires tools for recovering refrigerant from refrigerant pipes connected to the installed equipment and conversely to fill the installed refrigerant pipe with a predetermined amount of refrigerant. Tools are also required to connect piping to the units mainly through flare connection or brazing. Specialized skills, knowledge, and experience of the technicians are required; nevertheless, the use of the right tools for the right refrigerant is equally important due to the difference in pressure.

Table 13-1 below shows a list of tools and equipment to be used with the different refrigerants (JRAIA, 2016).

Table 13-1: List of tools used for the different refrigerants (JRAIA, 2016)

Tools, etc., to be used	**Purpose**	**Notes**
Manifold gauge	Evacuating, refrigerant filling & operation check	- Suitable type is required for each refrigerant according to pressure [a)] - Use of 4-valve manifold gauges for A3 refrigerants
Charging hose		Suitable type is required for each refrigerant [a)]
Refrigerant filling scale	Refrigerant filling	Can be used in common for all refrigerants
Refrigerant leak detector	Refrigerant leakage check	- Suitable type is required for HCFC-22. - Can be used in common except HCFC-22
Vacuum pump	Evacuating	- Suitable type is required for HCFC-22 - Can be used for the refrigerants with reverse flow prevention adapter [b)]
Vacuum pump with reverse flow prevention feature	Evacuating	Can be used in common
Flare tool	Flare processing of pipes	- Suitable type is required for R-410A and HFC-32 - Can be used with installation of adapter
Chamfering tool [c)]	Flared section chamfering	Can be used in common
Bender	Pipe bending	Can be used in common
Expander [d)]	Pipe flaring (Brazing)	Can be used in common
Recovery device	Refrigerant recovery	Suitable type for each refrigerant
Recovery container	Refrigerant recovery	Suitable type for each refrigerant
Refrigerating machine oil [g)]	Applied on the inside of a flare	Refrigerating machine oil designated by the equipment manufacturer
Torque wrench	Flare nut fastening	- Suitable type is required for R-410A and HFC-32 - Can be used with installation of adapter
Pipe cutter	Cutting pipes	Can be used in common

Tools, etc., to be used	Purpose	Notes
Refrigerant container [e)]	Refrigerant filling	Suitable type for each refrigerant
Charge port & gasket [f)]	Refrigerant filling	Suitable type for each refrigerant
Brazing/welding machine & nitrogen gas	Pipe welding	Can be used in common

Note[a)] *Pressure gauges and associated hoses should be selected according to the specifications of the refrigerant.*

Note[b)] *Vacuum pump without reverse flow control should not be used because it will cause the flow of lubricant (mineral oil) to reverse within the pump, mixing with synthetic oil and causing contamination.*

Note[c)] *Chamfering tools (reamer & scraper)*
· Reamer: Be sure that the blade does not crack, and uniform chamfering is possible.
· Scraper: Be sure that uniform chamfering is possible.

Note[d)] *Brazing tools*
Tools capable of processing to satisfy standards for gap in fitting and length of contact must be used.

Note[e)] *Refrigerant container to show the name of the refrigerant on the outside. Container colours specific to refrigerants.*

Note[f)] *Manifold tools and hose suited to HFCx to be used (older-type hose not to be used with HFC if there is possibility of slow leak). Also, use of appropriate tool is recommended for hose attachment and removal at servicing, to prevent leaking.*

General note: Instruments such as gauges, thermometers, and torque wrenches should be calibrated and monitored for variations

13.2.6 Probable impact on environment

Servicing is a critical element which might contribute to the pollution of the environment through actions and sub-standard practices creating a risk for emissions of substances. These practices can be rectified through actions, as per examples below, which are valid for any type of refrigerant.

- Cleaning of heat-exchangers that may cause abnormal pressures in the circuit;
- Checking oil quality and eventually replacing it;
- Monitoring or regular checking of normal operational parameters of the refrigerant circuit;
- Replacing malfunctioning equipment or modifying the installation;
- Recovering refrigerant and/or oil.

The pollution may not be limited to emissions to the atmosphere but can affect rivers, sea, ground, and underground water sources when heat exchangers use the ground as energy source or storage. On the other hand, regular service and inspection is essential to avoid sudden uncontrolled leaks. It is known that lack of regular inspection may create dangerous situations and pollutions. The example of the Philippine ice plant suspected pipe leak leaving two dead and 90 sickened in 2021 (AP News, 2021) is a case in point. Accidents were also reported in non-Article 5 parties; Canada reported an incident at an ice rink plant in which a pinhole in a tube led to a leak with a high concentration of ammonia that resulted in three casualties (IRSL, 2018). Regular inspection and control result in lower emission of refrigerants. As such, it is essential to provide proper training on good servicing practices and regular inspections.

Regulation on servicing enhance the adoption of good practices. In Europe, EU regulation 517/2014 (EU, 2014) the latter dated April 16, 2014, on fluorinated greenhouse gases are in place to avoid emissions of certain fluorinated greenhouse gasses but are not applicable to other refrigerants and oils that may create pollution as well. Recovery of some refrigerants may not be required from a climate change point of view; however, it is recommended to recover them from the perspective of safety, or where there are potential concerns about VOC, or TFA[22].

Standard EN 13313:2010 (Refrigerating systems and heat pumps- Competence of personnel) provides guidance for competence of personnel for refrigerating systems and heat pumps. The new standard describes the subject and activities to be assessed and the required level of expertise, differentiating between the theoretical and practical assessments. An ISO version of the standard is under preparation under ISO Technical Committee TC86/SC1 as standard ISO/DIS 22712 - Refrigerating Systems and Heat Pumps - Competence of Personnel (ISO, 2021). This standard contributes to SDG 9 on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation.

The cost of refrigerant is another factor: when refrigerants are relative expensive, it is normal that the handling is done with higher care due to economic consideration. This may be one of the reasons why the demand for service is reduced in Europe for certain greenhouse gases as the price has increased up to 13 times (EU, 2020).

13.2.7 Spare parts

Ensuring the availability of spare parts on the market and equal accessibility to all is the responsibility of the manufacturer towards the end customers. Manufacturers are responsible for ensuring that spare parts and repair facilities for products are available for a reasonable time after purchase. Manufacturers should not impose restrictions in the form of price barriers or other means in order to monopolize the supply of spare parts or the service of their products.

