Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee

2018 Assessment Report

Montreal Protocol on Substances that Deplete the Ozone Layer

UN environment
United Nations Environment Programme
Ozone Secretariat

MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

2018 REPORT OF THE REFRIGERATION, AIR CONDITIONING AND HEAT PUMPS TECHNICAL OPTIONS COMMITTEE

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The text of this report is composed in Times New Roman.

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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 an Annex.

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Acronyms

AC	Air Conditioning
AHRI	Air-Conditioning, Heating and Refrigeration Institute
APF	Annual Performance Factor
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
CRP	Cooperative Research Program
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 für 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 Horse Power)
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
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

LT	Low Temperature, around -18°C
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
MT	Medium Temperature, around 0°C to 8°C
MVC	Mechanical Vapour Compression
NEC	Natural Environment Council of the United Kingdom
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
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 Economics Assessment Panel
TEWI	Total Equivalent Warming Impact
TFA	Trifluoroacetic Acid
TR	Ton of Refrigeration (12,000 Btu per hour)
TTW	Through The Wall
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
VRV	Variable Refrigerant Volume
W	Watt

Key Messages

Refrigerants

- Since the publication of the RTOC 2014 Assessment Report, 35 new refrigerants, most of them blends, have received a standard designation and safety classification. Among the 35 new fluids there are five single-compound refrigerants.
- There is not a single "ideal" refrigerant. Refrigerant selection is a balanced result of several factors which include, suitability for the targeted use, availability, cost of the refrigerant and associated equipment and service, energy efficiency rating, safety, ease of use, and environmental issues.
- The HFC phase-down under the Kigali Amendment, as well as regional regulations, are driving the industry towards the use of low GWP refrigerants. Alternatives to high GWP refrigerants exist and new lower GWP refrigerants have been proposed, which creates a challenge to finding the best refrigerant for each application. Many of these newly introduced refrigerants are expected to play only a temporary role in the phase-down process, as their GWP may still be high for the average future application.
- 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.

Domestic appliances

- HC-600a (predominantly) or HFC-134a continue to be the refrigerant options for new production and currently, more than 1 billion domestic refrigerators use HC-600a. None of the other new refrigerants has matured to become an energy-efficient and cost competitive alternative.
- It is expected that, by 2020, about 75% of new refrigerator production will use HC-600a. North American industry has announced a voluntary goal to phase out HFC-134a in household refrigerators and freezers after 2024, with HC-600a as their leading alternative.
- The heat pump clothes (laundry) dryer (HPCD) sales are rapidly growing in the EU. HPCDs are still predominantly based on HFC-134a, but HPCDs using HC-290 are now available in the market. Low GWP refrigerant solutions, including R-744, HC-600a and HFOs are still in the exploration phase.

Commercial refrigeration

- Commercial refrigeration equipment, used for storing and displaying fresh and frozen food, is characterised by varied designs and mostly uses HCFC-22 or R-404A, with many large field-charged systems prone to high leak rates. Commercial refrigeration equipment operates continuously all through the year, therefore the proportion of indirect emissions to operate this equipment is typically dominant, unlike the proportion of direct emissions related to the emission of refrigerants.
- Lower GWP HFC/HFO blends and non-halocarbon options like R-744, HC-290, HC-600a and R-717 are growing in use, especially as research and development continues into improving system performance; this trend will increase once new safety standards and codes go into effect in the next few years.

- The change from high GWP HFCs to lower GWP options is being used as an opportune time to innovate system architectures that use less refrigerant, are more efficient, simple to install, easy to maintain and less prone to leaks.

Industrial refrigeration and heat pump systems

- Industrial refrigeration systems are used in a wide range of applications globally, applying a variety of refrigerants and technologies for a wide range of temperature levels.
- In larger industrial refrigeration plants, R-717 has been extensively used for more than 150 years. Current technological advances enable the use of low charge R-717 systems, as well as cascade systems using R-717 together with R-744, opening up new opportunities.
- Large size heat pumps are gaining market acceptance due to increased knowledge of the relevant technology benefits. There are several industrial processes where cooling and heating are needed at the same time, for example the dairy industry. These cases demonstrate how to fully use the potential of cooling and heating capabilities of heat pumps simultaneously.
- The industry has learned to work safely with R-717 by proper education and training. Accidents are less likely to happen when safety procedures are followed.

Transport refrigeration

- In some regions, a significant migration from R-404A to lower GWP has occurred since the last assessment. Today, R-404A has been completely replaced by R-452A in new truck and trailer equipment in Europe. This trend might extend across the rest of the world.
- R-744 and R-513A have been introduced in intermodal container applications. R-744 is being field tested on trucks and trailers.
- No mass production of equipment with flammable refrigerants has been introduced yet; however, field trials and technical publications are testimony of the large R&D effort ongoing in this area, with the goal of mitigating safety risks. Similar effort is going on in the area of codes, regulations and standards.
- While new ships use R-717 and R-744, either alone or in cascade systems, the majority of the existing global fleet of reefer ships and fishing vessels other than those trading in Europe continue to operate on HCFC-22.

Air-to-air air conditioners and heat pumps

- The phase-out of HCFC-22 in non-Article 5 countries is essentially complete and is progressing in Article 5 countries.
- There is an almost continuous introduction of new high, medium and low GWP refrigerants for use in air-to-air air conditioners and heat pumps, but few match or exceed the performance of HCFC-22. Component and system optimisation remain a design challenge.
- Larger, distributed systems pose the greatest challenges to adoption of medium and low GWP alternatives.
- Despite the reported low risk for certain applications, safety standards remain restrictive to several low GWP flammable refrigerants in certain product types, but are under

revision for all refrigerants. There remains no large-scale shift to low GWP refrigerants as yet.

Water and space heating heat pumps

- Most water and space heating heat pumps systems commercialised today make use of refrigerants R-410A, HFC-134a, R-407C, HC-290, HC-600a, R-717, R-744, or recently also HFC-32.
- In some Article 5 countries HCFC-22 is still used. There are technical solutions to replace HCFC-22 with a non-ODS refrigerant in new systems. The main parameters in the selection of alternatives when switching over from HCFC-22 are energy efficiency, temperature range, cost effectiveness, economic impact, safe use and ease of use. In the EU, the CO_2 equivalent quota that would be needed for the replacement is an extra, recent requirement.
- Water and space heating heat pumps with the low GWP refrigerant HC-290 and the medium GWP refrigerant HFC-32 are commercially available. Also, other medium and low-GWP HFC blends may become commercially available. R-744 based water heating heat pumps have been mainly developed and commercialised in Japan, where around 6 million units have been installed since 2001. In Europe, commercial sized units are being installed for multi-family houses and hotels. R-717 is also being used in a small number of reversible heat pumps as well as in absorption heat pumps.

Chillers

- The phase-out of ozone depleting refrigerants in new chillers is nearly complete. HCFC-22 in new, small chillers has been phased out in non-Article 5 countries, but limited use continues in Article 5 countries. However, there is a considerable number of chillers worldwide that use ozone depleting refrigerants, especially CFCs, which will remain in service for years to come.
- Since the HFCs in use today are considered to have a high GWP, there is global pressure to change to lower GWP refrigerants. Research for alternative refrigerants with lower GWP are nearly over and have yielded several acceptable alternatives.
- The introduction of products using lower GWP refrigerants has started. Where manufacturers of chillers will change to lower GWP refrigerants, the pace of change is uncertain. Manufacturers are reluctant to change quickly, because product development costs are high and consumer demand is relatively low in most countries. Government regulations and financial incentives today provide little to accelerate change. It is noteworthy that chillers using non-fluorinated refrigerants are available today and are part of the changing mix of commercially available products.
- Vapour compression technology dominates all chiller products. Absorption chillers are available today, just as they have been for decades. Broader use is limited by cost and comparatively lower efficiency. They can be used effectively where there are favourable utility rates, or in hybrid systems where waste heat or steam is available. It is unlikely that chillers using not-in-kind technologies will be commercialised in the foreseeable future.
- Chillers are a major user of power and indirect emissions related to energy consumption dominates their environmental impact. Regulators and customers alike are demanding higher performing, reliable chillers, regardless of any refrigerant used. As most chillers

are applied in large, multiple cooling systems, various application and control strategies are available that can significantly reduce the overall energy consumption of the system.

Vehicle air conditioning

- At present, more than one refrigerant is used for new car and light truck air conditioning: HFC-134a will remain widely accepted world-wide while, due to regulations, the use of HFO-1234yf will continue expanding mainly in the US, Europe and Japan. R-744, currently available for very few car models, is expected to be considered as an option for electrified vehicles, when used at the same time for a heat pump function.
- The global use of HFO-1234yf and other low GWP options will be impacted by additional aspects including safety, regulations, system reliability, heat pump capability and servicing.
- At the moment, it cannot be forecast whether or not the existing and new refrigerants will remain parallel options in the market for a longer period of time. It is also unclear if other mobile AC applications, such as buses and heavy-duty trucks, will follow the trends now apparent in light-duty vehicles.
- The use of hydrocarbons or hydrocarbon blends has not received widespread support from vehicle manufacturers, mainly due to safety concerns.
- The on-going electrification of road transport in Europe, China and US may represent a disruption to current refrigerants as well as to broader technical options that might result in a reconsideration of current refrigerant choices.

Energy efficiency and sustainability applied to refrigeration systems

- Industry and policymakers may consider the methods, tools and incentives described in this RTOC assessment report chapter to stimulate and support improvements on energy efficiency and sustainability. A wider range of relevant environmental and social aspects is briefly described in this chapter while keeping focus on possible environmental impacts of refrigeration systems.
- Comprehensive sustainable selection criteria for refrigerants are introduced for the first time. They address energy efficiency, impact on climate and hydrosphere, usage of renewable energy, and other options to reduce GHG emissions and consumption of natural resources, adaptability for thermal energy storage, costs, technological development level, safety, flammability and liability.
- Expected future emissions of TFA, being a degradation product of several HFOs and some HFCs, will increasingly pollute aquatic soil layers and drinking water systems. Lacking adequate knowledge of all TFA pollution impacts, more in-depth research will be required, particularly due to the rapid, widespread uptake of HFOs in MAC and other R/AC subsectors.
- The adoption of the UN Sustainable Development Goals (SDGs), in the RACHP sector, needs to include responsible choice and management of refrigerants, energy efficient design of refrigeration systems and efficient operation through optimised integration and controls.

Not-in-Kind technologies

- Not-In-Kind (NIK) technologies do not primarily use mechanical vapour compression (MVC) technology to produce air conditioning or refrigeration.

- These technologies can be classified as “widely commercially available”, “commercially available” or “emerging and R&D”. They are divided into three groups: (1) thermal, (2) solid-state, and (3) electro-mechanical technologies.
- Thermal technologies are predominantly available commercially; solid-state technologies are mostly available commercially with one technology in the R&D stage; electro-mechanical technologies are mostly in the R&D stage. The last ones are assumed to become the NIK technologies of the near future, with expected higher EERs compared to other NIK technologies.
- NIK technologies are expected to provide savings in operating costs. Their unique ability to use waste and renewable energy sources makes their applications achieve high energy efficiency.

High ambient

- There is more awareness of the challenges faced at HAT conditions in the design, implementation, and even servicing of equipment using low-GWP alternative refrigerants that are capable of delivering a high level of energy efficiency.
- Research done at HAT conditions reveal viable low-GWP refrigerant alternatives that can be effectively used.
- A limited range of small split units using flammable refrigerants can be found in some HAT country markets. The potential demand of HAT countries for air conditioning units with alternative refrigerants further drives the research and development efforts of global and local manufacturers. This in order to develop specially designed energy-efficient units that meet safety standards.

Modelling

- Calculating the energy efficiency related to refrigerant properties or related to RACHP equipment operation as well as calculating the direct and indirect emissions, dependent on efficiency and cooling load, is a task for separate scientific or technology studies; RTOC assessment reports can only refer to them.
- Determination of current and future refrigerant demand has been a task for RTOC experts when involved in recent Task Force reports. The demand follows from “bottom-up” calculations of banks and emissions that give good insight into future developments, albeit that these imply assumption of a large amount of parameters. This includes economic growth, equipment base and composition, leakage, end-of-life characteristics, recovery and recycling.
- When converting to alternative refrigerants, an important parameter to be studied is the duration of industry conversions to the use of this new refrigerant. The longer it takes to convert industries, the more equipment will continue to be built using the original refrigerant, implying substantial servicing demand for this refrigerant even after conversions will have been completed.
- Inventory model-based demand calculations have shown their value in recent reports that presented a comparison of climate benefits of various HFC reduction schedules -- before the 2016 Kigali Amendment was agreed. Based on data from studies on national HFC production and consumption undertaken (“HFC Surveys”), calculations using these “bottom-up” models should increasingly result in adequate predictions of future national or regional HFC consumption.

Executive Summaries

Refrigerants

The Refrigerants chapter discusses and provides tabular summaries for refrigerant designations or identifiers, as well as physical, safety, and environmental data for refrigerants.

Refrigerant selection is a balanced result of several factors which include, suitability for the targeted use, availability, cost of the refrigerant and associated equipment and service, energy efficiency rating, safety, ease of use, and environmental issues.

There is no single “ideal” refrigerant. Due to the phase-down under the Kigali Amendment, the target refrigerants for main applications will include low GWP refrigerants such as R-717, R-744, hydrocarbons (HCs), unsaturated halochemicals such as hydrofluoroolefins (unsaturated HFCs often referred to as HFOs) and hydrofluorochloroolefins (unsaturated HCFCs, often referred to as HCFOs), and blends of these refrigerants, some even with traditional refrigerant fluids (HFCs, some HCs). Alternatives to high GWP refrigerants exist and new more efficient refrigerants are being proposed which creates a challenge to finding the right refrigerant for each application. Many of the proposed alternatives are seen as intermediate solutions in the HFC phase-down.

A system redesign or an update to the system topology will be required for most systems to begin using the newer refrigerants, but in some cases, this update may be as simple as changing the refrigerant and lubricant. As examples, the earlier transition from CFC-12 primarily to HFC-134a required only changes to lubricants and some elastomeric seals, while the shift from HCFC-22 to R-410A required those changes along with extensive compressor, heat exchanger, control, and other modifications. The search is a trade-off between cost, safety, energy efficiency, environmental impacts, and limiting the need for redesign.

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 current safety levels, new technologies are being developed and increased levels of training will be needed.

Since the publication of the 2014 RTOC Assessment Report, 35 new refrigerants, most of them blends, have received a standard designation and safety classification. Among the 35 new fluids there are five single-compound refrigerants, HCC-1130(E), HFO-1132a, HCFO-1224yd(Z), HFO-1336mzz(E), and HFO-1336mzz(Z). The newly introduced molecules, HCC-1130(E), HCFO-1224yd(Z), HFO-1336mzz(E), and HFO-1336mzz(Z) have relatively high boiling points, making them relevant for high temperature heat pumps and centrifugal chillers. HFO-1132a is a lower toxicity flammable (safety class A2) high pressure fluid, with a boiling point of -86.7 °C; it has the potential to be used in cryogenic applications, as well as a component in new refrigerant blends, for instance those that will replace R-410A.

Domestic appliances

Under the domestic appliance category, the domestic refrigeration sub-sector is the major component and includes appliances that are broadly used domestically, such as refrigerators, freezers and combined refrigerator/freezer products. Small beverage dispensing machines are also included in domestic refrigeration, but represent only a small fraction of total units.

Globally, the movement away from the use of ODS in new refrigerator production was essentially completed by 2008. HC-600a (predominantly) or HFC-134a continues to be the refrigerant options for new production and currently, more than 1 billion domestic refrigerators use HC-600a. None of the other new refrigerants has matured to become an energy-efficient and cost competitive alternative. Refrigerant migration from HFC-134a to HC-600a is expected to continue, driven either by local regulations on HFCs or by the desire for reduced global warming impact from potential emissions. Significant progress is being made to convert the remaining applications of HFC-134a to HC-600a. With the market introduction of freezers and small refrigerators in the United States, service infrastructure is being developed. It is projected that by 2020 about 75% of new refrigerator production will use HC-600a (possibly with a small share by unsaturated HFC refrigerants) and the rest will use HFC-134a.

According to some industrial sources, initial developments to assess the use of HFO-1234yf in domestic refrigeration have begun, but it is not being pursued with high priority. No recent activity has been observed for the use of HFO-1234yf in refrigerators. Given the cost disadvantage, flammability, and investment requirements for product development, HFO-1234yf suffers significant disadvantages. With the lack of activity by manufacturers, HFO-1234yf is not likely to displace HC-600a or HFC-134a in the foreseeable future.

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 grid. In the absence of unique drivers, there are no known systems that are more efficient or cost effective than conventional vapour-compression technology for mass-produced domestic refrigerators.

The Association of Home Appliance Manufacturers (AHAM) of North America has announced a voluntary goal to phase out ~~of~~ HFC-134a in household refrigerators and freezers after 2024~~.~~ with HC-600a ~~is~~ as the leading alternative. Based on recent studies, HFO-1234yf and HFO-1234ze and their blends with HFC-134a as drop-in refrigerants, may be possible alternatives. And after system optimization, the energy consumption may also be comparable. However, one also has to consider all safety issues with respect to flammability of these refrigerants.

The other domestic appliance covered in this chapter is the heat pump clothes (laundry) dryer (HPCD). Heat pump clothes (laundry) dryer (HPCD) sales are rapidly growing in the EU with manufacturing in EU, Japan and China, but the current market share of HPCDs in Article 5 countries is still insignificant. HPCDs are still predominantly based on HFC-134a and refrigerant charge amounts vary from 200 to 400 g. HPCDs using HC-290 are available in the market. Low GWP refrigerant solutions, including R-744, HC-600a and HFOs are still being explored.

Commercial refrigeration

Commercial refrigeration, used for storing and displaying food and beverages at different temperature levels within commercial stores. Two main levels of temperature~~s~~ are generated by refrigeration systems from around 0 °C to 8 °C for the conservation of fresh food and beverages, and around -18 °C for frozen food and ice cream. HCFC-22, and more recently, R-404A are the commonly used refrigerants in these applications. Traditionally, commercial refrigeration applications are prone to significant refrigerant leakage due to the fact that most large systems are field installed. For all these reasons, the progressive phase-out of HCFC-22 in developing countries, and the phase-down of high GWP HFCs in many countries, requires making informed choices on the best replacement options.

Equipment can be classified as direct or indirect systems, or as stand-alone, condensing unit, centralised and distributed systems. The choice of a lower GWP alternate refrigerant depends greatly upon the type of equipment. In addition, since the equipment operates year-round and the condensing coils are typically located outdoors, the ambient temperature also plays a major role in equipment selection, this is particularly true for the high ambient regions of the world. Efficiency considerations are also a major factor due to the life cycle climate performance of such equipment tends to be dominated by the power consumed and the source of that energy. Commercial equipment typically has a life span of fifteen years or greater and retrofit (changing refrigerant) is a common occurrence. Therefore, both new and existing equipment have to be considered when reviewing the refrigerant candidates for lower GWP. The table below gives a high-level summary of the types of refrigerants available for these applications:

	Stand alone	Condensing Unit	Centralised
High GWP HFC (current)	DX	DX	DX
Lower GWP HFC/HFO	DX	DX	DX/ with HTF
R744	DX	DX	DX
R717	---	With HTF	With HTF
HC	DX	DX / with HTF	With HTF

AHRI in the USA has conducted studies comparing lower GWP HFC/HFO refrigerants used as drop-in candidates with little modification to system design and the results have been encouraging. Numerous other conferences and studies have also reported similar findings ~~and~~ for all climatic regions. In the past few years, non-halocarbon refrigerants like R-744 and R-290 systems have become common in global commercial refrigeration. While the adoption of new HFC/HFO blends is growing slowly and gradually, due to availability and to A2L standards and codes development, the growth of R-744 has not been uniform globally; this is due initially to cost and efficiency considerations in high ambient conditions. The growth in use of R-290 has followed a similar path, mainly due to the flammability of the refrigerant, which restricts the amount of refrigerant that can be used.

More recently, concerns about the efficiency of these alternate refrigerants have surfaced, but a study of field trials and existing literature on this topic shows that, in general, systems with the lower GWP alternate refrigerants can be as efficient as the high GWP HFC refrigerants they replace. Also, the methods of improving efficiency are not unlike those lower GWP refrigerant options.

In summary, several lower GWP refrigerant options have been identified for commercial refrigeration and more options are being announced as research and development continues. As the use of alternates increases globally, their availability, knowledge of use criteria, and the cost of the equipment can all be expected to improve. Refrigerant changes also give an opportunity to experiment with new system architectures that are aimed at reducing the total life cycle cost and climate impact of these equipment.

Industrial refrigeration and heat pump systems

Industrial refrigeration and heat pump systems are an integrated part of the global food chain from harvest to table. Industrial refrigeration is used for cooling a variety of food from ambient temperature to just above the freezing point of water or well below. Food and beverage (F&B) are important markets for industrial refrigeration, but-industrial refrigeration is also used in a range of other industries such as fishing ships, pharmaceuticals, petrochemicals, airport cooling, and heating systems.

The majority of the world's large industrial systems use R-717 refrigerant. Where R-717 is not acceptable for direct systems, options include R-744 or glycol and brine in secondary systems, or HCFCs, or HFCs in direct systems. In countries where R-717 is not the preferred solution, or in market segments with smaller systems, the transition from HCFC-22 is not always straightforward, since most of the HFC alternatives are blends with a temperature glide.
Due to accumulation of the separate components of a refrigerant blend in different parts of the system, blends form a challenge in industrial pumped and two stage systems. In larger systems, conversion to R-290 has been performed successfully e.g., in petrochemical installations where one more system with flammable gas does not raise any questions. It requires acceptance of

higher cost fluorochemicals in similar system types or the adoption of more expensive systems with the cheaper refrigerants R-717 and R-744. This transition is slow and is constrained by a lack of trained personnel and lack of experience of the local end-users. It has been facilitated by corporate policy from multinational food and beverage manufacturers. The process of moving from HCFCs to zero ODP, low GWP alternatives would be accelerated by a concerted education and training program for operators and service technicians including operational experience and lessons learned from existing systems, and following ISO 22712. This conclusion has been reinforced by several fatal accidents that have occurred in recent years.

Suitable safety standards already exist such as those published by EN, ASHRAE, and ISO, including ISO 5149. ISO 5149 is also available as regional standards via EN 378 and ASHRAE 15. Once again, employee training on the higher standards is key to ensure safety of the systems in use.

In markets where R-717 has been accepted as the preferred refrigerant**,** there is little to no indication that new refrigerants will gain any significant market share. The market use of the current HFC fluids has been limited due to their high cost and long-term availability. This does not give hope that new refrigerant fluids will be successful because they are expected to have a higher cost.

In large district heating systems HFO-1234ze (E) has shown to be a possible replacement for HFC-134a, however higher swept volumes and higher surface areas for the heat exchangers are required and its performance is not significantly better than that of HFC-134a. HFO-1234ze (E)) has also been demonstrated in centrifugal chillers, which could be used in process cooling or in district cooling installations. This may be a key player in addressing the challenge of a rapid market growth in the Gulf Co-operation Countries over the coming years.

Large size heat pumps are gaining market acceptance due to increased knowledge of the relevant technology benefits. There are several industrial processes where cooling and heating are needed at the same time, for example the dairy industry. These cases demonstrate how to fully use the potential of cooling and heating capabilities of heat pumps simultaneously.

The industrial sectors covered by this chapter are too diverse to facilitate the level of development expenditure required to bring a new fluid to market. It can therefore be stated that if any new development gains market share in industrial systems, it will be a fluid developed for some other purpose, either as a refrigerant in smaller mass-market systems or as a foam-blowing agent, solvent or other speciality chemical.

Transport refrigeration

Transport refrigeration is a small segment, mainly focused on the delivery of chilled or frozen products. This segment has specific challenges such as; shock, vibration, corrosion and broad operating conditions.~~:~~ Because of this, the refrigerant selection may be substantially different from other segments.

In truck and trailer refrigeration, one ~~a~~ major development since the last assessment has been the introduction of R-452A as the alternative to R-404A. Because R-452A is non-flammable and a simple drop-in, its penetration in Europe has been substantial, whereas Asia and North America are continuing using R-404A.

As Europe continues its planned phase-down, significate steps have been taken to ensure long-term solutions have been put into place. The first step has been to transition to R-452A, but due to its GWP of 2000, it will most likely not become a long-term solution. A list of non-flammable blends with GWPs of around 1400 (such as R-448A, R-449A) are being evaluated and could potentially represent a second step of the phase-down. And finally, R-744, HC-290 and other mildly flammable refrigerants with ultra-low GWP are undergoing research activity and field trials for the final step.

In intermodal refrigerated containers, some manufacturers have proposed R-513A as an alternative to HFC-134a. Also, the first production units running on closed loop R-744 have entered the market. R-744 is attractive for its non-flammable characteristics and ultra-low GWP. The challenge in finding a comparable alternative mainly lies in the efficiency at moderate and high ambient temperatures.

Interest in flammable refrigerants as possible longer term, ultra-low GWP solutions, is evident given the significant activity in codes and standards updates and in the formation of the ISO 20854 working group for thermal containers. At the same time, flammability mitigation still represents a major challenge. No product solutions are currently available in transport applications that rely on flammable refrigerants.

The shipping industry is another sector that has made design changes to incorporate new refrigerants. Some new ships now use R-717 or R-744 either alone or in cascade, while the majority of the global fleet (other than those trading in Europe) will likely continue to operate using HCFC-22.

Although railway air conditioning applications continue to relying heavily on HFC-134a and R-407C, alternatives such as R-513A and R-449A are being evaluated. Also, alternative air cycles and R-744 systems are being tested in niche applications.

Air-to-air air conditioners and heat pumps

Air conditioners, including reversible air heating heat pumps (generally defined as “reversible heat pumps”), range in size from 1 kW to 1,100 kW although the majority are less than 70 kW. The most populous are non-ducted single splits, which are produced in excess of 110 million units per year. All products sold within non-Article 5 countries use non-ODS refrigerants. There is an increasing proportion of production of air conditioners in Article 5 countries that do not use HCFCs. Approximately one half of all units produced globally use non-ODS refrigerants.

Enterprises within non-Article 5 regions are continuing to evaluate and develop products with various HFC/unsaturated HFC blends, such as those comprising HFC-32, HFC-125, HFC-134a, HFC-1234yf and HFC-1234ze. In addition to the introduction of HFC-32 in residential split air conditioners in Japan, increased production and uptake is continuing in South East Asia, India, and in Europe. Further production lines conversion to HC-290 in China is underway, and (except for small and portable units) there is limited market introduction. This is contributed to by the restrictive safety standard requirements for certain product groups. In India, production of HC-290 split air conditioners is continuing, with production line conversions underway in several other, high ambient, countries. Some enterprises within the Middle East still see R-407C and HFC-134a as favourable alternatives to HCFC-22.

Acknowledging that almost all medium and low GWP alternatives are flammable, there has been significant progress with the development of new requirements for safety standards, although as yet the published standards remain restrictive for several low GWP refrigerants. Numerous research activities are investigating a variety of aspects related to the application of flammable refrigerants in air conditioning equipment.

Water and space heating heat pumps

Within the category of water and space heating heat pumps there are heat pump water heaters, space heating heat pumps, and combined space and hot water heat pumps. The required warm water temperature affects the selection of refrigerant. For the same source temperature, heat pump systems are more efficient at lower sink temperatures, but each product must fulfil the required operating temperature. The main use of heat pumps is to replace fossil fuel water heating systems. This is done with the purpose of reducing life time cost and/or to reduce the impact of greenhouse gas emissions. To compete with fossil fuel water heating systems, cost and energy efficiency are the most important factors and these will have a direct impact on the selection of the refrigerant.

Most heat pumps commercialised today make use of non-ODS refrigerants, such as R-410A, HFC-134a, R-407C, HC-290, HC-600a, R-717, R-744 and recently HFC-32, with the majority of new equipment using R-410A. In some Article 5 countries, HCFC-22 is being used due to its favourable thermodynamic properties and high efficiency. There are no technical barriers in replacing HCFC-22 by non-ODS refrigerants. The technical and process changes related to pressure, lubrication and contamination control are well known. Replacements are commercially available, technically proven and energy efficient, and all replacements have a similar or lower environmental impact. The issue of high ambient temperature conditions is of minor or no importance for water heating heat pumps. The main parameters required to select the HFCF-22 alternatives are efficiency, cost effectiveness, economic impact, safe use and easiness of use. Replacements consisting of low GWP HFC blends are under way to become commercially available.

HFC-134a, R-744 and HFC blends R-407C, R-417A and R-410A are commercially available solutions that have the highest grade of safety and easiness to use. Due to the quota requirements, low or lower GWP solutions like HC-290 and HFC-32 show a growing use in Europe. Temperature operation ranges for HC-290 and HFC-32 are better than those for R-410A and their efficiency is similar or better. R-410A, HFC-32 and HC-290 are most cost effective for small and medium size systems, while for large systems, HFC-134a is the most efficient option. R-407C and R-417A are the easiest alternatives for HCFC-22 from a design point of view, but cannot compete with the other HFC solutions.

Chillers

The phase-out of ozone-depleting refrigerants in new chillers is nearly complete, and globally, CFCs have been phased out in new equipment. The use of HCFC-22 in new, small chillers has been phased out in non-Article 5 countries as of 2010, yet there are still some Article 5 countries that are still manufacturing chillers that use HCFC refrigerants. However, global production of such chillers is very small. Despite these positive changes, there is a considerable number of existing chillers worldwide which use CFCs (notably CFC-11, CFC-12 and R-500) and HCFCs (notably HCFC-22 and HCFC-123) as refrigerants and, will remain in service for years to come, unless government regulations or financial incentives drive them to earlier retirement.

The current generation of chillers using zero-ODP refrigerants, dominated by HFCs, was introduced without sacrificing reliability or energy efficiency. Though most HFCs in use today are considered to have high GWPs, this is not a governing factor for chillers, because emissions are minimal and emissions related to their energy consumption dominate the environmental impact. None-the-less, the Kigali Amendment, which has entered into force, is a global agreement to change to refrigerants that have lower GWP.

Investigations into alternative refrigerants with lower GWP started several years ago and is now nearly complete. Understanding the tradeoffs between GWP, efficiency, safety, and applied cost, along with the possibility of new single component refrigerants and blends, was a large task and yielded several acceptable alternatives. It is encouraging to report that the introduction of chillers with new lower GWP refrigerants has started and that chiller manufacturers will make that transition. However, the pace and intensity of the change is uncertain. Manufacturers are reluctant to change quickly, because product development costs are high and consumer demand is relatively low in most countries. Also, government regulations and financial incentives today provide little to accelerate change. As a result, the complete change to lower GWP refrigerants is likely to take several years. It is noteworthy that chillers that use non-fluorinated refrigerants are available today and will be part of a changing mix of commercially available products.

Vapour compression technology dominates all chiller products. Absorption chillers using lithium bromide/water or ammonia/water are available today, just as they have been for decades. Broader use is limited by cost and comparatively lower efficiency. They can be used effectively where there are favourable utility rates or in hybrid systems where waste heat or steam is available. It is unlikely that chillers using not-in-kind technologies will be commercialised in the foreseeable future.

The energy consumption of chillers dominates their environmental impact because the latest generation of chillers has low leak rates and, therefore, low direct global warming impact. The issue then is to introduce complete lines of chiller products, both air and water cooled, with new refrigerants, while not sacrificing performance. It goes without saying that there can be no compromise in reliability or safety for those products that use flammable refrigerants. Safety codes and standards that give complete requirements for the application of flammable refrigerants are not yet published in all regions.

Regulators and customers alike are demanding higher performing, reliable chillers regardless of the refrigerant that is used. As most chillers are applied in large, multiple chiller systems, various application and control strategies are available that can significantly reduce the overall energy consumption of the system.

Vehicle air conditioning

Due to the enforcement of regulations, HFO-1234yf is rapidly increasing its market share in US and Europe in new AC equipped passenger cars, while HFC-134 remains widely used in other regions. Although the transition away from CFC-12 has been successful, there is still a transitional lag in Article 5 countries in that their existing automobiles still use CFC-12.

It is expected that as of 2019 and beyond, air conditioning for cars and light trucks will be met by several refrigerants such as HFC-134a, HFO-1234yf for use in new car models, and R-744. R-744 is expected to be considered as an option for electrified vehicles, when used at the same time for a heat pump function.

The de-carbonization of road transport and its progressive electrification will lead to a change in vehicle air conditioning. The vapour compression cycle will, by far, remain the most adopted technology; however, it will be implemented using different configurations, where the direct expansion will be in part be replaced by liquid cooled systems, to allow the electric and battery thermal management.

The global vehicle air conditioning market will be significantly governed by additional considerations such as safety, costs, regulatory approval, system reliability, heat pump capability (especially for electric driven vehicles) and servicing. The transition to new and more expensive refrigerants is driven by regulations; that is, where there are, or will be specific regulations, HFO-1234yf will be further adopted. Otherwise the old refrigerant (HFC-134a) will continue to be the main option unless (or until) less expensive solutions are available. Within this framework, it should be mentioned that there are studies to evaluate the adoption of less expensive, but flammable, low GWP refrigerants in Article 5 countries (e.g., in India).

Finally, it is unclear whether the bus and heavy-duty truck MAC will follow the evolution in passenger vehicles, utilising for example HFO-1234yf or other options (HFO blends, R-744, etc.)

Energy efficiency and sustainability applied to refrigeration systems

The term sustainable refrigeration is linked to understanding and assessing the efficient use of resources, especially energy for operating refrigeration systems. Energy efficiency considerations were one of the considerations for the introduction of the chapter on sustainable refrigeration in the UNEP assessment reporting period 2010-2014. During 2014-2018, the importance for the selection of refrigerants has increased significantly.

This chapter moves beyond the traditional approach to refrigerant sustainability and uses a more holistic look of an air conditioning and refrigeration system lifecycle, with consideration given to the assessment tools and the aspects of efficient equipment and building design. Other opportunities were identified to achieve sustainability improvements along the lifecycle of a refrigeration system. Reduction in the use of raw materials and the establishment of codes of ethical conduct for suppliers along the value chain are two notable improvements.

Refrigeration, air conditioning, and heat pump equipment are vital means for sustainability in order to address the fundamental needs of humans in areas such as food conservation, food security, healthcare, water heating, and thermal comfort worldwide. There are, however, a number of negative environmental impacts from the use of this equipment that need to be minimised through careful consideration of design, operation, and end of life aspects of these equipment and the refrigerants they use. While keeping focus on possible environmental impacts of refrigeration treated throughout the report - namely the depletion of the stratospheric ozone layer and global warming - a wider range of relevant environmental, as well as social considerations, are briefly described in this chapter, for attention by decision makers.