Additionally, and with the introduction of the new EU energy label (EU, 2021) the EU has formulated new regulations regarding spare parts, which took effect on March 1st, 2021. The often called “right to repair” regulation makes it mandatory for manufacturers to have spare parts available for at least seven to ten years after the last unit of a model has been placed on the EU market (Bluhum, 2021). It makes repairs systematic and affordable through the provision of spare parts for products within a reasonable waiting period and at a reasonable price. New York State passed a similar “right-to-repair” legislation in 2022 requiring manufacturers to enable independent repair of products by providing documentation, parts, diagnostics, and additional items upon request and on reasonable terms (AHRI, 2022).

The right to repair rules are designed to tackle "built-in obsolescence" where manufacturers deliberately build appliances to break down after a certain period to encourage consumers to buy new ones (BBC, 2021). For electronic devices, it provides consumers with the freedom to have their products and appliances fixed by a repair shop or service provider of their choice, a practice that was taken for granted a generation ago but is now becoming increasingly rare in a world of planned obsolescence. Some manufacturers are concerned a right to repair could potentially put consumer’s safety and privacy in danger, undermine intellectual property protections, and diminish their brand’s image (Londono, 2021).

13.2.8 Gender issues

There is currently an enhanced need for skilled technical servicing and engineering personnel to meet the increasing demand for refrigeration and air conditioning equipment. Women are significantly and noticeably underrepresented in the refrigeration and air conditioning sector;

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[22] Refer to discussion on TFA in Chapter 2

nonetheless, there is a lack of reliable official records or statistics regarding the proportion of women working in the sector. In engineering, more generally, data indicates that women are significantly under-represented, constituting an average of 10 to 20 % of engineering professionals around the globe. An industrial group in the United States (Women in HVACR, 2017) reported in 2017 that women constituted only around 1.2 % of the heating, refrigeration and air-conditioning mechanics, technicians, and installers. The proportion was similar for Canada. Given the paucity of representative information, the International Institute of Refrigeration carried out a preliminary survey to gather data on the number of women registered as private members of national refrigeration associations. This was intended to shed some light on potential figures for female representation in the sector. The great majority of results indicated levels of female membership that ranged from zero to less than 10 %, with only two countries reporting significantly higher percentages: China and Romania, with 19.5 % and 33 % respectively (UNEP, 2019).

Society has changed since the 1960s, and the rights of women, in many aspects, are gradually being taken into consideration. Women's role in STEM (Science, Technology, Engineering, and Mathematic) tends to increase. Even in the traditionally male-dominated refrigeration and air conditioning (RAC) sector, the number of female engineers, technicians, trainers, practitioners, and professors is steadily increasing.

According to the paper "Women in the Refrigeration, Air Conditioning and Heat Pump Industry" (Colombo, 2020), the percentage of women registered in the national associations/institutions has increased significantly from 2015 to 2019, especially in UK, Norway, USA, Australia, and South-Africa. The majority of these countries have effectively doubled their female membership by establishing specific steering committees to attract more women in this industry. Several initiatives are undertaken by these national association groups, including social media campaigns, networking, outreach to schools, awards, and scholarships.

In 2022, the International Institute of Refrigeration, (IIR) and the OzonAction of UN Environment Programme (UNEP), in cooperation with other partners, undertook a global survey to better understand the background, motivations, challenges faced by women working in the RAC sector. In total, 810 women from all continents responded to the survey (UNEP-IIR, 2022). The following results were obtained:

- The environmental impact of RAC sector is a clear motivation factor and can be used to promote careers in this sector;
- There are limited training and career development opportunities in the RAC sector presenting an opportunity for national organizations and industry to work together to address this issue;
- Role models and mentoring schemes will increase visibility of women working in the field; and,
- Building awareness of women working in the sector.

Promoting gender mainstreaming is an important element of the United Nations as an organization and it is also reflected in SDG 5: Achieve gender equality and empower all women and girls. In this sense, the financial mechanism of the Montreal Protocol (the Multilateral Fund - MLF) has been seeking more systematic ways to mainstream gender in the project lifecycle. Four main aspects concerning the way gender differences are reflected in the Montreal Protocol have been identified: the effects of exposure to ozone depleting substances; the decision-making process; the capacity building opportunities; and the working environment.

The MLF has hinted that institutional strengthening projects could consider indicators like the recruitment of gender experts, the number of gender-specific content disseminated, the number of events focusing on gender, the number of women and men that receive/access information, and the percentage of women present and presenting at training workshops.

Examples of programs that could promote increasing women's role in the field job of RAC servicing are as:

- Prioritize women when it comes to similar competencies on recruiting;
- Write more gender-neutral job descriptions;
- Adapt tooling to make jobs more attractive;
- Provide proper maternity leave and childcare;
- Establish networks and communities of women technicians in RAC sector;
- Shine the light on female RAC technician role models and create awareness.

13.3 Refrigerant conservation life cycle

Refrigerant conservation is an effective part of reducing consumption of virgin refrigerants. Recovery, recycling, and reclamation, when properly applied, can have a high degree of effectiveness (see case study about Japan Initiative on Fluorocarbon Life Cycle Management – IFL); however, for such programs to be successful, tools and equipment need to be made available and the logistics of deploying them facilitated. Moreover, the management of recovered refrigerants that are stockpiled requires urgent action as many countries are running out of options to safeguard leaking cylinders in which these stockpiles exist. The MCTOC Assessment report chapter on EOL management and destruction technology chapter extends consideration back to the source of EOL refrigerants. i.e., ODS/HFCs, emphasizing the importance of integrating their capture and securing accumulation in storage stockpiles to achieve economies of scale for destruction within the refrigeration servicing system. This includes, as well, the potential for scaling down technologies or using locally available industrial facilities, such as cement kilns (MCTOC, 2018).

Besides reducing refrigerant emissions, service assures the efficient operation of the equipment. Energy consumption is by far the largest climate impact of the equipment during its lifetime.

The reduction of emissions in combination with the proper recovery and reclaim of refrigerant makes it technically feasible to use reclaimed refrigerants for existing installations and even for new equipment. Reclaimed refrigerants can be used in a pure reclaimed status or mixed with virgin refrigerant. Where mixtures are recovered, the components can be, after distillation, reused as single component or in other mixtures.