Sustainable selection criteria, such as energy efficiency, climate impact, and adaptability for thermal energy storage, costs, technological level, safety, flammability and finally liability and responsibility for refrigerants are introduced in this chapter for the first time. Two environmental metrics – life cycle climate performance (LCCP) and total equivalent warming impact (TEWI) are used to select refrigerant options for reducing direct emissions and the sustainable use of refrigerants in service, maintenance, recycling, recovery, and disposal are described.

TFA, as a degradation product of several HFOs and HFCs used (as well as other chemicals containing a CF_3 group), is and will be increasingly emitted to the ambient, thereby polluting aquatic soil layers and drinking water systems, with largely unknown impacts on the biosphere. Emission estimates for 2030 for HFOs *that are TFA related*, made in this report, are at about 60 ktonnes for non-Article 5 countries and at about 90 ktonnes for Article 5 countries. Even with a large number of studies done, adequate knowledge of HFOs decomposing to TFA and TFA pollution impacts is lacking. It implies that substantially more research is needed, particularly in light of the observed rapid, widespread uptake of HFO-1234yf in MAC applications and certain HFOs in other R/AC sectors between now and 2030.

The effects of political and regulatory measures, industry commitments, labeling of energy efficient products and other factors are explained using general technological and regional examples. It is emphasised that sustainable developments often conflict with the goal of minimising investment costs versus minimising energy consumption, thereby increasing energy efficiency.

For the first time, chapter 11 also addresses lifecycle considerations related to sustainable equipment design, sustainability within the refrigeration and air-conditioning servicing, the cold chains, sustainable building concepts and thermal energy storage.

This chapter also describes environmental impacts of refrigeration systems, which can be minimised by:

a. The proper management of the selected refrigerants in response to growing environmental, regulatory, and economic concerns associated with refrigerant emissions, through:
   - Charge minimization through simple measures such as checking the amount of refrigerant being charged, or by innovative technologies such as cascade systems and secondary loops;
   - Improved design for leak tightness;
   - Care taken during manufacturing, installation, service, and maintenance;
   - Refrigerant conservation, using commercially available equipment for recovery, recycling and recovery, as well as destruction of refrigerants at the end of life.

b. The reduction of CO_2 emissions from energy use, achievable through:
   - Minimum energy efficiency performance standards applied through national regulation;
   - The use of renewable energy sources; and
   - Better energy management related to smart grid technologies, waste energy analysis, heat recovery, and anti-cyclical storage.

c. The adoption and enforcement of responsible national and regional policies, legal requirements, and voluntary initiatives aiming to reduce refrigerant emissions through ban on venting and other measures.

d. Environmentally sound end-of-life procedures in response to the growing demand of national and regional regulations.

Not-in-Kind technologies

This chapter analyses technologies that do not employ mechanical vapour compression (MVC) technology and further explores those Not-In-Kind (NIK) technologies that offer at least 15% energy savings compared to MVC technology. The chapter compares their attributes and properties. The technologies are classified as follows:

Commercially Available: At least one manufacturer produces this technology.
Widely Commercially Available: Available at more than one manufacturer.
Emerging: Passed R&D phase and is now established prior to commercial availability.
R&D: In research and development phase, not yet established.

All NIK technologies can be divided into three types:
- Solid state based,
- Electro-mechanical based, or
- Thermal based.

In all, 17 technologies were chosen for evaluation. Thermally based technologies are the ones that are most widely mentioned.

Thermally based technologies: nine technologies examined.
Commercially available or widely available. Examples are Absorption heat pumps, Adsorption heat pumps, Ejector heat pump, Duplex-Stirling heat pump for cryocooling (low temperature cooling) and Stand-Alone Solid Desiccant AC. Primarily for space cooling and some industrial applications. Four other technologies are in the Emerging or R&D stages.

Electro-Mechanical based technologies: five technologies examined.
Evaporative Cooling-both direct/indirect, also used in conjunction with other cooling systems to improve efficiency and reduce water consumption, for space cooling primarily. Bryton cycle Heat Pump for aircraft AC systems, liquefaction of natural gas and for freezing tunnels. Three other technologies are in the R&D stage.

Solid-State based technologies: three technologies examined.
Magnetocaloric and Thermoelectric are widely commercially or commercially available. One technology is in R&D stage.

A table at the end of the chapter describes all technologies. In conclusion, the future is bright for NIK technologies. Plans are underway for assembling a one TR (3.52 kW) window air conditioner prototype operating on Thermoelastic technology (Electro-Mechanical Driven Technologies), at the University of Maryland, USA. In the US, one manufacturer developed a one TR (3.52 kW) prototype space-conditioning system that operate on Membrane Heat Pump technology (electro-mechanical technology) using this two-stage, latent and sensible stages technology. High EERs are predicted here.

Absorption heat pumps are commercially available and have an inherent advantage since they can operate on heat energy, thus saving precious peak electric power. Evaporative cooling has always been an attractive alternative in hot-dry conditions. In addition, Indirect/Direct evaporative cooling extended the use of this technology in mostly hot humid ~~hot~~ as well as hot dry conditions. Its water consumption rates have improved. Evaporative Liquid Desiccant technology (thermal based), in R&D stage, also consumes water. Careful selection is needed in regions where water is scarce. Ground coupled Solid Desiccant AC (thermal based) is also in R&D stage and uses thermal energy. Magnetocaloric technology (solid-state based technology) is commercially available for the commercial refrigeration sector; since only one company claims production, it cannot be considered as widely commercially available. Vuilleumier heat pump technology (thermal based technologies) is in the emerging phase and can be considered a promising technology.

Absorption fuel fired technology and Vuilleumier heat pumps (thermal based technology) both use heat energy and serve both cooling and heating modes. For colder climates where cooling efficiency is offset by a much-improved heating efficiency, these technologies will offer important energy savings despite their lower cooling efficiency.

High ambient

The high ambient temperature (HAT) condition requires a design at 46°C (T3 in ISO 5151:2014) with appropriate operation up to 52°C ambient temperature. At HAT conditions, the heat load of a conditioned space can be up to six times more than that of moderate climates. Larger capacity refrigeration systems are needed which also implies larger refrigerant charges.

As ambient temperatures increase, the system capacity decreases due to higher condensing temperatures and thus compressor discharge temperatures also increase, leading to higher risks of reliability problems. This impacts the efficiency of the system installed, which will lead to a higher energy consumption for the cooling capacity to be provided.

HAT product should be specifically designed for HAT conditions, using a refrigerant suitable for that application and should also have all the safety measures incorporated for appropriate operation. Designing to meet the Minimum Energy Performance Standards (MEPS) in HAT countries is another important factor, as most of these countries have new and upgraded MEPS in place. This requires special design of bigger, more efficient units with an obvious impact on the unit size and cost to meet these new MEPS.

Modelling

There are a number of models used to calculate data for refrigeration and air conditioning applications, such as (1) thermodynamics based models that calculate energy efficiency and energy consumption, (2) combined thermodynamic, flow and heat transfer models used to investigate the impact of various refrigerant properties, (3) models that focus on total (climate relevant) emission reductions from the application of RACHP equipment, departing from assumptions or data on the number of pieces of equipment of certain types in the RAC(HP) subsector, and (4) inventory (bottom-up) models that calculate the amounts of refrigerant charged into RACHP equipment (i.e., the demand), where the equipment numbers are based on sales data of various types of equipment for a country or region; this can also be defined as the (global or regional) bank of refrigerants. A description of the latter model is given in the Annex to the 2010 RTOC Assessment Report. This type of model has been applied for the scenario calculations up to the year 2050 in various TEAP Task Force reports that investigated possible future high GWP HFC as well as low GWP refrigerant demand. Reports were published in the period 2012-2016.

It is quite challenging to find good data on the production of various types of equipment and the related sales for domestic use and export; needless to say that these are extremely important data for any "bottom-up" inventory method. Good progress has been made up to 2018 in determining these parameters; it is expected that the availability of all the data and parameters will enable to develop adequate "bottom-up" scenarios for the refrigerant demand (as well as the related banks and emissions) during the next assessment period (2019-2022).

In 2014 and 2015, the RTOC inventory model was used for studies described in the XXV/5 and XXVI/9 Task Force reports. In 2016, the inventory model was used in the Decision XXVII/4 Task Force report, in order to further investigate the demand for high GWP HFCs and low GWP fluids for the RACHP sector until 2050. In particular, the impact of the length of the conversion period of the manufacturing in certain refrigeration and AC sub-sectors was considered. In 2016, the results of the RTOC inventory model were used to create a sort of database for the demand of all RACHP subsectors for a business as usual scenario for the period 2015-2050; this was done separately for non-Article 5 and Article 5 parties. Next to the RACHP sectors, data estimates were generated (and extrapolated into the future) for other HFC consuming sectors (foams, aerosols, fire protection). Using all these data, the HFC amendment proposals available in 2016 were evaluated and compared, this in particular where it concerns their climate benefits compared to a BAU scenario. Growth rates assumed for the various subsectors for the period until 2050 were given in the XXVII/4 Task Force report. This report paid a great deal of attention to the length of the manufacturing conversion period and its impact on total (manufacturing and servicing) demand, dependent on various mitigation scenarios. All scenarios were determined for the groups of both non-Article 5 and Article 5 parties. It will be clear that this method can also be used for separate countries, once sufficient input data on the equipment base and past refrigerant demand will be available.

The adoption and ratification of the Kigali Amendment is expected to drive new studies on the impact of the use of lower and low GWP fluids. This is likely to also include further emphasis on the impact of energy efficiency and the consequences for energy demand and related CO_2 emissions. The quality of rapidly evolving technical data will be important. This for modelling all aspects needed to provide timely conclusions on mitigation offered by lower and low GWP fluids and by lower indirect emissions, thereby enabling to prioritise policies.

Chapter 1

Introduction

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1 Introduction

1.1 The Refrigeration, Air Conditioning and Heat Pump Sector - General Remarks

Refrigeration, air conditioning and heat pump applications represent the largest part of the ODS and replacement substances used; it is also one of the most important energy using sectors in the present-day society. Estimates are difficult to give but according to the IIR (2015) the refrigeration and air conditioning sector consumes about 17% of the overall electricity used worldwide. The IIR also estimates that the total number of refrigeration, air-conditioning and heat pump systems in operation worldwide amounts to roughly 3 billion. Global annual sales of such equipment is at a level of about 300 billion USD. Almost 12 million people are employed worldwide in this sector.

The economic impact of refrigeration technology is much more significant than generally believed. This is one of the reasons that the economic impacts of the phase-out of refrigerants such as CFCs in the past and HCFCs in Article 5 countries, as well as the phase-down of high GWP (HFC) refrigerants in the foreseeable future, have been and still are difficult to estimate.

Refrigeration, air conditioning, and heat pump applications (RACHP) vary enormously in size and temperature level. A domestic refrigerator has an electrical input in the range of 50-250 W and contains in the range of 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 -10°C and -40°C, with electrical inputs of up to several MW and refrigerant contents of many hundreds of kilograms. Air conditioning and heat pumps often show higher evaporation temperatures, significantly different from refrigeration applications, and also vary enormously in energy input, capacity and size.

In principle one can therefore discriminate between four main areas each of which have subsectors: (i) the food chain in all its aspects, from cold storage via transport to commercial and domestic refrigeration, (ii) process air conditioning and refrigeration, (iii) comfort air conditioning, from unitary equipment to centralised systems using water chillers, including heat pumps, and (iv) mobile air conditioning, with very specific, different aspects. Due to the wide types of equipment used in those areas, this report assesses the RACHP sector in a large number of separate chapters and sections.

In all applications, or sub-sectors, as described in the separate chapters in this report, the attention is focused on the vapour compression cycle. Options and aspects for this technology are described, since it is unlikely that during the next 10-20 years (or, rather, in the near future) other technologies will take over a substantial part of the market. Vapour compression cycle technology has so far provided the simplest, economic, efficient and reliable way for refrigeration. Nonetheless, in a specific chapter this report also provides information about non-vapour compression cycle technologies, called “Not-In-Kind”, which have become commercially available for certain applications, but are mostly in the research or the development stage.

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 parameters such as ODP, GWP and atmospheric lifetime;
- thermodynamic and transport properties;
- pressure and temperature ranges;
- operation pressure and pressure ratios;
- compressor requirements;

- material and oil compatibility;
- material resource efficiency;
- impact on equipment volume and weight, energy efficiency and sound produced;
- health, safety, (acute and chronic) toxicity and flammability aspects;
- training and technical expertise to select and apply alternative refrigerants in the field.

These selection criteria were elaborated upon in various chapters of various UNEP RTOC assessment reports, and these selection criteria have not changed during the last years.
The future of mankind, and his food supply in particular, depends on the availability of sufficient energy and on the availability of efficient refrigeration methods. Of course, this aspect must be more than balanced by a concern for the conservation of the biosphere, including in particular the global warming effect. Energy efficiency, or using energy efficiently, resulting in low energy consumption and related emissions, is therefore one of the most important aspects.

1.2 Montreal Protocol Developments

At the Twenty-Seventh Meeting of the Parties (Dubai, 1-5 November 2015), parties decided, through Decision XXVII/6, to request the three Montreal Protocol Assessment Panels to prepare quadrennial assessment reports in 2018, to submit them to the Secretariat by 31 December 2018 for consideration by the Open-ended Working Group and by the Thirty-First Meeting of the Parties to the Montreal Protocol in 2019, and to present a synthesis report by 30 April 2019.

The decision mentioned:

- To encourage the assessment panels to more closely involve relevant scientists from parties operating under paragraph 1 of Article 5 with a view to promoting gender and regional balance, to the best of its ability, in the work of producing the reports;
- To encourage the assessment panels to use defined, consistent units and consistent terminology throughout for better comparability;
- To request the assessment panels to bring to the notice of the parties any significant developments which, in their opinion, deserve such notice.

Additionally, the Technology and Economic Assessment Panel and their TOCs were requested, in their 2018 report, to consider the following topics, among others:

(a) The impact of the phase-out of ozone-depleting substances on sustainable development;

(b) Technical progress in the production and consumption sectors in the transition to alternatives and practices that eliminate or minimize emissions to the atmosphere of ozone-depleting substances, taking into account those factors stipulated in Article 3 of the Vienna Convention;

(c) Technically and economically feasible choices for the reduction and elimination of ozone-depleting substances in all relevant sectors, including through the use of alternatives, taking into account their performance, and technically and economically feasible alternatives to ozone-depleting substances in consumption sectors, taking into account their overall performance;

(d) The status of banks containing ozone-depleting substances and their alternatives, including those maintained for essential and critical uses, and the options available for handling them;

(e) Accounting for production and consumption for various applications and relevant sources of ozone-depleting substances and their alternatives;

1.2.1 The Kigali Amendment

After 9 years of intense discussions, the parties to the Montreal Protocol overcame the main obstacles for reaching a consensus decision, and at the 28th Meeting of the Parties on 15 October 2016 in Kigali, Rwanda, the parties decided on the Kigali Amendment, with an addition of 18 HFCs as controlled substances under the Montreal Protocol (17 HFCs in a Group I, with HFC-23 in a Group II). Most HFCs were included; HFC-161 was excluded on the basis of its GWP. Since one wanted to address high GWP HFCs, unsaturated HFCs and HCFCs, i.e., HFOs and HCFOs with low GWP, were not included.

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

Under the Amendment, non-Article 5 and Article 5 countries (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 countries will follow with a freeze of HFC production and consumption levels in 2024 (Group 1), with some Article 5 countries (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. The Kigali Amendment has entered into force on 1 January 2019, since it had been ratified by at least 20 parties to the Montreal Protocol (65 parties had ratified the Amendment by 1 January 2019).

HFCs are given with Global Warming Potentials as listed in the IPCC AR4 report (IPCC, 2007), in a separate (new) Annex F to the Montreal Protocol. The Amendment also presents updated Annexes A and C that include GWPs of CFCs and HCFCs. In Annex F, it also mentions HFC-23 (in Group II), a chemical that mainly originates as a by-product in HCFC-22 production facilities. Table 1-1 presents the information contained in the Annex F (and updated Annexes A and C).

Table 1-1: Annex F to the Montreal Protocol (left column) and GWP values for HCFCs and CFCs as given in Annexes A and C (right column) (UNEP, 2017)

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 GWP values listed in the new Annex F must be used for the conversion of HFC mass quantities to carbon dioxide equivalents (CO_2-eq.) in all the reporting that countries will need to submit in relation to the implementation of the HFC control schedules.

Including HFCs as controlled substances under the Montreal Protocol will not affect obligations that the developed (or Annex I) countries have under the United Nations Framework Convention on Climate Change (UNFCCC). While signatories to the Kigali Amendment, parties will still be committed to submit HFC emissions inventory reports to the UNFCCC (as established in Articles 4 and 12 of the UNFCCC). Therefore, HFC consumption and production will be controlled under the Montreal Protocol, while HFC emissions will continue to be reported to the UNFCCC.

The Kigali Amendment has different years for HFC production and consumption values used in the baseline and various phase-down schedules, i.e., two for the group 1 and 2 of Article 5 parties and two for the group 1 and 2 of non-Article 5 parties. The table and figure presented below show the baseline (freeze) and the phase-down schedules (all expressed in CO_2-eq. units).

Table 1-2: Kigali Amendment baseline calculations (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%

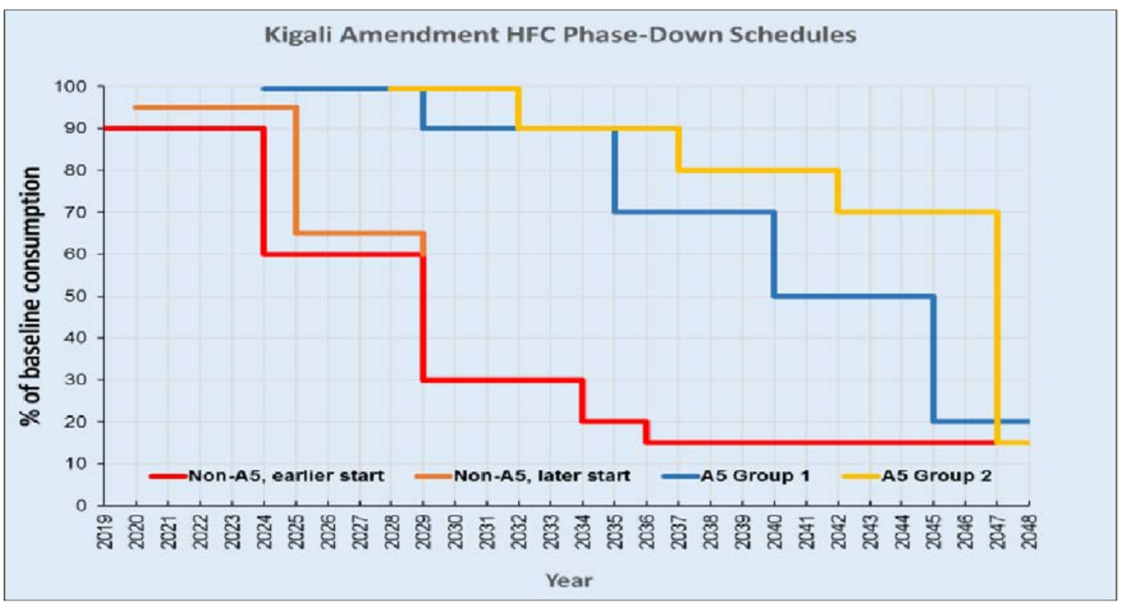

Figure 1-1: Phase-down schedules for the two groups of non-Article 5 parties (a) and the two groups of Article 5 parties (b) (UNEP, 2016)

The reason for including both HFC consumption values and a percentage of the HCFC consumption value (all expressed in CO_2-eq. units) in the calculation of the baseline is due to the fact that HFCs are considered to be utilised 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.

During the preparatory amendment discussions that took place during the last years, one of the issues that Parties had to deal with was the one presented by the countries experiencing high ambient temperatures (HAT) conditions. In these regions, due to their high ambient temperatures, the refrigerant condensing temperature in RACHP equipment is relatively high during a certain part of the year. For RACHP systems, the closer the ambient temperature (i.e., the condensing temperature) is to the refrigerant critical temperature, the less efficient will be the thermodynamic cycle resulting in lower capacity, thus increasing energy consumption, or lowering its COP values.

Operation of a RACHP system at high ambient temperatures intrinsically results in a lower coefficient of performance (COP) (provided evaporation temperatures have to be maintained at a certain level, leading to higher temperature differences). This is the case for all refrigerants but the COP reduction is different among the various refrigerants (Motta and Domanski, 2000). Over the last years, countries experiencing HAT conditions expressed their concerns and worries of meeting an HFC freeze (date and level of consumption) as well as reduction targets. This is where lower-GWP alternatives to HCFC-22 in small/medium size air-conditioning applications have not yet been introduced and verified by local markets. Nevertheless, some of these countries have already started to apply new minimum energy performance standard (MEPS) requirements.

In the discussion of the HFC Amendment proposals, the above issues were addressed. The solution agreed on was found in a different phase-down schedule for the countries India and those experiencing high ambient temperatures, specifically Iran, Pakistan and the Gulf States, and others. This exemption allows for a delay in the HFC freeze date and following phase-down obligations by a period of four years. It applies to the following equipment types:

- Multi-split air conditioners (residential and commercial);
- Split ducted air conditioners (residential and commercial);
- Ducted commercial packaged (self- contained) air conditioners.

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.

Table 1-3: The Article 5 country phase-out schedule for HCFC production and consumption

Schedule	Year
Base line	Average of 2009 and 2010
Freeze	2013
90% (reduction of 10%)	2015
65% (reduction of 35%)	2020
32.5% (reduction of 67.5%)	2025
Annual average of 2.5%	2030 to 2040
0% (reduction of 100 %)	2040

The Kigali Amendment has reinforced the momentum towards applications that will use low-GWP refrigerants and accelerates the innovation for sustainable RACHP technologies. One of the key issues for the Kigali Amendment implementation is the replacement of HCFC-22 and high-GWP HFCs with lower-GWP refrigerants (Peixoto et al, 2017; Kuijpers, 2017). Tables 1-3 and 1-4 show the schedules for Article 5 and non-Article 5 countries for the phase-out of production and consumption of HCFCs.

Table 1-4: The schedule for non-Article 5 country phase-out for production and consumption of HCFCs

Schedule	Year
Baseline	1989 HCFC consumption + 2.8% of 1989 consumption
Freeze	1996
35% reduction (65% of baseline)	2004
75% reduction (25% of baseline)	2010
90% reduction (10% of baseline)	2015
Total phase-out	2020
0.5% of baseline restricted to servicing of refrigeration & air-conditioning equipment until 2030	2020 - 2030

1.3 TEAP Task Force reports

Before the Kigali Amendment was agreed in October 2016, TEAP was requested several times to submit Task Force reports on the progress in identifying and developing ODS (HFC) alternatives. Particularly the XXV/5, XXVI/9 and XXVII/4 Task Force reports can be mentioned here (TEAP, 2014; TEAP, 2015, TEAP, 2016). Apart from a description on progress in developing new refrigerants and on the progress in the various RACHP sub-sectors, they contained scenario investigations on the impact of the phase-in of low GWP alternatives between 2015 and 2050, using the bottom-up model described in the 2010 RTOC 2010 Assessment Report. Bottom-up results for the RACHP sectors (including servicing) were also used (together with data on consumption in non RACHP sectors) in the Ex.III/1 working group report (TEAP, 2016a), in order to determine the climate benefit of various HFC phase-down proposals that were circulated before the 2016 Kigali MOP-28 meeting. Some results of these scenario investigations are given in Chapter 14 of this 2018 assessment report.

Decision XXVIII/2 (para 3) taken at MOP-28 in Kigali, mentioned: “To recognize the importance of timely updating international standards for flammable low-global-warming potential (GWP) refrigerants, including IEC60335-2-40, and to support promoting actions that allow safe market introduction, as well as manufacturing, operation, maintenance and handling, of zero-GWP or low-GWP refrigerant alternatives to hydrochlorofluorocarbons and hydrofluorocarbons”.

It is for that reason that, at the Kigali meeting, parties took Decision XXVIII/4 (“Establishment of regular consultations on safety standards”). It requested the Technology and Economic Assessment Panel to establish a task force that included outside experts as needed:

(a) To liaise and coordinate with standards organizations, including IEC, to support the timely revision of IEC standard 60335-2-40 and ensure that the requirements for the A2, A2L and A3 categories are revised synchronously using a fair, inclusive and scientifically sound approach;

(b) To submit to the Open-ended Working Group at its thirty-ninth meeting a report on safety standards relevant for low-GWP alternatives, including on the following:

- Progress in the revision of international safety standards by the IEC, the International Organization for Standardization (ISO) and other international standards bodies;
- Information concerning tests and/or risk assessments and their results relevant to safety standards;
- Assessment of the implications of international standards for the implementation of the decisions of the Meeting of the Parties to the Montreal Protocol on the accelerated phase-out of HCFCs and HFC control measures, and recommendations to the parties;

It also requested the Ozone Secretariat to organize a workshop on safety standards relevant to the safe use of low-GWP alternatives back to back with the 39th meeting of the Open-ended Working Group, within existing resources (this workshop was held in Bangkok, preceding the OEWG-39 meeting). A report of the workshop is given in UNEP/OzL.Pro.WG.1/39/5 (meeting report of the OEWG-39, 27 July 2017).

A TEAP Task Force was composed of 15 RTOC members (including the two RTOC co-chairs) and 9 outside experts, the beginning of 2017. This Task Force reported to the parties at OEWG-39 via its XXVIII/4 Task Force report (TEAP, 2017). As one of the results, parties requested the Ozone Secretariat to provide them with a tabular overview of relevant standards which should be regularly updated; this tabular overview was first provided to OEWG-40 in 2018.

Decision XXVIII/2 (para 22) taken in Kigali, mentioned: "To request the Executive Committee to develop cost guidance associated with maintaining and/or enhancing the energy efficiency of low-GWP or zero-GWP replacement technologies and equipment, when phasing down hydrofluorocarbons, while taking note of the role of other institutions addressing energy efficiency, when appropriate".

It is for that reason that, at MOP-29, parties took Decision XIX/10 (Issues related to energy efficiency while phasing down hydrofluorocarbons). They requested:

- The Technology and Economic Assessment Panel in relation to maintaining and/or enhancing energy efficiency in the refrigeration, air-conditioning and heat-pump sectors, including in high-ambient-temperature conditions, while phasing down hydrofluorocarbons under the Kigali Amendment to the Montreal Protocol in parties operating under paragraph 1 of Article 5, to assess the following items:
  - Technology options and requirements including:
  - Challenges to their uptake;
  - Their long-term sustainable performance and viability;
  - Their environmental benefits in terms of carbon dioxide equivalents;
  - Capacity-building and servicing sector requirements in the RACHP sectors;
  - Related costs including capital and operating costs;

- The Technology and Economic Assessment Panel to provide an overview of the activities and funding provided by other relevant institutions, as well as definitions, criteria and methodologies used in addressing energy efficiency in the refrigeration, air-conditioning and heat-pump sectors in relation to maintaining and/or enhancing energy efficiency in the refrigeration, air-conditioning and heat-pump sectors while phasing down hydrofluorocarbons under the Kigali Amendment to the Montreal Protocol, as well as those related to low-GWP and zero-GWP hydrofluorocarbon alternatives including on different financing modalities;

- The Technology and Economic Assessment Panel to prepare a final report for consideration by the Open-ended Working Group at its fortieth meeting, and thereafter an updated final report to be submitted to the Thirtieth Meeting of the Parties to the Montreal Protocol on

Substances that Deplete the Ozone Layer taking into consideration the outcome of the workshop described in paragraph 4 below;

- The Secretariat to organize a workshop on energy efficiency opportunities while phasing down hydrofluorocarbons at the fortieth meeting of the Open-ended Working Group.

A TEAP Task Force was formed of 21 members (including 3 co-chairs, of which one RTOC co-chair); ten of them were RTOC members. The Task Force submitted its XXIX/10 Task Force report to OEWG-40 (TEAP, 2018). Parties then listed additional requests for a final Task Force report to MOP-30, which was submitted to MOP-30.

The Ozone Secretariat organised the workshop on energy opportunities back to back with the 40th meeting of the Open-ended Working Group (this workshop was held in Vienna, preceding the OEWG-40 meeting). A report of the workshop is given in UNEP/OzL.Pro.WG.1/40/5 (meeting report of the OEWG-40, August 2018).

On the energy efficiency issue, some more information is given in section 1.4 below.

1.4 The Energy Efficiency issue

Energy (electricity) consumption for refrigeration and air conditioning has been increasing over the last years all over the world, where the developing countries are showing a much larger growth than the developed. The reasons for that include:

- the increase in the number of RACHP products,
- increasing penetration of refrigerators and freezers in homes,
- population growth,
- fast urbanization,
- electrification and changes in consumer patterns,
- the development of the cold chain (especially commercial refrigeration), and
- increase of automobile air conditioning equipment (fuel consumption).

The commercial building cooling demand in the cities will present a higher increase, due to higher levels of building insulation (in many cities), and the trend for modern buildings to have lower thermal mass, and larger glazed areas than traditional buildings. Additionally, there is the need to remove the internally generated heat, due to the rapid growth in the use of IT and other electronic systems in offices.

According to the IIR (2017), the refrigeration and air conditioning (R/AC) sector consumes about 17% of the overall electricity used worldwide. This figure highlights the importance of the RACHP sector energy consumption, which is expected to grow further in the coming years. Additionally, there is the fact that global warming (i.e., climate change) will tend to increase the demand for cooling, particularly in major cities, where temperatures (i.e., in the so-called urban heat islands) are expected to increase much more than the global average.

From a global view, most of the global warming impact of RACHP systems (80% according to the IIR (2017)) is associated with the generation of electricity to operate them (leading to indirect (CO_2) emissions). A lower proportion comes from the emission of HFC refrigerants (hydrofluorocarbons), as well as from the emission of HCFC (hydrochlorofluorocarbon) refrigerants in countries that have not yet banned their use (i.e., the direct emissions). Of course, depending on the way the electricity is generated in a particular region or country (from renewable sources or from thermal power plants), this will be different (i.e., related to the indirect emissions).

The efficiency of RACHP systems can be maximised by a large number of initiatives, thereby minimising their total global warming impact.

In brief, one can say that the energy consumption of RACHP equipment is related to the efficiency of the conversion process as effectuated in the operation of RACHP equipment and systems. This is also particularly related to the amount of cooling/heating that needs to be provided instantaneously to meet the cooling/heating demand. So, *the increase of system and component energy efficiency as well as the reduction of cooling loads* form the most important parts of the RACHP energy consumption reduction, a holistic strategy therefore.

Improving the efficiency of RACHP systems and reducing the energy consumption to adequately deal with cooling loads is very important for decreasing both the end user costs as well as the societal costs (e.g., investment costs for new plants for electricity generation), and to minimize the environmental impact (i.e., reducing greenhouse gas emissions, associated to energy consumption), in this way delivering cooling and heating energy in a best possible, sustainable way.

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

1.5 CFC-11 emissions

Recently, Montzka et al. (2018) reported an unexpected increase in the CFC-11 stratospheric concentration. This issue raises a question about the illegal production and use of CFC-11, which was the main foam blowing agent used by the industry before the CFC phase-out (in Article 5 countries, this was around 2003-2004). When producing CFC-11 via the usual process route, using CTC as a feedstock, there is a certain associated CFC-12 production; the fraction between the two compounds will vary, dependent on the plant and process (catalyst) conditions. Where this remains somewhat speculative, a possible use of the CFC-12 produced in the (illegal) CFC manufacturing process, might be for the maintenance of CFC-12 based equipment, such as mobile air conditioning. Further, CFC-12 could also be put in containers and being sold for a variety of uses. The CFC-11 issue has been discussed in length during 2018 Montreal Protocol meetings and is currently under evaluation by all relevant Montreal Protocol bodies (see Decision XXX/3: Unexpected emissions of trichlorofluoromethane (CFC-11) in the report of MOP-30, UNEP/OzL.Pro.30/11; XXX/3, where paragraph 2 says: “To request the Technology and Economic Assessment Panel to provide the parties with information on potential sources of emissions of CFC-11 and related controlled substances from potential production and uses, as well as from banks, that may have resulted in emissions of CFC-11 in unexpected quantities in the relevant regions….”). An important issue here is to establish CFC-11 emissions that would originate from known banks in foam products and from CFC-11 chillers that are assumed to be still in operation.

1.6 Long term options

In the long term, the role of non-vapour compression methods such as absorption, adsorption, Stirling and air cycles etc. may become more important; however, vapour compression cycles are considered to remain the most important candidates in the near future.

For the long term, there remain, in fact, only five important different refrigerant options for the vapour compression cycle in all refrigeration and A/C sectors, listed alphabetically:

- ammonia (R-717);
- carbon dioxide (R-744);

- hydrocarbons and blends (HCs, e.g. HC-290, HC-600a, HC-1270 etc.);
- hydrofluorocarbons (unsaturated HFCs (HFOs) with a four-digit number, lower GWP HFCs and HFC-HFO blends with 400 and 500 numbers);
- water (R-718).

For the long term, high-GWP and lower GWP HFCs can continue to be applied, as long as their consumption will remain within a country's production and consumption limits (in CO_2-eq. tonnes), in particular if they are used in HFC-HFO mixtures with a lower GWP.

Technologies using the above refrigerant options are in different stages of development or commercialisation. Although high GWP HFCs are (still) widely used in many sectors, low GWP refrigerants are now increasingly being applied. Applications using ammonia and hydrocarbons continue to grow in those sectors where they can be easily accommodated, and for certain applications, CO_2 based equipment is under further development, mainly for small store formats, and supermarket refrigeration, where one targets enhancement of efficiency, even at higher ambient temperatures.

HFOs are being applied in several applications, mainly in mobile air conditioning and in chillers, and as a "side-use" in other RACHP applications, such as equipment where they can be used as lower GWP HFC-HFO mixtures. Water is being applied and may see some increased use in limited applications. Work is being done by several committees in developing standards to permit the application of flammable refrigerants; it is the intent of companies (via intensive work in standard organisations) to reach world-wide accepted flammability limits to be laid down in the different standards.

One can make some clear statements regarding the use lower GWP refrigerants for the long term. Based on the high GWP HFC emphasis, the following substances will not be affected by Kigali Amendment schedules:
ammonia (R-717), carbon dioxide (R-744), hydrocarbons, HFOs, and water (R-717).