13.3.1 Leakage and impact on climate

Proper service and end-of-life (EOL) treatment of refrigerants impacts the climate depending on the quantity emitted and the global warming potential of the refrigerant. Presently, leakage and lack of EOL treatment are the main contributors towards climate impact.

Apart from the climate impact, refrigerant leaks lead to compressor failure and the need to major repairs. Corrosion accounts for 77 % of causes of leakage according to a study in Japan (Sauma, 2022) even though copper pipes used in RACHP are resistant to corrosion. Refrigerant leaks are common; in 2014, a British study found that 10 % of residential heat pumps leaked, and 3.8 % of the total refrigerant charge was lost to the atmosphere annually (Baddeley, 2014). The study reported that 92 % of the losses could be attributed to catastrophic leaks, in which systems lost 50 % or more of their initial charge.

Monitoring of leakage in refrigeration systems in Slovakia showed that the highest rates were in transport refrigeration at 13 % followed by commercial refrigeration at 8 % (Tomlein & Tomlien M., 2019). Data from Poland, Germany, Slovakia, and Italy taken from electronic logbooks showed a decrease in leakage rates for AC systems between 2010 and 2020 in response to measure imposed by the European F-Gas regulation as shown in Table 13-2 below.

Table 13-2: Leakage rates from four European countries over the period 2010 to 2020

Product groups	Data source	2010	2015	2020
AC split units	Market data Poland		5.63%	1.70%
	Market data Germany		1.60%	1.19%
	Market data Slovakia	5%	2.50%	
	Market data Italy		3.20%	
AC VRF systems	Market data Poland		5.63%	1.70%
	Market data Germany		1.80%	1.48%
	Market data Slovakia	5%	2.50%	
	Market data Italy		3.20%	
AC water chillers	Market data Germany		1.40%	1.26%
Hydronic heat pumps	Market data Poland		6.70%	1.74%

Source: Compiled by authors from (Kozakiewicz, 2021) *and* (VDKF, 2021)*, and* (ISPRA, 2018)

Leakages can be reduced by proper design and proper service. Reducing refrigerant leakage to between 1 % and 2 % on a yearly base is feasible. EOL treatment reduces emissions from discarded equipment but requires a good market mechanism and supporting regulations and their enforcement; circular economy is key to EOL management (refer to section 13.3.4). In order to reduce emissions of residual refrigerants into the atmosphere, it is a good practice to take measures to limit the emission during service such as those from charging hoses. There is an established process of E-waste in most countries, example the REACH regulation in the EU (EU, 2006). Such programmes can be extended to cover refrigerant management.

13.3.2 RRR initiatives

Recovery, recycling and reclaim of all refrigerants should be considered as a good practice to avoid any adverse effect to the environment; this is valid for fluorinated as well as non-fluorinated substances.

Recovery: The collection and storage of controlled substances from machinery, equipment, containment vessels, etc., during servicing or prior to disposal.

Recycling: The re-use of a recovered controlled substance following a basic cleaning process such as filtering and drying. For refrigerants, recycling normally involves recharge back into equipment. This often occurs “on-site.”

Reclamation: The re-processing and upgrading of a recovered controlled substance through such mechanisms as filtering, drying, distillation and chemical treatment in order to restore the substance to a specified standard of performance. It often involves processing “off-site” at a central facility.

Note: Reclamation removes contaminants such as water, HCl and HF reaction products, other acids, high boiling residue, particulates/solids, non-condensable gases, and impurities including other refrigerants. Chemical analysis of the refrigerant is required to determine that appropriate specifications are met. For refrigerant blends this includes ensuring that the composition of the mixture is within the allowed tolerances for the blend. The identification of contaminants and required chemical analysis are specified by reference to national or international standards for new product specifications.

At the end-of-life there may be the need to recover the refrigerant or to collect the equipment with the refrigerant inside. Both methods exist and depend on the configuration of the system and of local regulations. In Europe and Japan there are specific regulations for the treatment of waste electric equipment. This may include also large equipment. In France there is a specific system, (ADC3R) to support installers for an easy return of the recovered refrigerant. Recovery needs to have value to the technician to lea to waste management.

Some companies are offering the recovery of refrigerant as a service to installers. Projects are running now under the EU LIFE (EU, 2017) programme funding aiming to facilitate the recovery, recycle, and reclaim of refrigerants. Specific knowhow is required on handling refrigerants in the recovery, recycle, reclaim or destruction stages.

The recovery stage should assure that mixing different types of refrigerants is minimised, and heavy polluted refrigerants are not mixed with other refrigerants. This requires multiple cylinder handling by the service technician. Care needs to be taken that, when recovering multi-component refrigerants, that a check is made by equipment that is sufficiently accurate for a composition control such a gas chromatography. Such equipment is expensive, is often housed at a specialised facility, and is handled by technicians capable of adjusting mixtures back towards their original composition. Refrigerants mixtures need more complex handling in specialised facilities which requires in-country transportation or even cross border transportation.

Refrigerants sent to a specialised facility for reclaim need to be checked for the requirements related to the mixture of different refrigerants. Typical HFCs and HFOs are one group that can be mixed. Historically when CFCs and HCFCs were mixed, the refrigerant could not be reclaimed making destruction the only possibility with the consequent loss of circularity. Recently some companies have installed distillation plants that can separate refrigerant mixtures making it possible to reclaim a wider range of recovered material; however, there is little or no access to this technology in Article 5 parties, but it may become available in the future. Investment in destruction facilities depends on the quantities available. When only small quantities are available, investment in destruction facilities, if not already available, may become less economically feasible; however, quantities could be systemized to become larger with the right framework in place (see section 13.3.3).

Case Study: Fluorocarbon Life Cycle Management in Japan

Japan appliance recycling law (METI-MoE, 2021) covers three types of economic operators: dischargers, retailers, and recycling entities including centres for rational use:

- Dischargers are the end users who pay the fees for the appliance to be collected and disposed of in a proper manner;
- Retailers have the obligation to collect they discharged appliances they sold and transport them to the recycling centres;
- Recycling entities have the obligation to collect and recycle according to a recycling criterion.

The relationship between the three entities is shown in Figure 13-2 below.

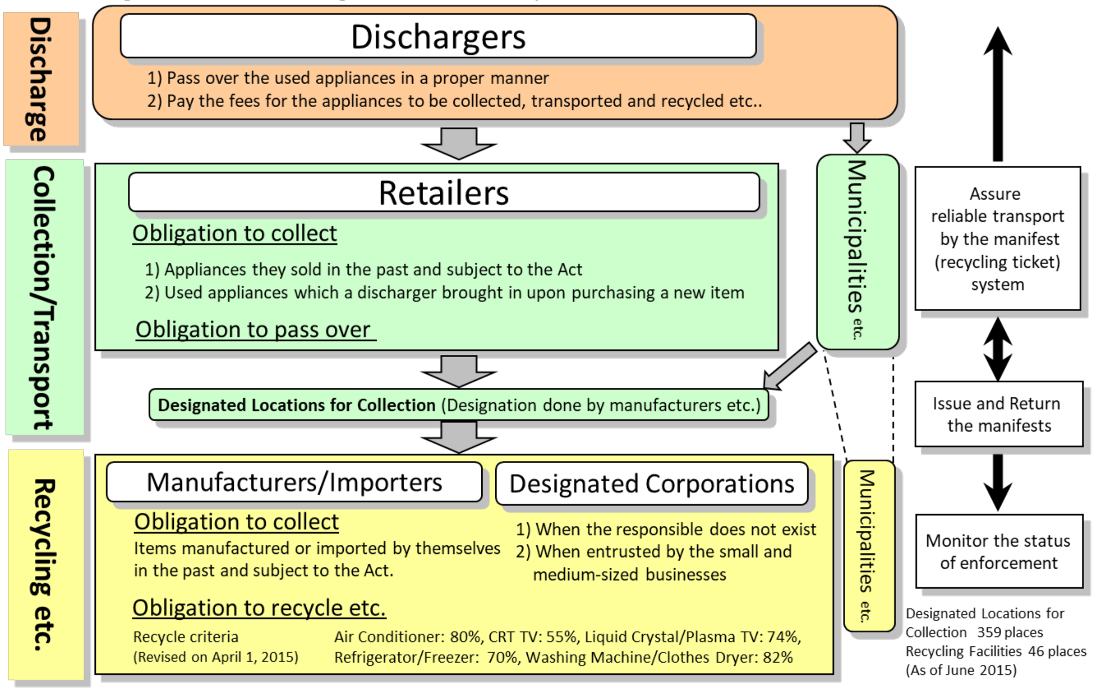

Figure 13-2: Elements of Japan recycling law (METI-MoE, 2021)

Japan launched an Initiative on Fluorocarbon Life Cycle Management, known by the acronym IFL, at COP 25 in Madrid in 2019. The initiative addresses fluorocarbon emissions throughout the life cycle including leakage and venting at the end-of-life by facilitating actions, innovation, and collaboration among governments, the private sector, and international institutions. As of June 2022, there are 13 state and inter-governmental organizations partnering with 10 private sector companies and NGOs. Japan and France partnered with the Climate and Clean Air Coalition's Cooling Hub (CCAC) to promote lifecycle management of fluorocarbons to slow global warming and ozone depletion.

To illustrate the potential of destroying recovered HFCs using cutting-edge technology, Japan's Ministry of the Environment funded a demonstration project to transfer technology and expertise between Japanese enterprises and Vietnamese counterparts. The initial project is taking place in the suburbs of Hanoi and, dependent upon its success; it is planned to be scaled up across Vietnam and other developing countries (CCAC, 2021)

13.3.3 Disposal and destruction at end-of-life

Refrigerant banks are stockpiles of refrigerants contained in millions of refrigerators, air conditioners, and other cooling and refrigerating equipment as well as in chemical stockpiles and insulating foams. If not managed, gases trapped in these banks at the end-of-life of equipment are released into the atmosphere over a long period of time. While the Montreal Protocol explicitly encourages parties to minimize emissions, refrigerant banks are currently not explicitly controlled as an obligation for Parties under the Montreal Protocol. Many countries including the United States, the UK, and the EU have voluntary or regulatory requirements to reduce emissions of ODS at the end of the useful life of these equipment and products (ICF, 2018). For developing countries, however, the collection, recycling, and destruction of waste containing ODS and HFCs present challenges.

In 2014, the ODS active banks in Article 5 parties were around 2.6 million ODP tonnes with 42 % attributed to the RACHP sector and 56 % to the foam sector. Those active ODS banks are equivalent to 2.4 Gt of CO_2 equivalent if released. The active ODS bank amount peaked in 2013, with the trend decreasing on an annual basis thereafter (Papst, 2018). When adding

HFC banks the overall trend of the amount of active ODS and HFC banks (metric tonnes) decreases beyond 2010 until 2030 and then increases.

The aggregated potential for EOL emissions from ODS banks is around 2 Gt of CO_2 equivalent. HPMP mitigation actions will result in 0.5 Gt reduction in Article 5 parties (Papst, 2018).

The MCTOC EOL management chapter for the 2022 Assessment Report analyses banks in terms of amounts reported to be captured and destroyed at EOL. The analysis indicates that, globally, and particularly in non-Article 5 parties, a large gap currently exists between quantities destroyed and quantities emitted at EOL, and that in Article 5 parties there is negligible EOL ODS/HFC destruction taking place.

The balance and dynamics in managing EOL ODS/HFC between recovery, recycling, and reclamation (RRR) and destruction can be challenging in Article 5 and non-Article 5 parties. Preference usually exists for RRR over destruction, at least initially. A system of financial and market incentives, along with regulation, is needed to support the preference for RRR early in the phaseout/phasedown cycle. As the cycle evolves and accelerates, the balance between RRR and destruction changes depending on the stage in the cycle, the policies to support the phaseout/phasedown, and the availability and accessibility to low-GWP equipment, which can influence the need for on-going RRR for higher-GWP refrigerant. This balance varies between countries and needs to be tailored nationally. The data from Japan and Australia indicates that this might not be a linear process, with the observation that for both countries there appeared to be some (perhaps short-term) resurgence for demand for reclaimed HCFC-22 when imports stopped. A further consideration could be carbon revenues that over incentivize destruction.