Technologies applying these refrigerants have been commercialised or are in different stages of development. Next to these refrigerants, the refrigerants (i.e., HFCs) that are controlled under the Montreal Protocol Kigali Amendment can also be used, however, only in limited CO_2-eq. amounts. Applications for these refrigerants are also under development, focusing of the CO_2-eq. amounts required for the production of new substances. This situation is likely to lead to increased application of recovery and reuse of refrigerants as they have to be reported under the Montreal Protocol.

Similarly, energy efficiency research is partly spurred by the role of energy production and related carbon dioxide emissions. Options for energy efficient operation of equipment are an important issue addressed in each of the chapters of this 2018 RTOC Assessment Report.

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

The 2018 RTOC committee includes 40 representatives from Asian, European, Middle-East, Latin and North American companies, universities and governments, as well as independent experts. Affiliations of the members are listed in Table 1-2.

The 20 "member countries" of the RTOC membership are given in Table 1-3. The names and email addresses of all members are given in the annex of this RTOC 2018 Assessment Report.

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

1	A/genT Consultancy Ltd.	Netherlands
2	Alaa Olama Consultancy	Egypt
3	Anna University	India
4	Bassam Elassaad, Consultant	Lebanon
5	Braunschweig University	Germany
6	Carrier Corporation	U.S.A.
7	The Chemours Company	U.S.A.
8	CRT Cambridge	UK
9	Daikin Europe N.V.	Belgium
10	Danish Technological Institute	Denmark
11	Devotta Consultancy, Chennai	India
12	Emerson	U.S.A.
13	Fiat Ricerche Torino	Italy
14	General Electric, Consumer and Industrial	U.S.A.
15	Ingersoll Rand	Czech Republic
16	James M. Calm, Engineering Consultant	U.S.A.
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	Nelson Consultancy	Jamaica
23	Panasonic	Japan
24	PAWHT	Indonesia
25	Petra Industries	Jordan
26	ref-tech engineering	Germany
27	Re/genT Ltd.	Netherlands
28	Re-phridge Consultancy	United Kingdom
29	Shanghai JiaoTong University	P.R. China
30	SINTEF Energy Research, Trondheim	Norway
31	Sun Yat-sen University, Guangzhou	P.R. China
32	The Trane Company	U.S.A.
33	University of Zagreb	Croatia
34	Università delle Marche	Italy
35	U.S. Environmental Protection Agency	U.S.A
36	Vonsild Consulting	Denmark
37	Zhejiang University, Hangzhou	P.R. China

Table 1-6: "Member countries" of UNEP's Refrigeration, A/C and Heat Pumps Technical Options Committee (RTOC)

Belgium	*Germany*	*Lebanon*
Brazil	*India*	*Netherlands*
China	*Indonesia*	*Norway*
Croatia	*Italy*	*Saudi Arabia*
Czech Republic	*Jamaica*	*United Kingdom*
Denmark	*Japan*	*United States*
Egypt	*Jordan*	

1.8 Set up of the 2018 RTOC Assessment Report

This 2018 Refrigeration, A/C and Heat Pumps Technical Options Committee Assessment Report (hereafter called "2018 RTOC Assessment Report") forms part of the UNEP review pursuant to Article 6 of the Montreal Protocol. It is part of the 2018 assessment work of the Technology and Economic Assessment Panel.

The information collected (particularly in the form of the Key Messages and Executive Summaries) will also be part of the 2018 Technology and Economic Assessment Report, as well as the overall 2018 Synthesis Report that will be composed by the three Assessment Panels in April 2019.

The RTOC assessment report was developed by all full RTOC (reporting) members; as resource persons, the RTOC also had a small number of reviewing members. Each of the chapters was developed by 2-6 experts in the specific sector, and the chapter was chaired by a Chapter Lead Author (CLA) - who did the larger part of the drafting and the co-ordination.

Several drafts of the report were made, reviewed by the separate chapters and discussed in five RTOC meetings (2015-2018). Drafting and reviewing meetings were held in Paris (2015), Kingston, Jamaica (2016), Amman, Jordan (2017) and Bruges, Belgium (2017), as well as in Delhi, India (2018). A last meeting to discuss peer review comments and to decide on the final 2018 RTOC Assessment Report contents was held in Rome, Italy (December 2018).

After the meeting in India (March, 2018) a peer review draft was developed. This August 2018 draft has subsequently been peer reviewed by a number of institutions and associations (twenty in total); each of them reviewed (via their experts) the different chapters sections in a co-ordinated effort. This took place between late August 2018 and early October 2018 (see Table 1-4 for the organisations involved). As a result, 2000 comments were received in total.

All peer review comments received were collected, were sorted out per chapter, and subsequently sent to all separate RTOC chapters (CLAs and members) for further study and addressing comments as far as possible already before the RTOC Meeting in December 2018.

During the December Rome meeting, the RTOC members decided in the respective chapter meetings (and thereafter in plenary) on whether and how to amend the chapter texts 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 involved in their personal capacities, reporting back to associations and institutions.

As a final step, the Key Messages and Executive Summaries were edited by a professional editor. The chapters were put together and once more edited and formatted. UNEP's Ozone Secretariat checked the formatting again before posting the RTOC 2018 Assessment Report.

Table 1-7: Organisations that participated in the peer review of the UNEP 2018 RTOC Assessment Report

1 AICARR	*Ass. Italiana Condizionamento dell'Aria Riscaladamento e Refrigerazione*
2 AIRAH	*Australian Institute of Refrigeration, Air Conditioning and Heating*
3 ASHRAE	*American Society of Heating, Refrigeration and AC Engineers*
4 CAR	*Chinese Association of Refrigeration*
5 CARB	*California Air Resources Board*
6 CHEAA	*China Household Electric Appliances Association*
7 CRAA	*Chinese Refrigeration and Air Conditioning Association*
8 CSE	*Center for Science and Environment, CSE India*
9 DKV	*German Refrigeration Association*
10 EHPA	*European Heat Pump Association*
11 EIA	*Environmental Investigation Agency*
12 EPEE	*European Partnership for Environment and Energy*
13 eurammon	*European Industry - Association for Ammonia etc (some late comments)*
14 JRAIA	*Japanese Refrigeration and Air-conditioning Industry Association*
15 IIR	*International Institute of Refrigeration*
16 IOR	*Institute of Refrigeration, UK*
17 ISHRAE	*Indian Society Heating Refrigeration Air Conditioning Engineers*
18 NIST	*National Institute of Standards and Technology*
19 SAE	*SAE Interior Climate Control Steering Committee*
20 shecco	*R/AC Market Development Expert Organisation Brussels*

1.8.1 Specific items in the 2018 RTOC Assessment Report chapters

The 2018 RTOC Assessment Report has been drafted in the form of a number of chapters. There are chapters on refrigerants and their properties, on the different RACHP application areas and there is one chapter on sustainable refrigeration. The structure of the report was decided to be more or less similar to the structure of the 2014 RTOC Assessment Report:

- Chapter 2 presents refrigerants and all their aspects. It elaborates on Ozone Depleting Potentials, and on ODP and GWP data for reporting purposes. It also investigates the status and research needs for data, i.e., thermophysical, heat transfer, compatibility and safety data. Chapters 3, 4, 5 and 6 deal with the food chain and investigate the technical feasibility of options. They all consider zero ODP refrigerant options and deal with aspects such as the use of non-fluorochemicals, the reduction of charges, energy efficiency improvements etc. Chapter 4 discusses the options for the 3 types of commercial refrigeration equipment. Chapter 5 deals with industrial refrigeration and cold storage, chapter 6 with transport refrigeration.
- Chapters 7 and 8 present options for air conditioners and heat pumps. Chapter 9 deals with the various aspects of chillers, which includes a number of important considerations on energy efficiency.
- Chapter 10 describes the options for mobile air conditioning; it evaluates the potential the options carbon dioxide, hydrocarbons, the unsaturated HFCs (i.e., HFO-1234yf) and other options will have.
- Chapter 11 deals with energy efficiency and sustainability issues in refrigeration.
- Chapter 12 looks into technologies that do not employ vapour compression technology and explore the status of those Not-in-Kind Technologies (NIK).
- Chapter 13 describes the High Ambient Temperature issue and the actions that are being selected to address the issue from a technological standpoint.

- Chapter 14 provides information about the modeling of refrigerant banks, emissions and demand.

All chapters have drafted key messages as well as executive summaries. These key messages, derived from the summaries, as well as the summaries have been put together, and form the first part of this 2018 RTOC Assessment Report.

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Chapter 2

Refrigerants

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2 Refrigerants

2.1 Introduction

The refrigerant focus in recent years has been on unsaturated fluorochemicals and most of them hydrofluoro-olefins (HFOs, unsaturated hydrofluorocarbons), hydrochlorofluoro-olefins (HCFOs, unsaturated hydrochlorofluorocarbons), and blends of them with hydrofluorocarbons (HFCs) and hydrocarbons in some cases, to replace fluids with high Global Warming Potential (GWP). The use of hydrocarbons (HCs), R-717 (ammonia), and R-744 (carbon dioxide) continues. Interest also continues for R-718 (water), already in very limited commercial use, and R-729 (air), but there has been no significant progress with either application so far.

Since the publication of the 2014 RTOC Assessment Report, 35 new refrigerants, most of them blends, have received standard designation and safety classification in American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 34 and addenda thereto (ASHRAE 34-2016) with anticipated adoption also in International Standards Organisation (ISO) 817 (ISO 817:2014).

Among the 35 new fluids there are five single-compound refrigerants, HCC-1130(E), HFO-1132a, HCFO-1224yd(Z), HFO-1336mzz(E), and HFO-1336mzz(Z). The newly introduced single compounds, HCC-1130(E), HCFO-1224yd(Z), HFO-1336mzz(E), and HFO-1336mzz(Z) have relatively high boiling points, making them relevant for high temperature heat pumps and centrifugal chillers. HFO-1132a is a lower toxicity flammable (safety class A2) high pressure fluid, with a boiling point of -86.7°C; it has potential to be used in cryogenic applications, and as a component in new refrigerant blends, for instance to replace R-410A.

The remaining 30 refrigerants are blends. Of these, 21 are blends of traditional HFCs and either HFO-1234yf or HFO-1234ze(E).

2.2 Background

2.2.1 Refrigerant progression

It has been proposed that the historic progression of refrigerants encompasses four phases based on defining selection criteria (Calm and Didion, 1997; Calm, 2002):

- 1830s-1930s – whatever worked: 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), HCs, water (H_2O, R-718), carbon tetrachloride (CCl_4, R-10), hydrochlorocarbons (HCCs), and others; many of them are now regarded as “natural refrigerants” (more exactly those which are found in large quantities in nature, even though the quantities used as refrigerants are usually synthesised, refined, or at least industrially purified).
- 1931-1990s – safety and durability: primarily chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), ammonia, and water (mostly used in absorption cycles).
- 1990s – 2010s – avoidance of ODSs, following attention to stratospheric ozone protection arising from the Montreal protocol in 1989.
- 2010s onwards – intention to adopt refrigerants with as low a GWP as practicable due to the focus on climate change.

However, in practice the application of refrigerants has been far more disparate, with differing approaches occurring in different regions and at different times. For instance, R-717 has been used continuously throughout the entire period since the advent of refrigeration systems. Use of

HCs became widespread in certain other applications since the early 1990s thus bypassing HFCs and unsaturated HFCs entirely. Many countries introduced policies to encourage avoidance of HFCs as far back as the late 1990s.

Indeed, the 1970s and 1980s saw discussions on global warming, leading to increasing interest in non-synthetic refrigerants around the turn of the century, and legislation in the early 2000s, and eventually the Kigali Amendment to the Montreal protocol in 2016 which is a global agreement to phase down HFCs.

The refrigerants which will be selected for global warming mitigation are yet unknown. They are likely to include refrigerants with very low ($< 10^{-3}$) or no significant ozone depletion potential (ODP), low global warming potential (GWP), and high efficiency: unsaturated hydrofluorocarbons (hydrofluoroolefins, HFOs), unsaturated hydrochlorofluorocarbons (hydrochlorofluoro-olefins, HCFOs), unsaturated hydrochlorocarbons (hydrochloro-olefins, HCCs), ammonia, carbon dioxide, hydrocarbons, and water.

2.2.2 Climate impact metrics for refrigerants

The most commonly used metric for indicating the climate impact potential of refrigerant emissions is the 100-year GWP, which is the integrated radiative forcing of a refrigerant emitted to the atmosphere relative to that of the same mass of carbon dioxide (CO_2) over a 100-year time horizon. Some parties advocate use of GWP values for shorter or longer integration time horizons or various instantaneous or sustained metrics such as the global temperature potential (GTP) (Shine et al., 2005; Hodnebrog et al., 2013; see §8.7 of (IPCC, 2014) for detailed discussions of pulse GTP and sustained GTP).

In this chapter, both the 20 year GWP and the 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 global warming over the next decades; it is also better for differentiating between substances with short lifetimes.

The advantage of using the 100 year GWP is that it is more commonly used in scientific literature, standards, and regulations, and this is important when communicating issues that impact climate. Moreover, the 100 year GWP is also better for differentiating between substances with longer lifetimes. Examples are PFC-116 and HFC-143a; the difference for their 20 year GWPs is less than 20%, while the difference for the 100 year GWPs is more than a factor of 2.

As long-lived substances can be used in small amounts in blends, with the short-lived substances used to create lower GWP blends, the use of a 20 year GWP may lead to decisions favouring the shorter term at the cost of the longer term.

A classification of 100 year GWP levels which is a repetition of the proposal in the previous RTOC assessment report (UNEP, 2015) is given in Table 2-1. The complication of defining a substance as “low GWP” or “high GWP” is that the climate impact is the product of the GWP and the amount (in kg) emitted, so even though CO_2 is classified in Table 2-1 as ultra-low GWP, the amount emitted by mankind is large enough to yield significant climate impacts; even though very little of that impact results from its use and emission as a refrigerant.

Table 2-1 categorizes using “less than” or “more than” and this enables a refrigerant such as HFO-1234yf to be included regardless of whether its label is ultra-low, very low, or low GWP. Likewise, a refrigerant such as HFC-23 is then included in the groups ultra-high, very high, and high GWP.

For gases with lifetimes of a century or more, the uncertainties are of the order of ±20% and ±30% for 20- and 100-year time horizons. For shorter lived gases the uncertainties in GWPs will be larger (IPCC, 2014). This is one reason why care must be taken when comparing the GWP of refrigerants. For substances with very low GWP the picture is complicated further since, for historical reasons, GWPs for hydrocarbons are indirect GWPs, which include breakdown products such as CO_2, as opposed to the GWPs for HCFCs, HFCs etc., which do not cover breakdown products.

Table 2-1: Classification of 100 year GWP levels

100 Year GWP	Classification
< 30	Ultra-low or Negligible
< 100	Very low
< 300	Low
300-1000	Medium
> 1000	High
> 3000	Very high
> 10000	Ultra-high

Comparing carbon emissions associated with the use of refrigerants should be done with caution so as to also include a comparison of energy efficiency of the refrigerant in the given application. Emissions from energy production may have a greater climate impact than the refrigerant emissions only. Further discussion can be found in chapter 11.

2.2.3 Selection of refrigerant

There are several factors that should be considered when selecting an alternative refrigerant for refrigeration, air conditioning and heat pump systems and applications. The chosen solution will be a trade-off between several factors including:

- Suitability for the targeted use;
- Performance (capacity and efficiency);
- Safety, including flammability and toxicity, and available risk mitigation measures;
- Availability of the refrigerant;
- Zero or near-zero ODP;
- Climate change impact (reduced direct and indirect — energy-related — emissions);
- Other environmental impacts, including bi-products from the production;
- Commercial availability of refrigerant (with reasonable cost);
- Equipment and servicing cost;
- Skills and technology required to use;
- Recyclability;
- Stability and materials compatibility.

The selection of a refrigerant for a given application must necessarily be a compromise of the above criteria. Other than zero or near-zero ODP, the rest of the parameters will to be traded-off against one another to arrive at the optimum for each type of system and application. In particular, the carbon emissions include both the “direct” and “indirect” emission contributions of the product over its lifetime.

A number of approaches have been documented in the literature including: Total Equivalent Warming Impact (TEWI), Life Cycle Climate Performance (LCCP), Life-Cycle Warming Impact (LCWI), Multilateral Fund Climate Impact Indicator (MCII) and other methods.

For new refrigerants for existing systems, there are a number of criteria that should be considered in order to select a suitable refrigerant. In summary, with respect to the refrigerant being replaced, these are:

- Similar volumetric refrigerating capacity over the range of normal operating evaporator and condenser temperatures;
- No lower energy efficiency consequence;
- Not exceeding the condensing pressure at maximum condenser temperature;
- As close a match to the temperature glide, or negligible temperature glide if the original was a single component or a fluid with minimal glide;
- Similar oil solubility and miscibility gap;
- Non-flammable or not having higher flammability;
- Low toxicity or not having higher toxicity;
- Commercial availability (at reasonable cost);
- Availability of equipment and infrastructure for recovery and reuse or destruction.

There are a number of other parameters that have to be considered. However, in practical terms, it is unlikely that any of the commercially available refrigerants now can meet all of the above criteria; therefore, one can expect some compromise in the selection process.