An important aspect when looking at suitable destruction technologies is the economic feasibility. Destruction technologies can be expensive, depending on the technology, not only for initial investments but also regarding operational costs specifically in energy use. The economic feasibility is linked more to quantities to be destroyed that are available, less to the destruction technology itself being intrinsically uneconomic. Many countries already have cement kilns, which are widely used for destruction of refrigerants, and which might not require additional infrastructure investment other than for handling waste into the cement kiln. Cement kilns manage their energy operational costs very carefully already.

Executive Committee Decision 90/49 provides flexibility for Article 5 parties to include activities in KIPs and HPMPs related to the environmentally sound management of used or unwanted controlled substances, including disposal, taking into account paragraphs 19 to 24 of document UNEP/OzL.Pro/ExCom/89/9 regarding inventories of controlled substances and the development of strategies for the sound management of waste controlled substances plus lessons learned from previous ODS disposal projects, including in relation to the integration with hazardous waste rules and regulations (MLF, 2022).

In order to successfully adopt a solution, new industry product stewardship programs and policies/ regulations for refrigerant management may need to be formulated and implemented worldwide. Strong regulations, including the enforcement of a complete ban on venting of refrigerants, and economic incentives for the recovery of refrigerants may also need to be introduced in national legislations. Weak regulations on controlling refrigerants and weak economic incentives are most probably the main factors contributing to venting. Shortage of trained and competent technicians is also one of refrigerant management barriers since malpractice causes system leakage with the uncontrolled refrigerant released into the atmosphere.

Extended producer responsibility (EPR) programs, which often rely on levies or licensing fees on the production/import of ODS, or HFC-containing equipment, and rebates for the return of recovered ODS/HFC can be used to encourage producers to safely manage the manufacture, operation, and decommissioning of ODS/HFC-containing equipment. Producer responsibility programs are thought to work best in countries with strong public support and/or government support, and in situations where few players are involved (MLF, 2008)

The potential for improved economic viability/affordability of destruction exists with the strengthening of source based EPR, the imposition of usage fees, and by directing carbon finance revenues back to the refrigeration servicing sector. This would make scaled-down destruction technologies closer to source more viable, as well as exploiting co-disposal in existing industrial facilities such as cement kilns. This is addressed in the MCTOC EOL management and destruction chapter in the 2022 Assessment Report.

Recovering the ODS and HFC banks for management and destruction can significantly reduce greenhouse gas emissions. For refrigerant banks management, a successful waste management scheme depends on four elements:

- Establishing policy measures including regulatory, fiscal, and industry-based programs;
- Establishing a sustainable financing mechanism;
- Setting-up a collections system mechanism, and;
- Establishing a functioning recovery, recycling, and destruction infrastructure.

A detailed assessment of the situation is needed to help making the proper decisions.

In Article 5 parties, where often the informal service sector takes care of waste collection and disposal, the main interest is the recovery of metals from the appliances or even the reuse of the crates of old refrigerators as racks or cabinets. Only few developing and emerging countries were successful in establishing a controlled collection of compressors, their drainage, and the storage of (H)CFC and HFC in cylinders. Adequate framework conditions and collection systems are rarely well established, resulting in low amounts of ODS and HFCs being collected.

Investments in destruction technologies are recommended when relatively high amounts of ODS and HFCs are collected annually (EU, 2020) (GIZ, 2017). A study in 2008 found that minimum quantities of 60 metric tonnes are needed for a mechanism to be financially viable (MLF, 2008); however, this is subject to economies of scale as refrigerants can use the same destruction facility as other chemicals such as persistent organic pollutants (POPs). Export for destruction is another solution. It is therefore key to have well-functioning framework conditions before considering investing in a destruction facility. As HFCs are still widely used, they will be collected for destruction if they cannot be re-used, recycled, or reclaimed.

Regional cooperation is obviously one of the solutions; however, this is governed by national laws, transboundary logistics, and the rules of the Basel convention. An example of global coordination of efforts is shown in

Case Study **13-2** below.

Case Study 13-2: Management and destruction of existing substances in ODS banks
(GIZ, 2021)

Case Study: Management and destruction of existing substances in ODS banks

Location: Columbia, The Dominican Republic, Ghana, Iran, and Tunisia

Implementing Agency: GIZ

The project is a best practice programme on refrigerant conservation. It assists its partners in establishing appropriate collection, recovery, and destruction procedures for ODS by helping them improve prevailing conditions, and by transferring good practices and technology for the management and destruction of ODS banks.

A study in preparation for the programme identified that, new policies and regulations on refrigerant management need to be formulated and implemented worldwide in order to successfully adopt the solution.

Strong regulations, including a complete ban on venting of refrigerants, need to be introduced in national legislations

Initial Outcome: The project established an ODS-reclaim facility in Bogotá, Colombia and 14 technicians have been trained on the installation and operation of the facility.

13.3.4 Market mechanisms to enhance conservation

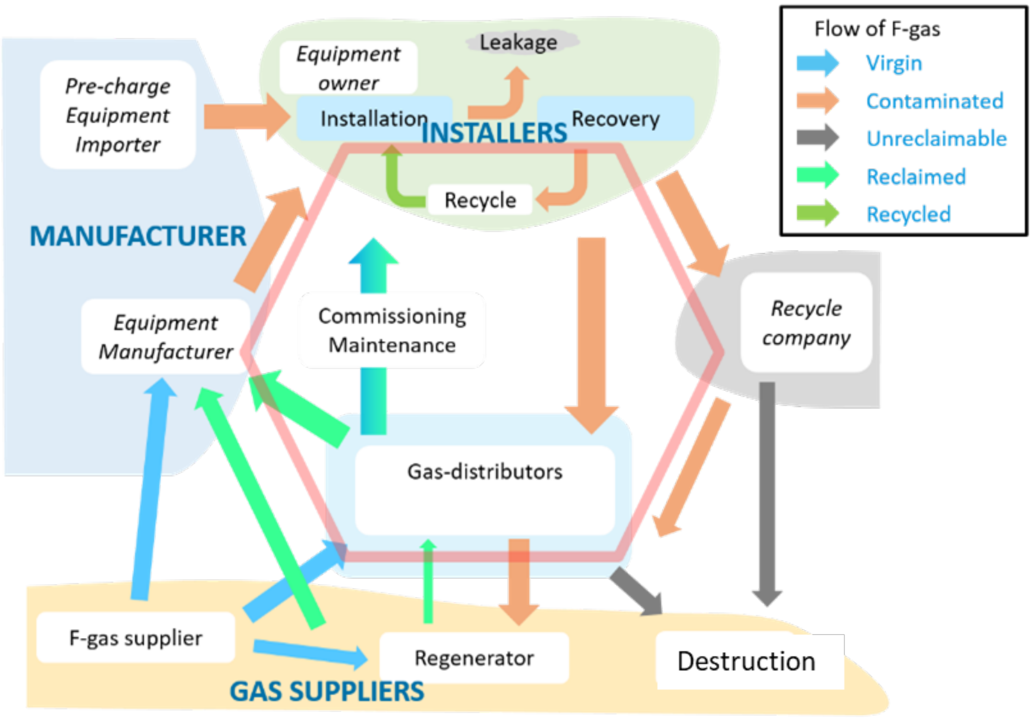

Figure 13-3: Circular chain of F-gases (WEEE, 2021)