A refrigerant that is capable of replacing an existing refrigerant without a need for changing any major system components, including the oil, is sometimes referred to as a drop-in refrigerant. The term “drop-in” is somewhat misleading, as safety standards require the system to be upgraded to the latest safety requirements for any change of refrigerant type, and the trade-offs mentioned above may affect the performance and durability of the system (See Chapter 7, section 7.4).

2.2.4 Refrigerants choice and energy efficiency

In two studies, Mc Linden (2015, 2017) investigated potential future low GWP refrigerants, starting from a database of > 60 million chemicals. The two studies also deal with the theoretical energy efficiency of refrigerating cycles with both traditional high GWP refrigerants and with the low GWP candidates. The conclusion is that, if a refrigerant is used properly, the COP of the various refrigerants will not differ much, with differences up to +/-5%. Similar improvements can typically be made by improving other components of the system, such as heat exchangers and compressors, while reducing cooling or heating loads that typically have a much larger effects on energy consumption. This makes energy efficiency improvements more a function of capital investment than of the refrigerant selection.

2.3 Recent developments

2.3.1 New refrigerants since the 2014 RTOC Assessment Report

Since the 2014 RTOC Assessment Report, 35 new refrigerants have received ASHRAE designations and safety classifications (ASHRAE 34-2016 and addenda thereto). These refrigerants are listed in tables 2-4, 2-5, and 2-6. For a complete list of refrigerants with ASHRAE designation and detailed description of the sources of data, see Annex 1 to Chapter 2.

Among the 35 new fluids are five single-compound refrigerants, HCC-1130(E), HFO-1132a, HCFO-1224yd(Z), HFO-1336mzz(E), and HFO-1336mzz(Z). The newly introduced molecules, HCC-1130(E), HCFO-1224yd(Z), HFO-1336mzz(E), and HFO-1336mzz(Z) have relatively high boiling points, making them relevant for high temperature heat pumps and centrifugal chillers. HFO-1132a is a flammable (safety class A2) high pressure fluid, with a boiling point of -86.7°C it has potential to be used in cryogenic applications, as well as a component in new refrigerant blends, for instance to replace R-410A.

The remaining 30 refrigerants are blends. Of these, 21 are blends of traditional HFCs and either HFO-1234yf or HFO-1234ze(E). Seven are blends of traditional HFCs, some containing low levels of hydrocarbon to facilitate oil-miscibility. One blend, R-514A, is a mixture of the newly introduced molecules HFO-1336mzz(Z) and HCC-1130(E), this blend has a boiling point of +29°C and like its constituents is relevant for high temperature heat pumps and axial turbo (centrifugal) and hybrid turbo chillers, as are its components

Table 2-4: 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
HCC-1130(E)	CHCl=CHCl	trans-1,2-dichloroethene	96.9	47.7	B2				
HFO-1132a	CF_2=CH_2	1,1-difluoroethylene	64.0	–86.7	A2	4.0 days	0.004	<1	<1
HCFO-1224yd(Z)	CF_3CF=CHCl	(Z)-1-chloro-2,3,3,3-tetrafluoropropene	148.5	14.5	A1				
HFO-1336mzz(E)	CF_3CH=$CHCF_3$	trans-1,1,1,4,4,4-hexafluoro-2-butene	164.1	7.4	A1				
HFO-1336mzz(Z)	CF_3CH=$CHCF_3$	cis-1,1,1,4,4,4-hexafluoro-2-butene	164.1	33.4	A1	22.0 days	0.07	2	6

Table 2-5: 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
R-407G	R-32/125/134a (2.5/2.5/95.0)	100.0	–29.2/–27.2	A1	1 400	3 800
R-407H	R-32/125/134a (32.5/15.0/52.5)	79.1	–44.7/–37.6	A1	1 500	3 800
R-407I	R-32/125/134a (19.5/8.5/72.0)	86.9	–39.8/–33.0	A1	1 400	3 800
R-436C	R-290/600a (95.0/5.0)	44.6	–41.5/–39.5	A3	1	1
R-447B	R-32/125/1234ze(E) (68.0/8.0/24.0)	63.1	–50.1/–46.0	A2L	750	2 200
R-449B	R-32/125/1234yf/134a (25.2/24.3/23.2/27.3)	86.4	–46.1/–40.2	A1	1 400	3 200
R-449C	R-32/125/1234yf/134a (20.0/20.0/31.0/29.0)	90.3	–44.6/–38.1	A1	1 200	2 900
R-452B	R-32/125/1234yf (67.0/7.0/26.0)	63.5	–51.0/–50.3	A2L	710	2 100
R-452C	R-32/125/1234yf (12.5/61.0/26.5)	101.9	–47.5/–44.2	A1	2 200	4 100
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	1 700	4 100
R-454A	R-32/1234yf (35.0/65.0)	80.5	–48.4/–41.6	A2L	250	890
R-454B	R-32/1234yf (68.9/31.1)	62.6	–50.9/–50.0	A2L	490	1 700

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	Safety Class	GWP 100 Year	GWP 20 Year
R-454C	R-32/1234yf (21.5/78.5)	90.8	–46.0/–37.8	A2L	150	540
R-455A	R-744/32/1234yf (3.0/21.5/75.5)	87.5	–51.6/–39.1	A2L	150	540
R-456A	R-32/134a/1234ze(E) (6.0/45.0/49.0)	101.4	–30.4/–25.6	A1	650	1 900
R-457A	R-32/1234yf/152a (18.0/70.0/12.0)	87.6	–42.7/–35.5	A2L	150	520
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	1 600	3 900
R-459A	R-32/1234yf/1234ze(E) (68.0/26.0/6.0)	63.0	–50.3/–48.6	A2L	480	1 700
R-459B	R-32/1234yf/1234ze(E) (21.0/69.0/10.0)	91.2	–44.0/–36.1	A2L	150	530
R-460A	R-32/125/134a/1234ze(E) (12.0/52.0/14.0/22.0)	100.6	–44.6/–37.2	A1	2 100	4 100
R-460B	R-32/125/134a/1234ze(E) (28.0/25.0/20.0/27.0)	84.8	–45.2/–37.1	A1	1 300	3 000
R-460C	R-32/125/134a/1234ze(E) (2.5/2.5/ 46.0/49.0)	105.3	–29.2/–26.0	A1	730	2 000
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	2 700	5 300
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	2 200	4 700
R-464A	R-32/125/1234ze(E)/227ea (27.0/ 27.0/40.0/6.0)	88.5	–46.5/–36.9	A1	1 300	2 700
R-465A	R-32/290/1234yf (21.0/7.9/71.1)	82.9	–51.8/–40.0	A2	150	530

Table 2-6: Data summary for new azeotropic refrigerant blends

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	Safety Class	GWP 100 Year	GWP 20 Year
R-513B	R-1234yf/134a (58.5/41.5)	108.7	–29.2/–29.1	A1	560	1 600
R-514A	R-1336mzz(Z)/1130(E) (74.7/25.3)	139.6	29.0/29.0	B1		
R-515A	R-1234ze(E)/227ea (88.0/12.0)	118.7	–18.9/–18.9	A1	380	630
R-516A	R-1234yf/134a/152a (77.5/8.5/14.0)	102.6	–29.4	A2L	140	400

2.3.2 Unsaturated hydro-halochemicals

Facing regulatory pressures to eliminate refrigerants with high GWP, major refrigerant manufacturers have pursued unsaturated hydro-halochemicals. They are chemicals consisting of two or more carbon atoms with at least one double bond between two or more of them as well as hydrogen and also chlorine, fluorine, or other halogens. Unsaturated hydrochlorofluorocarbons and hydrofluorocarbons also are chemically identified as chlorofluoro-alkenes or fluoro-alkenes, respectively, and also as chlorofluoro-olefins or fluoro-olefins. Double carbon-carbon bond(s) make(s) the compounds more unstable, and therefore more reactive and for the majority also flammable. The result is short atmospheric lifetimes and, thereby, very low ODP and GWP. The unsaturated HCC (also identified as hydrochloro-alkene or hydrochloro-olefin), HCFC (also identified as hydrochlorofluoro-alkene or hydrochlorofluoro-olefin, HCFO), and HFC (also identified as hydrofluoro-alkene or hydrofluoro-olefin, HFO) families are focal examples.

Chemical producers are pursuing alternatives for the most widely used refrigerants. In the naming of unsaturated halocarbons the prefix for unsaturated HCFCs and unsaturated HFCs can alternatively be indicated as HCFO and HFO respectively, where the O for olefin – in spite of the fact that there are carbon atoms and no oxygen in the substance– replaces the carbon C (ASHRAE 34-2016, ISO 817:2014). In this report the prefix used is "HCFO" and "HFO", respectively, except for blends (with an R- prefix); for unsaturated HC and HCC chemicals the prefixes "HC" and "HCC" are used (preceded by the word "unsaturated" since the HO and HCO prefixes are not recognised according to ISO 817 (ISO 817:2014).

The unsaturated hydro-halochemicals are heavier than most traditional refrigerants and many are low-pressure fluids. Chemical producers are pursuing alternatives for the most widely used low-, medium-, and high-pressure refrigerants, and the medium- and high-pressure fluids are typically created by mixing unsaturated HFCs with other near-zero ODP or non-ODP refrigerants such as HFC-32, HFC-125, HFC-134a and R-744. These blends are mixed to closely match the performance of the refrigerants currently being used such as replacements for HCFC-22 and R-410A. Due to their compositions, most of these blends exhibit various levels of temperature glide (being the difference in dew- and bubble-point temperatures at a given saturated vapour pressure) and in many cases are flammable albeit many with low flammability.

Due to the growing use of unsaturated HFCs and HCFCs (HFOs), it is expected and indeed necessary that their properties continue to be studied. Available thermodynamic and thermophysical properties are included in (NIST, 2018).

TFA is a break down product of unsaturated HFCs which is hardly retained in soil (Likens et al., 1997 and Richey et al., 1997) and due to its high persistency considered to accumulate in the aqueous phase (Solomon et al., 2016). A number of initial studies looking at the trifluoroacetic acid (TFA) build-up resulting from the use of unsaturated HFCs in mobile air-conditioning indicate negligible environmental impacts (Kajihara et al., 2010; Luecken et al., 2010; Papasavva et al., 2009). More recent studies for a wider range of applications concluded that an increasing use of HFO refrigerants is expected to have a negligible effect on the environment (UNEP, 2015; Wallington, 2018). Based on estimates to 2040, increases are predicted to remain relatively low and are therefore not expected to be detrimental to the environment. While the effects of TFA on the environment are considered to be negligible for the next few decades (NEA, 2017), potential long-term impacts may require future assessments due to the combination of high environmental persistence and mobility of TFA and uncertainty in future uses of HFOs (WMO, 2014). Further detailed discussion can be found in Chapter 11.

Like the saturated HFC and HCFC fluids, unsaturated HFCs and HCFCs create toxic substances when exposed to high temperatures or high doses of UV light combined with heat. The toxic substances concerned are especially hydrofluoric acid (HF) and carbonyl fluoride (COF_2). The lower degree of chemical stability arising from the double bond of unsaturated fluids leads to a higher propensity to break down to these substances, and has given rise to concern over the toxicity hazards in work environments.

2.3.3 Refrigerants for high temperature heat-pumps

Medium or high pressure fluids such as HFC-134a or R-410A and their alternatives are not suitable to high temperature heat pumps (typically above 80°C) because the condensing temperature is too close or above the critical temperature (de Larminat, 2012).

The new candidates, HCC-1130(E), HCFO-1224yd(Z), HFO-1336mzz(E), and HFO-1336mzz(Z) have relatively high boiling points (+47.7°C, +14.5°C, +7.4°C and +33.4°C respectively). HCC-1130(E) and HFO-1336mzz(Z) are used in the new blend R-514A (boiling point +29°C).

These boiling points are much higher than traditional refrigerants used for ACR. For instance HCFC-22, HFC-134a, and R-410A have boiling points of -41°C, -26°C, and approximately -51.5°C respectively.

The high boiling points make the new fluids good candidates for high temperature heat pumps, for example for hot water for district and service water heating use (typically +80°C) from waste heat. The low evaporation pressure of the fluids also makes them candidates for turbo-radial (centrifugal) and hybrid turbo compressor.

There is also a continued interest in ammonia and hydrocarbons including hydrocarbon blends for these kinds of application.

2.3.4 Fluoroiodocarbon, CF_3I

Trifluoroiodomethane, CF_3I, is a fluoroiodocarbon which has been considered several times over the couple of decades (Nimitz et al, 1994; Meycr, 1999; Youn et al, 2010). It is currently being used by the industry as a fire suppressant (Meycr, 1999), and has potential to be used as a component of refrigerant mixtures to produce low flammability refrigerants with significant low GWP. There has been concerns about the stability of CF_3I, and there is ongoing researched on this topic.

CF_3I has an atmospheric lifetime of 5 days (WMO, 2014). Due to the very short atmospheric lifetime, CF_3I has 100-year GWP of 0.4 (IPCC, 2007), and an ODP of 0.008 (WMO, 2014; Youn et al 2010). The very short lifetime is also the reason that the ODP varies significantly, depending on when and where it is emitted to the atmosphere (WMO, 2014), see Table 2-7. This variation calls for more research on which factors affects the ODP.

Table 2-7: ODP values from (WMO, 2014). Values in brackets show seasonal variability.

North America	Europe	East Asia	Indian Subcontinent
0.0068	0.0034	0.0120	0.0940
[0.0022 – 0.0120]	[0.0013 – 0.0061]	[0.0020–0.0310]	[0.0290–0.1900]

The occupational exposure limit (OEL) of CF_3I has been assigned by the (OARS, 2018) to be 500 ppm. The EU CLP regulation classifies the substance H341 “Suspected of causing genetic defects” (EU CLP, 2008).

2.3.5 Developments of R-744 (carbon dioxide) systems

R-744 (CO_2) was used as a working fluid in refrigeration systems since the late 19^{th} century. It disappeared from marine applications in the 1950’s mainly due to technical difficulties and the introduction of synthetic working fluids, operating at lower working pressures. These technical difficulties have been solved and there is a wide range of applications where R-744 is the preferred working fluid (deep freezing applications, commercial refrigeration, hot water heat pumps, mobile AC and heat pumps, etc.).

The use of R-744 has until recently been limited to areas with medium to low ambient climate, however the use of ejector technologies have made R-744 useable for refrigeration in high ambient temperature climates (Blust, 2018).

There is a strong growth in R-744 use driven by legislation, especially the EU F-gas regulation (517/2014).

2.3.6 Assessment of current and future refrigerants and GWP

Figure 2-1 and 2-2 shows the A1 and A2L refrigerants which have been added to ASHRAE 34 (ASHRAE 34-2016) since the 2014 RTOC Assessment Report, along with a few commonly used traditional refrigerants. The figure shows the 100 year GWP, boiling point and glide for each refrigerant.

These figures illustrate the relationship between the boiling point and the flammability and GWP of new refrigerants. Note that stating that a fluid has a low boiling point is equivalent to stating that it has a high pressure, and high pressure is correlated with high capacity. There is a clear trend that a low boiling point (high pressure/capacity) is correlated with a higher GWP, and that higher flammability is correlated with lower GWP.

A notable exception to this is R-744, which is non-flammable, high pressure, and has a GWP of 1. Adding R-744 to a blend lowers the GWP and the flammability, but also increases the refrigerant glide, and a too high glide can make the fluid unsuitable in many applications.

The figures below give a good estimate of which levels of GWP are to be expected for various capacity/pressure levels for a given flammability class.

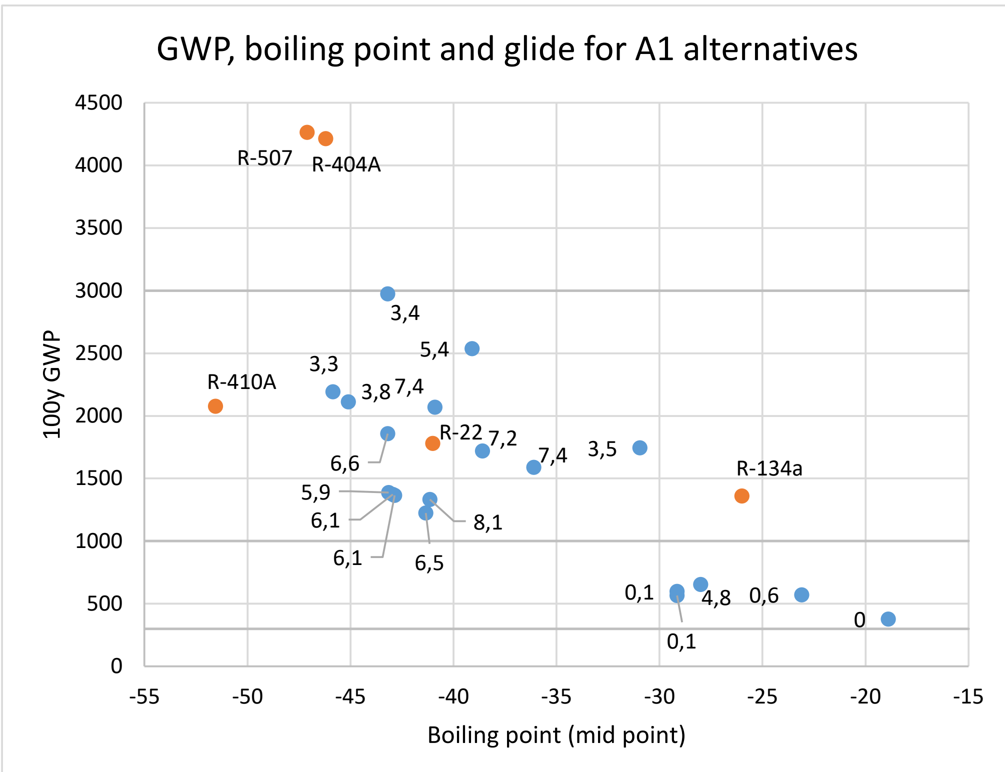

Figure 2-1: Refrigerants of safety class A1 proposed since 2010, with values of 100 year GWP, boiling point, and glide. The number next to each blue dot is the glide. The orange dots are selected traditional HFC and HCFC refrigerants for comparison with zero or almost zero glide.