Refrigerant conservation involves several market players including equipment suppliers as well as refrigerant distributors, as shown in Figure 13.3 above. Recovery, recycling, and reclamation are central to the process of conservation, but so is refrigerant destruction at the EOL to ensure that stockpiles do not end up in the atmosphere.

In general, the more steps that are required in the process, the higher the cost of the process. The required steps depend on the quality level and the complexity of the recovered refrigerant. For refrigerant handling, single component substances can mostly be managed with simple cleaning equipment while mixtures and blends require more sophisticated equipment to control mixture quality and to adjust the percentages. As such, these more complex substances need to be handled by refrigerant distributors or suppliers which entails more transport and processes and consequently a higher cost. This is important in remote locations that are not close to refrigerant distributors and for countries that do not have the required facilities.

Market mechanisms and cost levels are known in many regions in the world from the experience gained through phaseout management plans. The mechanism will not be viable as long as the price of the virgin refrigerant is lower than that of reclaimed refrigerant. The impact of a phasedown can be seen from the European data as in Figure 13-4 below, as reported by a European Environment Agency report (EEA, 2021). The data does not properly reflect the real quantities of reclaimed or destroyed refrigerants because of incomplete reporting obligations. The numbers still likely remain far below what could be captured at EOL but are emitted. Furthermore, recycling may be high but is not shown in the report.

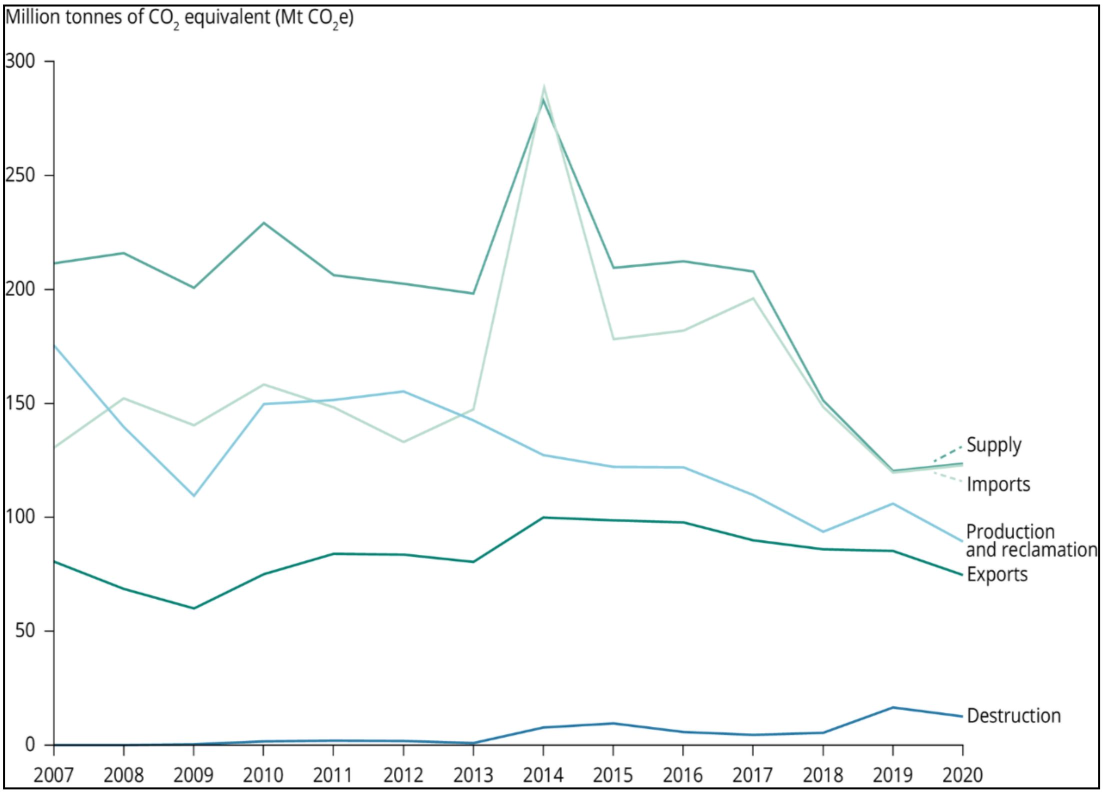

Figure 13-4: Impact of phasedown on emissions (EEA, 2021)

Since all refrigerants are contributing to pollution in one way or another, the creation of a market mechanism is most important to sustain a circular economy. The availability of process facilities and transportation that can operate without barriers is important to circulatory. At present, the cross-border transport of recovered refrigerants is complex since refrigerants are considered as waste, sometimes hazardous waste. Facilitation to reduce the complexity of transport may enhance circularity and reduce the impact to the environment of all refrigerants.

In March 2020, the European Commission published its plan of action for a circular economy concerning the life span of products. In order to reduce waste and encourage consumers to purchase ecologically, the plan considers including lifespan on the labelling of the product (EECNet, 2022).

13.4 Education, training, and certification

Refrigerant impact over time is sometimes greater than expected, and this could be true across all installed systems. Installed refrigerant banks have continued to grow over the past several decades, and, because of mechanical issues and a lack of awareness on these issues, refrigerant leaks have unfortunately proliferated.

It is likely that most installed RAC systems could be significantly leaking refrigerants that are considered pollutants as mentioned in section 13.3.1. The men and women who install, service, repair and dismantle RAC equipment are at the heart of the phaseout of HCFCs, the phasedown of HFCs, and the introduction of energy efficient and low-GWP alternatives.