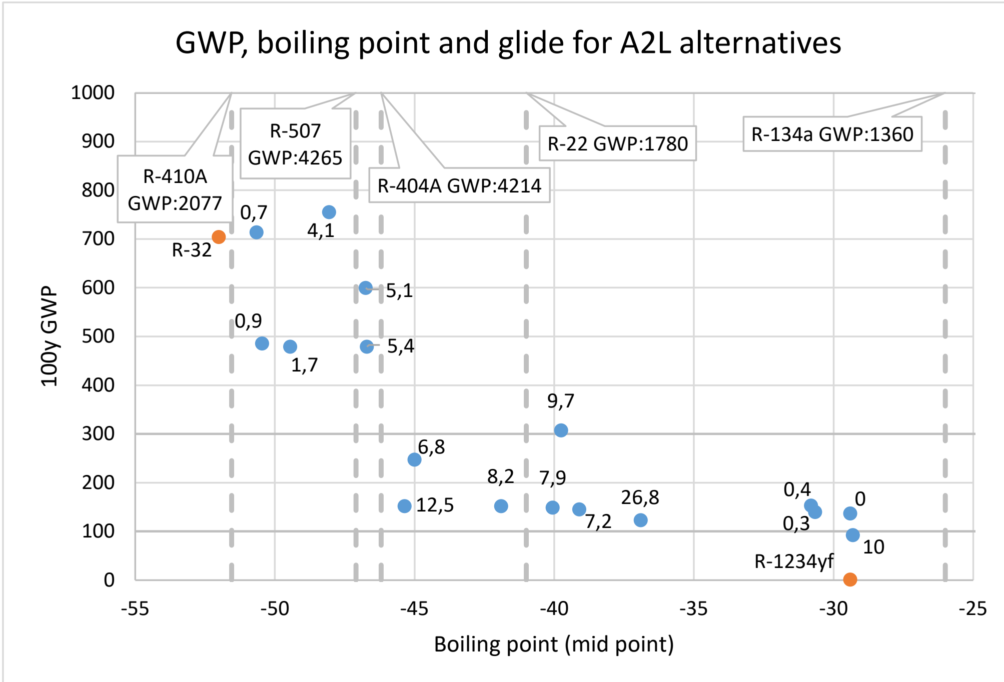

Figure 2-2: Refrigerants of safety class A2L proposed since 2010, with values of 100 year GWP, boiling point, and glide. The number next to each blue dot is the glide. The orange dots are selected pure refrigerants introduced before 2010. The boiling point of selected HFC and HCFC refrigerants with zero or almost zero glide are marked with dotted grey lines for comparison.

One recent study (McLinden, 2017) started with a database of more than 60,000,000 chemical structures, screening the molecules and finding all to be non-ideal, hence again the need for trade-offs (Midgley 1937, Calm and Didion, 1997). The study is limited to compounds consisting of C, H, F, Cl, Br, O, N or S, as only a small portion of the periodic table forms substances volatile enough to be used as refrigerant (Midgley 1937), the study is also limited to compounds with GWP up to 1000. A main conclusion presented in the study is that the ideal energy efficient, non-toxic, non-flammable, and broadly applicable refrigerant with negligible GWP does not and probably cannot exist. A critique of the study is that it does not include compounds containing iodine, though some of these compounds are volatile enough to be used as refrigerants. Another critique is that compounds with GWP above 1000 can play a role as components of blends, or even as pure fluids during the transition to low and very low GWP refrigerants.

The phase-down of HFCs under the Kigali Amendment and under some national legislations is measured in CO_2 equivalents. It is difficult to estimate how this will impact specific refrigerants; however, the average GWP in the market can be estimated as a function of time (Pachai, 2018), see figure 2-3 for an illustration. The average GWP gives an idea about which refrigerants can be used in high volume applications, however if a majority of the market uses refrigerants with GWP well below the average, then a few market segments can use refrigerants with GWP significantly higher than the average. Approximately half to two-thirds of a new refrigerant is used for servicing and the design of existing systems limits the flexibility of which refrigerants to use. The lifetime of equipment in the RAC market is 10-20 years (but can be much longer). This means that when a phase-down starts, the service sector will use a very high fraction of the CO_2 equivalents available, and the average GWP for new systems will have to come down faster than indicated by the phase down curves.

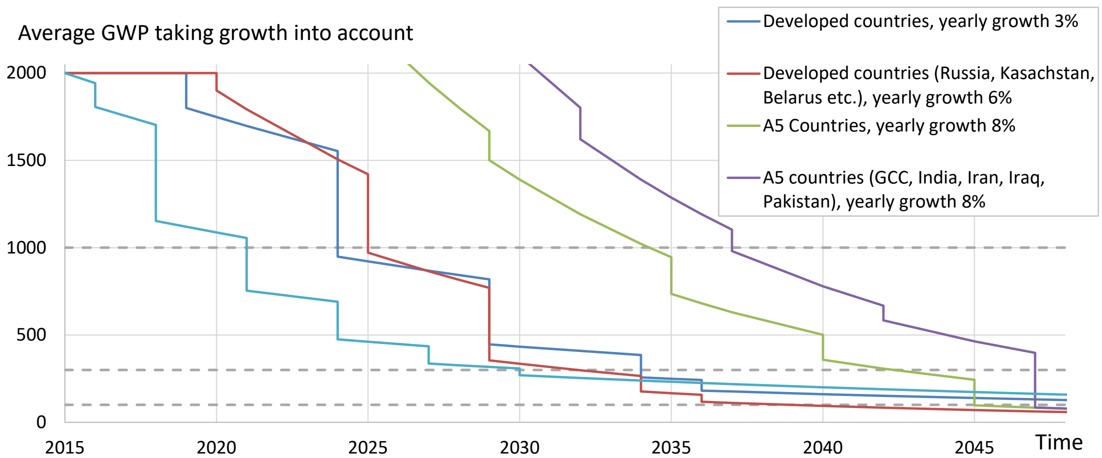

Figure 2-3: Average GWP over time, taking market growth into account (Pachai, 2018). Higher growth rates give steeper slopes of the curves.

An analysis conducted by the California Air Resources Board (CARB) indicates that due to long equipment lifetimes, the reduction of emissions from HFCs lag 10 to 15 years behind equivalent reduction in the production and consumption of HFCs (CARB, 2017). Another factor which will influence the average GWP over time is the growth in refrigerant use. When the amount of refrigerant brought to market increases, the average GWP has to decrease to keep the same amount of CO_2 equivalents. The effect is that most of the refrigerants currently being introduced in the market are intermediary solutions, and will be confined to niche applications in the long run.

The market is unlikely to be willing to support many different refrigerants for the same application owing to safety and distribution issues. However, industry will have to work with both the currently established refrigerants and new refrigerants addressing ozone depletion and/or climate change concerns for several decades. In the long run, the number of candidates is likely to decrease, but it is too early to tell which or even how many of the refrigerant candidates will survive.

Training and education will have increasing importance going forward given the growing use of flammable refrigerants, and maybe in the future also increasing toxicity as the limits of acceptability is explored by the industry.

A new standard on competences, ISO 22712, is under development to support global training and education, and will be necessary to investments in increasing competences to facilitate the HFC phase down. The education is required for a good design and installation of an energy efficient system. Proper training and education is also required for technicians to keep the system in safe condition and to keep it running efficiently all the service life of the system.

2.4 Flammable refrigerants and safety standards

Most refrigerant producers seek addition of new refrigerants in the refrigerant standards ISO 817 (ISO 817:2014) and ASHRAE 34 (ASHRAE 34-2016) and addenda thereto.

ASHRAE 34 (ASHRAE 34-2016) and ISO 817 (ISO 817:2014) classify each refrigerant for safety, for instance “A2L”. The first letter of the safety class describes the toxicity, A for lower level of toxicity and B for higher level of toxicity, while the second part is the flammability of the refrigerant: 1 (no flame propagation at stipulated conditions), 2L (lower flammability), 2 (flammable), and 3 (higher flammability). As mentioned above, there often is a trade-off between GWP and flammability. A low GWP can be achieved by having the refrigerant break down quickly in the atmosphere, however this also means that the refrigerant breaks down easier when subjected to ignition sources. For many applications, flammability considerations were avoidable prior to phase downs for GWP.

Although safety standards are not mandatory in most countries, unless explicitly adopted by regulation, they are one source where the industry looks for guidance for handling the flammability. For instance, ISO 5149 (ISO 5149:2014) Part 1 specifies limits to charge amount depending on safety class, system type, system location, and accessibility by people unaccustomed with the safety procedures relating to the system. Legislation will also have an influence, for instance national, state or even local legislation and building codes.

The requirements for flammable refrigerants are very similar across the different flammability classes, the different flammability properties result in different risks (probabilities) and consequences; therefore, varying refrigerant charges and thereby system designs for each refrigerant. Further discussion can be found in the Task Force XXVIII/4 report (UNEP, 2017). An overview from this report of the scope of different international standards is in Table 2-8.

It is still not clear which classes of flammability will be accepted for each application and for the capacities required. The acceptance of flammable refrigerants and the appropriate updates of standards and legislation is clearly a contemporary challenge for the refrigeration air conditioning, and heat-pump industry.

Table 2-8: Scope of different international and regional safety standards for R/ACHP systems from the TF XXVIII/4 report (UNEP, 2017)

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[1]	ISO 20854[2]	ISO 5149 -1	ISO 5149 -2	ISO 5149 -3	ISO 5149 -4
Domestic refrigeration		X					X	X	X	X
Commercial refrigeration				X			X	X	X	X
Industrial systems							X	X	X	X
Transport refrigeration							X	X	X	X
Air-to-air air conditioners & heat pumps			X				X	X	X	X
Water heating heat pumps			X				X	X	X	X
Heat pump tumble driers	X						X	X	X	X
Chillers			X				X	X	X	X
Vehicle air conditioning					X					X[3]
Refrigerated containers						X	X	X	X	X

[1] ISO 13043 only covers R134a, R744 and R1234yf, so all other alternative refrigerants are out of scope.
[2] ISO 20854 Thermal containers — Safety standard for refrigerating systems using flammable refrigerants – Recommendations Requirements for design and operation is under preparation.
[3] 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.

2.5 Concluding remarks

This chapter addresses a number of refrigerant (existing as well as new) aspects and provides tabular summaries of refrigerant designations as well as physical, safety, and environmental data for refrigerants.

Refrigerant choices must balance several factors including the suitability for the targeted use, availability and cost of the refrigerant and associated equipment, service thereof, implications for energy efficiency, safety, ease of use and environmental issues.

The refrigerants that have emerged since the last, 2014 RTOC Assessment Report have been developed in response to climate concerns, with climate impacts considerably lower than most of the currently used substances. Among the new refrigerants are 22 blends based on unsaturated HFCs (21 are mixes of traditional HFCs and either HFO-1234yf or HFO-1234ze(E), and one is an HFO-1336mzz(Z)/HCC-1130(E) blend), and of these, ten (10) refrigerants have lower flammability (2L).

When considering the refrigerants that have received ASHRAE designations since 2010, there is a clear pattern that a low boiling point (high pressure/capacity) is correlated with a higher GWP, and that higher flammability is correlated with lower GWP. The focus on lowering GWP has therefore increased the attention to safety standards, and work is ongoing in the standardisation organisations to enable more use of flammable refrigerants.

The ideal refrigerant does not exist, and is unlikely to come into existence. The selection will therefore have to made from the group of low GWP refrigerants (e.g., R-717, R-744, HCs, or unsaturated halochemicals such as the HFOs, HCFOs, or unsaturated HCC) and mixtures of these refrigerants and the traditional refrigerant fluids. Many new alternatives are proposed which creates a challenge in finding the right refrigerant for each application. One of the important aspects is that refrigerants with low direct impact on climate change are – except for R-744 – either flammable to some extent or have a very high boiling point.

There lies a complex selection process ahead, where industry will need to determine which of the many proposed new or existing refrigerants will and can be used in the various applications. A system redesign or an update to the system topology will be required for most systems to begin using the newer refrigerants, but in some cases, this update may be as simple as changing the refrigerant and lubricant. The search is a trade-off between cost, safety, energy efficiency, and limiting the need for redesign.

Part of the complexity is that the market is unlikely to be willing to support many different refrigerants for the same application owing to safety and distribution issues. This will leave a period in time, likely to last decades in which industry will have to work with both the currently established refrigerants and new refrigerants addressing ozone depletion and/or climate change concerns. In the long run, the number of candidates is likely to decrease, but it is too early to tell which or even how many of the refrigerant candidates will survive.

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ANNEX I to Chapter 2

Data summary

This Annex summarizes physical, safety, and environmental data for refrigerants with a safety classification in ISO 817 (ISO 817:2014) or ASHRAE 34 (ASHRAE 34-2016).

Table 2.I-1 covers single component refrigerants; Table 2.I-2 is the summary for zeotropic refrigerant blends, while Table 2.I-3 covers azeotropic refrigerant blends.

Refrigerants which are new since the 2014 RTOC Assessment Report and changes in GWP values are highlighted in yellow.

Table 2.I-1: Data summary for single component refrigerants

Refrigerant Designation	Chemical Formula	Chemical Name	Molecular Weight (kg/kmol)	Boiling Point (°C)	ATEL/ODL (kg/m^3)	LFL (kg/m^3)	Safety Class	Atmospheric Lifetime (Years)	Radiative Efficiency (W/m/ppm)	GWP 100 Year	GWP 20 Year	ODP
Methane series												
CFC-11	CCl_3F	trichlorofluoromethane	137.4	24	0.006 2	NF	A1	52	0.26	5 160	7 090	1
CFC-12	CCl_2F_2	dichlorodifluoromethane	120.9	–30	0.088	NF	A1	102	0.32	10 300	10 800	0.73
CFC-13	$CClF_3$	chlorotrifluoromethane	104.5	–81	ND	NF	A1	640	0.25	13 900	10 900	1
BFC-13B1	$CBrF_3$	bromotrifluoromethane	148.9	–58	ND	NF	A1	72	0.30	6 670	7 930	15.2
PFC-14	CF_4	tetrafluoromethane (carbon tetrafluoride)	88.0	–128	0.40	NF	A1	50000	0.09	6 630	4 880	
HCFC-22	$CHClF_2$	chlorodifluoromethane	86.5	–41	0.21	NF	A1	12	0.21	1 780	5 310	0.034
HFC-23	CHF_3	trifluoromethane	70.0	–82	0.15	NF	A1	228	0.18	12 690	11 085	
HCC-30	CH_2Cl_2	dichloromethane (methylene chloride)	84.9	40	ND	NF	B1	0.4	0.03	9	33	
HFC-32	CH_2F_2	difluoromethane (methylene fluoride)	52.0	–52	0.30	0.307	A2L	5.4	0.11	704	2 530	
HC-50	CH_4	methane	16.0	–161	ND	0.032	A3	12.4	3.63e-4	30 [b]	85 [b]	