The complete ratification Kigali Amendment by all Parties will bring important changes in technology including:

- The progressive reduction of widely used HFCs both in Article 5 and non-Article 5 parties.
- The increasing use of alternative refrigerants both in Article 5 and non-Article 5 parties (both natural and synthetic low-GWP refrigerants).

Reducing/phasing out of high-GWP HFCs leads to the increased adoption of alternative refrigerants of which many have flammable and/or higher toxicity properties or operate at high pressures. Technicians may not be familiar with the new refrigerants and the different care needed for their handling. The installation, servicing, repair, and dismantling of refrigeration and air-conditioning equipment operating with such refrigerants need to be carefully evaluated and considered in the context of safety issues. It is therefore recommended that minimum requirements for training and certification of contractors handling low-GWP refrigerants are adopted at the national levels. Collaboration with industry groups will contribute to an accelerated adoption of such requirements.

Technicians who are not trained on new technologies are the biggest barrier against the adoption of these technologies especially when safety is concerned. Training and certification of technicians on equipment handling, including the safe disposal and recycling of equipment, is essential. If this is not done properly, the market will switch to safer products which are presently all high-GWP refrigerant based.

13.4.1 Vocational and higher education

Vocational and higher educational institutions in the RAC sector need to be informed and assisted to incorporate material about alternative refrigerants in their curricula including the provision of additional equipment and tools for conducting those courses. These educational institutions are the most sustainable sources to produce qualified technicians on a continuous basis. A good cooperation between vocational / higher education institutions with industry on technology transfer will benefit the goals of reducing leakage and the introduction of energy efficiency and low-GWP refrigerants alternatives. In some countries, vocational schools could also become assessment centres for technicians' certification programmes and schemes as authorized professional certification bodies thus providing additional financing to these institutions to support their overall activities.

13.4.2 Training

Informed and well-trained servicing technicians are basic to the adoption of alternative refrigerants including hydrocarbons, ammonia, carbon dioxide, and HFOs. Training involves coping with the specific properties of alternative refrigerants such as flammability, toxicity, and high working pressures, and understanding the pros and cons of the different refrigerants and equipment that uses them. The training needs to be continuous, and technicians need to apply their learning while servicing actual installations.

Specialized technician training, both theoretical and practical, linked with national technician certification programmes is the best way of building and verifying the competency of personnel handling refrigerants, performing installations, and carrying out servicing. RAC technician training is one part of the national refrigerant management strategies promoted by the HPMPs and will feature also on Kigali Implementation Plan (KIP) strategies. Ensuring that developing countries have well trained and certified technicians will significantly contribute to the dual objective of gaining climate and ozone benefits from the servicing sector.

OzonAction-UNEP supports the upgrading of the skills and knowledge of technicians as part of an overall refrigerant management strategy for Article 5 parties (UNEP, 2022). It recommends that countries adopt minimum requirements for training and certification of contractors handling low-GWP refrigerants at the national level. OzonAction provides training to refrigeration servicing technicians including in-person training courses, online e-courses, training curricula, smartphone applications, and fact sheets. The country-level activities are frequently organised in cooperation with national refrigeration associations or RAC training institutes. OzonAction also has partnerships with associations and industry to jointly promote RAC technician training.

Although many projects have provided assistance in the form of training for RAC technicians in Article 5 parties, it still needs further consideration on training program sustainability to get more outreach of well-trained technicians. Systematic review is needed on support requirements prior to allocating resources and for building long term vision to maintain program sustainability.

13.4.3 Certification

Training is essential to transfer knowledge to service technicians; however, training alone does not verify the level of comprehension, competence, and skills of a participant in a training programme. Certification gives official proof for technicians of their ability to competently complete a job or task. Certification can be a legally mandatory requirement, or a measure undertaken voluntarily for professional advantage. Mandatory Certification schemes have the advantage of providing a strong incentive for technicians and enterprises to comply and ensures the inclusion of the informal sector in development and training activities. Certification schemes need to be properly and publicly advertised at all levels (end-users, service companies, manufacturers, government institutions) to guarantee a wider participation of stakeholders.

Since there are differences in the practical safety requirements for the different refrigerants depending on the level of flammability and toxicity, the same needs also to apply to certification. Where there is certification in place, technicians are well trained for handling the substance, on the other hand, where no certification is in place, there is a doubt that the involved service technicians are properly trained to handle refrigerants and equipment.

There are possible barriers to the proliferation of certification when it is perceived as an added cost or ‘tax’ to enter the sector, or that the process may appear to be too bureaucratic to warrant engaging with.

Monitoring systems consist of putting in place several requirements within the national certification scheme, these can include:

- A registry of certified personnel and companies publicly available online or held by a national authority;
- Regulation that only certified personnel and companies can purchase refrigerants;
- Regulation that only certified personnel and companies can install, repair, maintain, recover, and dismantle RAC systems;
- A registry with the quantity of purchased and recovered refrigerants available to the authorities;

- Refrigeration system logbook containing relevant historical data of the installation, maintenance, and repair available for each system.

Table 13-3 below shows examples of certification schemes from around the globe for both Article 5 and non-Article 5 parties in alphabetical order (Buoni, 2015).

Table 13-3: A glimpse of service certification in countries around the globe (Source: compiled by authors from UNEP and ASHRAE)

Australia

Technicians who operate refrigeration and AC equipment as well as automobile industry operating on MAC are required to hold a "Refrigerant Handling License" and those who purchase as well as possess and dispose of refrigerants require a "Refrigerant Trading Authorization." The system is administered by a private organization "the Australian Refrigeration Council Ltd" on behalf of the Australian Government.

China

The operation and monitoring of the certification scheme for technicians is the responsibility of the Ministry of Human Resources and Social Security (MHRSS). The Foreign Economic Cooperation Office (FECO) / Ministry of Environmental Protection (MEP) recently completed a feasibility study on updating China's existing qualification authentication systems aiming to cover good practices during servicing and maintenance, as well as to cover handling the new generation of refrigerants which can be flammable, toxic refrigerants, or those with higher working pressures. In consultation with MHRSS, FECO/MEP signed an agreement with the Vocational Training and Qualification Certification Association of China in October 2013 for the study of the implementation of the current certification system, and later for the development of the certification syllabus as well as the how to build the delivery capacity of various training institutes.

A number of different certification practices exist within China. Under one system, the technicians are encouraged to receive their qualification certificates before they are allowed to enter the refrigeration servicing sector as technicians. Under another system, the technicians are required to have compulsory certificates or permits to be qualified to work in legally defined, specialised sectors due to nature of the safety concerns.

European Union (EU)

In the European Union (EU), there are several European standards and regulations that control certification, including the EU "F-Gas" Regulation No 517/2014. This regulation, which covers all 28 EU member states, includes specification requirements for personnel covering a large variety of tasks and equipment related to the RAC sector.

Interesting Highlight 1: An example of a regional regulation which is specifically implemented into relevant national legislation.

Interesting Highlight 2: Results show that measures put in place contributed to avoid emissions

Japan

In Japan RAC technicians are required to hold a "Refrigeration Safety Manager Certificate". This certification in required by law (the High-Pressure Gas Safety Regulations). The Japanese society of RAC Engineers also provides additional certification including focusing on refrigerant leak prevention.

In Japan, service operations, RAC equipment manufacturers take the lead in training service engineers. Courses on refrigerants are held in accordance with the qualification system sponsored by the equipment supplier associations, and participants will be given certification after a final test. Certification has also been recognized by the Government of Japan.

<u>Interesting Highlight:</u> There are three categories of "Refrigeration Safety Manager Certificate" depending on the equipment type and capacity.

Saint Lucia

In Saint Lucia, technicians are required to complete and successfully pass a training and certification course entitled: "Good Refrigeration and Air-conditioning Management Practices, Recovery, Recycling and Retrofitting and Alternative Technologies." Candidates must have 3-5 years' experience or have a diploma in refrigeration from a recognised institution. The course and assessment run for six days with an examination and practical test. The fee for the course in US$30 (circa 2020). Successful certified technicians receive a certificate and an identification card. Unsuccessful technicians are issued only with a note of participation and are required to repeat the entire course and examination.

<u>Interesting Highlight:</u> The recognised implementing body for the training and certification course and issuing of the ID cards/certificates is the Saint Lucia National Ozone Unit (Ministry of Sustainable Development, Energy, Science and Technology).

South Africa

In South Africa national standard, SANS 10147 requires, *inter alia,* that RAC technicians involved in servicing and handling of refrigerants be registered as being competent in their specific fields. The scheme is implemented by the South African Qualification & Certification Committee.

<u>Interesting Highlight:</u> The national standard requiring registration is under the country's Occupational Health and Safety Act.

United States

In the United States, the Environmental Protection Agency (EPA) established a mandatory certification programme. RAC technicians are required to pass an EPA approved test implemented by an approved certifying organisation (if the technician is not under close and continual supervision from a certified technician). Some states and local jurisdictions have specific licensing and certification requirements. There also exists in the US a number of voluntary certification programmes.

<u>Interesting Highlights:</u> The mandatory certification programme applies to the handling of CFCs and HCFCs and is likely to be extended to HFCs.

Zambia

In Zambia, the ODS control regulations, which are under the Environmental Management Act of 2011, apply to the servicing of RACs as well as people or institutions using controlled substances. The corresponding regulations include specific guidelines for technicians in the handling of ODSs including on banning venting and retrofitting to HCFCs. The regulation specifies that certification is required for the servicing of products or technology that contain or use ODS. A request is made to the Zambia Environmental Management Agency with a certificate from the Vocational Training College which is overseen by the Government of the Republic of Zambia with assistance of GIZ. If approved, a permit to handle refrigerants is issued.

<u>Interesting Highlight:</u> The Scheme relies on the close cooperation between the NOU, the Refrigeration and Air-conditioning Association of Zambia (RAAZ) and the vocational training institutions.

13.5 Effect of temperature on service

RTOC 2018 Assessment Report (RTOC 2018) had a dedicated chapter on the impact of high ambient temperature (HAT) on refrigerant selection and a discussion on the special requirements for equipment design. Equipment designed for HAT tend to be larger and the hours of operation longer which affects the servicing frequency and consequently special attention for technicians' wellbeing working at extreme temperatures needs to be taken into consideration.

Natural Resources Canada (NRCAN, 2015) links maintenance frequency with factors including severity of use and operating environment. According to the Electrical Apparatus Service Association (website: easa.com), the recommended frequency of maintenance for motors doubles if they are operating 24 hours per day vs. a standard eight hours. Longer operating hours are linked to higher ambient temperatures.

The study of the 56 homes in Florida mentioned under 13.2.2 also concluded that the median degradation rate in efficiency increased from a median of 3 % per year for moderate temperatures to 5.2 % due to the harsher operating conditions linked to higher temperatures (Fenaughty & Parker, 2018).

For equipment installed on rooftops, technician wellbeing needs to be taken into consideration to reduce their exposure to extreme heat conditions. Some countries issue heat warnings and forbid outdoor work during peak temperature hours. Working at HAT conditions might drive some technicians to speed up the working process and pay less attention to details, such as searching for leaks, which might impact safety or the performance of the machines. Fatigue can also drive technicians to neglect non-refillable refrigerant cylinders after service with the risk of eventual leaks of the residual refrigerant in the cylinder.

13.6 Concluding remarks

Proper installation, maintenance, and servicing practices have an effect on the safety of both technicians and end-users, on energy consumption of the system, and consequently the impact on the environment. Any action that releases refrigerant into the atmosphere will harm the environment. Using the right tools for the right refrigerants and following guidelines and codes of good practices have a positive impact on the quality of service and the lifetime of air conditioning and refrigeration systems.

Proper practices contribute to reducing refrigerant consumption of ODS refrigerants and those with high GWP. The effective recycling and reclamation of refrigerants also contributes to lower consumption. The disposal of equipment at the end-of-life and the removal of residual refrigerants reduces direct emissions to the atmosphere and reduce climate impacts of RACHP systems.

Awareness and updating of technicians on servicing techniques related to newer technologies through continuous training is vital to the introduction and sustainability of those technologies in the respective applications. Technician certification is being increasingly applied across the globe to ensure that only those technicians who are properly trained to handle substances can service products thus reducing the risk of leakage and voluntary emissions. Taking measures to remove obstacles to female participation in the technician workforce will ensure gender equality.

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