Ethane series													
CFC-113	CCl_2FCClF_2	1,1,2-trichloro-1,2,2-trifluoroethane	187.4	48	0.02	NF	A1	93	0.30	6 080	6 560	0.81
CFC-114	$CClF_2CClF_2$	1,2-dichloro-1,1,2,2-tetrafluoroethane	170.9	4	0.14	NF	A1	189	0.31	8 580	7 710	0.5
CFC-115	$CClF_2CF_3$	chloropentafluoroethane	154.5	–39	0.76	NF	A1	540	0.20	7 310	5 780	0.26
PFC-116	CF_3CF_3	hexafluoroethane	138.0	–78	0.68	NF	A1	10000	0.25	11 100	8 210	
HCFC-123	$CHCl_2CF_3$	2,2-dichloro-1,1,1-trifluoroethane	152.9	27	0.057	NF	B1	1.3	0.15	79	292	0.01
HCFC-124	$CHClFCF_3$	2-chloro-1,1,1,2-tetrafluoroethane	136.5	–12	0.056	NF	A1	5.9	0.20	527	1 870	0.02
HFC-125	CHF_2CF_3	pentafluoroethane	120.0	–49	0.37	NF	A1	31	0.23	3 450	6 280	
HFC-134a	CH_2FCF_3	1,1,1,2-tetrafluoroethane	102.0	–26	0.21	NF	A1	14	0.16	1 360	3 810	
HCFC-142b	CH_3CClF_2	1-chloro-1,1-difluoroethane	100.5	–10	0.10	0.329	A2	18	0.19	2 070	5 140	0.057
HFC-143a	CH_3CF_3	1,1,1-trifluoroethane	84.0	–47	0.48	0.282	A2L	51	0.16	5 080	7 050	
HFC-152a	CH_3CHF_2	1,1-difluoroethane	66.1	–25	0.14	0.130	A2	1.6	0.10	148	545	
HC-170	CH_3CH_3	ethane	30.1	–89	0.008 6	0.038	A3			1.4	5.2	
Ethers													
HE-E170	CH_3OCH_3	methoxymethane (dimethyl ether)	46.1	–25	0.079	0.064	A3	0.015	0.02	1	1	
Propane series													
PFC-218	$CF_3CF_2CF_3$	octafluoropropane	188.0	–37	0.34	NF	A1	2600	0.28	8 900	6 640	
HFC-227ea	CF_3CHFCF_3	1,1,1,2,3,3,3-heptafluoropropane	170.0	–16	0.19	NF	A1	36	0.26	3 140	5 250	
HFC-236fa	$CF_3CH_2CF_3$	1,1,1,3,3,3-hexafluroropropane	152.0	–1	0.34	NF	A1	242	0.24	8 060	6 940	
HFC-245fa	$CHF_2CH_2CF_3$	1,1,1,3,3-pentafluoropropane	134.0	15	0.19	NF	B1	7.9	0.24	882	2 980	
HC-290	$CH_3CH_2CH_3$	propane	44.1	–42	0.09	0.038	A3	12.5 days		<1	<1	
Cyclic organic compounds													
PFC-C318	$-(CF_2)_4-$	octafluorocyclobutane	200.0	–6	0.65	NF	A1	3200	0.32	9 540	7 110	
Hydrocarbons													
HC-600	$CH_3CH_2CH_2CH_3$	butane	58.1	0	0.002 4	0.038	A3			<1	<1	
HC-600a	$CH(CH_3)_2CH_3$	2-methylpropane (isobutane)	58.1	–12	0.059	0.043	A3	6.0 days		<1	<1	
HC-601	$CH_3CH_2CH_2-CH_2CH_3$	Pentane	72.2	36	0.0029	0.035	A3	3.4 days		<1	1.4	
HC-601a	$CH(CH_3)_2CH_2-CH_3$	2-methylbutane (isopentane)	72.2	27	0.0029	0.038	A3	3.4 days		<1	1.4	
Inorganic compounds													
R-702	H_2	Hydrogen	2.0	–253			A3					
R-704	He	Helium	4.0	–269		NF	A1					
R-717	NH_3	Ammonia	17.0	–33	0.000 22	0.116	B2L					
R-718	H2O	Water	18.0	100		NF	A1					
R-720	Ne	Neon	20.2	–246		NF	A1					
R-728	N_2	Nitrogen	28.0	–196		NF	A1					
R-740	Ar	Argon	39.9	–186		NF	A1					
R-744	CO_2	carbon dioxide	44.0	–78[a]	0.072	NF	A1		1.37e-5	1	1	
Unsaturated organic compounds													
HCC-1130(E)	CHCl=CHCl	trans-1,2-dichloroethene	96.9	47.7			B2	12,7 days				0,000 24
HFO-1132a	$CF_2=CH_2$	1,1-difluoroethylene	64.0	–86.7			A2	4.0 days	0.004	<1	<1	
HC-1150	$CH_2=CH_2$	ethene (ethylene)	28.1	–104	ND	0.036	A3			3.7	14	

HCFO-1224yd(Z)	$CF_3CF{=}CHCl$	(Z)-1-chloro-2,3,3,3-tetrafluoropropene	148.5	14.5			A1					
HCFO-1233zd(E)	$CF_3CH{=}CHCl$	trans-1-chloro-3,3,3-trifluoro-1-propene	130.5	18.1	0	NF	A1	26.0 days	0.04	1	5	0.000 34
HFO-1234yf	$CF_3CF{=}CH_2$	2,3,3,3-tetrafluoro-1-propene	114.0	–29.4	0.47	0.289	A2L	10.5 days	0.02	<1	1	
HFO-1234ze(E)	$CF_3CH{=}CHF$	trans-1,3,3,3-tetrafluoro-1-propene	114.0	–19.0	0.28	0.303	A2L	16.4 days	0.04	<1	4	
HC-1270	$CH_3CH{=}CH_2$	propene (propylene)	42.1	–48	0.001 7	0.046	A3	0.35 days		<1	<1	
HFO-1336mzz(E)	$CF_3CH{=}CHCF_3$	trans-1,1,1,4,4,4-hexafluoro-2-butene	164.1	7.4			A1					
HFO-1336mzz(Z)	$CF_3CH{=}CHCF_3$	cis-1,1,1,4,4,4-hexafluoro-2-butene	164.1	33.4			A1	22.0 days	0.07	2	6	

[a] Sublimes

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

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	ATEL/ODL (kg/m³)	LFL (kg/m³)	Safety Class	GWP 100 Year	GWP 20 Year	ODP
R-401A	R-22/152a/124 (53.0/13.0/34.0)	94.4	–34.4/–28.8	0.10	NF	A1	1 100	3 500	0.02
R-401B	R-22/152a/124 (61.0/11.0/28.0)	92.8	–35.7/–30.8	0.11	NF	A1	1 200	3 800	0.03
R-401C	R-22/152a/124 (33.0/15.0/52.0)	101	–30.5/–23.8	0.083	NF	A1	880	2 800	0.02
R-402A	R-125/290/22 (60.0/2.0/38.0)	101.5	–49.2/–47.0	0.27	NF	A1	2 700	5 800	0.01
R-402B	R-125/290/22 (38.0/2.0/60.0)	94.7	–47.2/–44.9	0.24	NF	A1	2 400	5 600	0.02
R-403A	R-290/22/218 (5.0/75.0/20.0)	92	–44.0/–42.3	0.24	0.480	A2	3 100	5 300	0.03
R-403B	R-290/22/218 (5.0/56.0/39.0)	103.3	–43.8/–42.3	0.29	NF	A1	4 500	5 600	0.02
R-404A	R-125/143a/134a (44.0/52.0/4.0)	97.6	–46.6/–45.8	0.52	NF	A1	4 200	6 600	
R-406A	R-22/600a/142b (55.0/4.0/41.0)	89.9	–32.7/–23.5	0.14	0.302	A2	1 800	5 000	0.04
R-407A	R-32/125/134a (20.0/40.0/40.0)	90.1	–45.2/–38.7	0.31	NF	A1	2 100	4 500	
R-407B	R-32/125/134a (10.0/70.0/20.0)	102.9	–46.8/–42.4	0.33	NF	A1	2 800	5 400	
R-407C	R-32/125/134a (23.0/25.0/52.0)	86.2	–43.8/–36.7	0.29	NF	A1	1 700	4 100	
R-407D	R-32/125/134a (15.0/15.0/70.0)	91	–39.4/–32.7	0.25	NF	A1	1 600	4 000	
R-407E	R-32/125/134a (25.0/15.0/60.0)	83.8	–42.8/–35.6	0.27	NF	A1	1 500	3 900	
R-407F	R-32/125/134a (30.0/30.0/40.0)	82.1	–46.1/–39.7	0.32	NF	A1	1 800	4 200	
R-407G	R-32/125/134a (2.5/2.5/95.0)	100.0	–29.2/–27.2		NF	A1	1 400	3 800	
R-407H	R-32/125/134a (32.5/15.0/52.5)	79.1	–44.7/–37.6		NF	A1	1 500	3 800	
R-407I	R-32/125/134a (19.5/8.5/72.0)	86.9	–39.8/–33.0		NF	A1	1 400	3 800	
R-408A	R-125/143a/22 (7.0/46.0/47.0)	87	–45.5/–45.0	0.33	NF	A1	3 400	6 200	0.02
R-409A	R-22/124/142b (60.0/25.0/15.0)	97.4	–35.4/–27.5	0.12	NF	A1	1 500	4 400	0.03
R-409B	R-22/124/142b (65.0/25.0/10.0)	96.7	–36.5/–29.7	0.12	NF	A1	1 500	4 400	0.03
R-410A	R-32/125 (50.0/50.0)	72.6	–51.6/–51.5	0.42	NF	A1	2 100	4 400	
R-410B	R-32/125 (45.0/55.0)	75.6	–51.5/–51.4	0.43	NF	A1	2 200	4 600	
R-411A	R-1270/22/152a) (1.5/87.5/11.0)	82.4	–39.7/–37.2	0.074	0.186	A2	1 600	4 700	0.03
R-411B	R-1270/22/152a (3.0/94.0/3.0)	83.1	–41.6/–41.3	0.044	0.239	A2	1 700	5 000	0.03
R-412A	R-22/218/142b (70.0/5.0/25.0)	92.2	–36.4/–28.8	0.17	0.329	A2	2 200	5 300	0.04
R-413A	R-218/134a/600a (9.0/88.0/3.0)	104	–29.3/–27.6	0.21	0.375	A2	2 000	4 000	
R-414A	R-22/124/600a/142b (51.0/28.5/4.0/16.5)	96.9	–34.0/–25.8	0.10	NF	A1	1 400	4 100	0.03
R-414B	R-22/124/600a/142b (50.0/39.0/1.5/9.5)	101.6	–34.4/–26.1	0.096	NF	A1	1 300	3 900	0.03
R-415A	R-22/152a (82.0/18.0)	81.9	–37.5/–34.7	0.19	0.188	A2	1 500	4 500	0.03

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	ATEL/ODL (kg/m^3)	LFL (kg/m^3)	Safety Class	GWP 100 Year	GWP 20 Year	ODP
R-415B	R-22/152a (25.0/75.0)	70.2	–23.4/–21.8	0.15	0.13	A2	560	1 700	0.009
R-416A	R-134a/124/600 (59.0/39.5/1.5)	111.9	–23.4/–21.8	0.064	NF	A1	1 000	3 000	0.008
R-417A	R-125/134a/600 (46.6/50.0/3.4)	106.7	–38.0/–32.9	0.057	NF	A1	2 300	4 800	
R-417B	R-125/134a/600 (79.0/18.3/2.7)	113.1	–44.9/–41.5	0.069	NF	A1	3 000	5 700	
R-417C	R-125/134a/600 (19.5/78.8/1.7)	103.7	–32.7/–29.2		NF	A1	1 700	4 200	
R-418A	R-290/22/152a (1.5/96.0/2.5)	84.6	–41.2/–40.1	0.20	0.31	A2	1 700	5 100	0.03
R-419A	R-125/134a/E170 (77.0/19.0/4.0)	109.3	–42.6/–36.0	0.31	0.25	A2	2 900	5 600	
R-419B	R-125/134a/E170 (48.5/48.0/3.5)	105.2	–37.4/–31.5			A2	2 300	4 900	
R-420A	R-134a/142b (88.0/12.0)	101.8	–25.0/–24.2	0.18	NF	A1	1 400	4 000	0.007
R-421A	R-125/134a (58.0/42.0)	111.7	–40.8/–35.5	0.28	NF	A1	2 600	5 200	
R-421B	R-125/134a (85.0/15.0)	116.9	–45.7/–42.6	0.33	NF	A1	3 100	5 900	
R-422A	R-125/134a/600a (85.1/11.5/3.4)	113.6	–46.5/–44.1	0.29	NF	A1	3 100	5 800	
R-422B	R-125/134a/600a (55.0/42.0/3.0)	108.5	–40.5/–35.6	0.25	NF	A1	2 500	5 100	
R-422C	R-125/134a/600a (82.0/15.0/3.0)	113.4	–45.3/–42.3	0.29	NF	A1	3 000	5 700	
R-422D	R-125/134a/600a (65.1/31.5/3.4)	109.9	–43.2/–38.4	0.26	NF	A1	2 700	5 300	
R-422E	R-125/134a/600a (58.0/39.3/2.7)	109.3	–41.8/–36.4		NF	A1	2 500	5 100	
R-423A	134a/227ea (52.5/47.5)	126	–24.2/–23.5	0.30	NF	A1	2 200	4 500	
R-424A	R-125/134a/600a/600/601a (50.5/47.0/0.9/1.0/0.6)	108.4	–39.1/–33.3	0.10	NF	A1	2 400	5 000	
R-425A	R-32/134a/227ea (18.5/69.5/12)	90.3	–38.1/–31.3	0.27	NF	A1	1 500	3 700	
R-426A	R-125/134a/600/601a (5.1/93.0/1.3/0.6)	101.6	–28.5/–26.7	0.083	NF	A1	1 400	3 900	
R-427A	R-32/125/143a/134a (15.0/25.0/10.0/50.0)	90.4	–43.0/–36.3	0.29	NF	A1	2 200	4 600	
R-428A	R-125/143a/290/600a (77.5/20.0/0.6/1.9)	107.5	–48.3/–47.5	0.37	NF	A1	3 700	6 300	
R-429A	R-E170/152a/600a (60.0/10.0/30.0)	50.8	–26.0/–25.6	0.098	0.052	A3	16	55	
R-430A	R-152a/600a (76.0/24.0)	64	–27.6/–27.4	0.10	0.084	A3	110	410	
R-431A	R-290/152a (71.0/29.0)	48.8	–43.1/–43.1	0.10	0.044	A3	44	160	
R-432A	R-1270/E170 (80.0/20.0)	42.8	–46.6/–45.6	0.002 1	0.039	A3	1	1	
R-433A	R-1270/290 (30.0/70.0)	43.5	–44.6/–44.2	0.005 5	0.036	A3	1	1	
R-433B	R-1270/290 (5.0/95.0)	44	–42.7/–42.5	0.025	0.025	A3	1	1	
R-433C	R-1270/290 (25.0/75.0)	43.6	–44.3/–43.9	0.006 6	0.032	A3	1	1	
R-434A	R-125/143a/134a/600a (63.2/18.0/16.0/2.8)	105.7	–45.0/–42.3	0.32	NF	A1	3 300	5 800	
R-435A	R-E170/152a (80.0/20.0)	49	–26.1/–25.9	0.09	0.069	A3	30	110	
R-436A	R-290/600a (56.0/44.0)	49.3	–34.3/–26.2	0.073	0.032	A3	1	1	
R-436B	R-290/600a (52.0/48.0)	49.9	–33.4/–25.0	0.071	0.033	A3	1	1	
R-436C	R-290/600a (95.0/5.0)	44.6	–41.5/–39.5			A3	1	1	
R-437A	R-125/134a/600/601 (19.5/78.5/1.4/0.6)	103.7	–32.9/–29.2	0.081	NF	A1	1 700	4 200	
R-438A	R-32/125/134a/600/601a (8.5/45.0/44.2/1.7/0.6)	99.1	–43.0/–36.4	0.079	NF	A1	2 200	4 700	
R-439A	R-32/125/600a (50.0/47.0/3.0)	71.2	–52.0/–51.8	0.34	0.304	A2	2 000	4 200	
R-440A	R-290/134a/152a (0.6/1.6/97.8)	66.2	–25.5/–24.3	0.14	0.124	A2	170	590	
R-441A	R-170/290/600a/600 (3.1/54.8/6.0/36.1)	48.3	–41.9/–20.4	0.006 3	0.032	A3	1	1.1	
R-442A	R-32/125/134a/152a/227ea (31.0/31.0/30.0/3.0/5.0)	81.8	–46.5/–39.9	0.33	NF	A1	1 900	4 200	
R-443A	R-1270/290/600a (55.0/40.0/5.0)	43.5	–44.8/–41.2			A3	1	1	
R-444A	R-32/152a/1234ze(E) (12.0/5.0/83.0)	96.7	–34.3/–24.3			A2L	93	330	

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	ATEL/ODL (kg/m^3)	LFL (kg/m^3)	Safety Class	GWP 100 Year	GWP 20 Year	ODP
R-444B	R-32/1234ze(E)/152a (41.5/48.5/10)	72.8	–44.6/–34.9			A2L	310	1 100	
R-445A	R-744/134a/1234ze(E) (6.0/9.0/85.0)	103.1	–50.3/–23.5			A2L	120	350	
R-446A	R-32/1234ze(E)/600 (68.0/29.0/3.0)	62	–49.4/–44.0			A2L	480	1 700	
R-447A	R-32/125/1234ze(E) (68.0/3.5/28.5)	63	–49.3/–44.2			A2L	600	1 900	
R-447B	R-32/125/1234ze(E) (68.0/8.0/24.0)	63.1	–50.1/–46.0			A2L	750	2 200	
R-448A	R-32/125/1234yf/134a /1234ze(E) (26/26/20/21/7)	86.4	–45.9/–39.8		NF	A1	1 400	3 100	
R-449A	R-32/125/1234yf/134a (24.3/24.7/25.3/25.7)	87.2	–46.0/–39.9		NF	A1	1 400	3 100	
R-449B	R-32/125/1234yf/134a (25.2/24.3/23.2/27.3)	86.4	–46.1/–40.2		NF	A1	1 400	3 200	
R-449C	R-32/125/1234yf/134a (20.0/20.0/31.0/29.0)	90.3	–44.6/–38.1		NF	A1	1 200	2 900	
R-450A	R-1234ze(E)/134a (58/42)	108.7	–23.4/–22.8		NF	A1	570	1 600	
R-451A	R-1234yf/134a (89.8/10.2)	112.7	–30.8/–30.5			A2L	140	390	
R-451B	R-1234yf/134a (88.8/11.2)	112.6	–31.0/–30.6			A2L	150	430	
R-452A	R-1234yf/32/125 (30/11/59)	103.5	–47.0/–43.2		NF	A1	2 100	4 000	
R-452B	R-32/125/1234yf (67.0/7.0/26.0)	63.5	–51.0/–50.3			A2L	710	2 100	
R-452C	R-32/125/1234yf (12.5/61.0/26.5)	101.9	–47.5/–44.2		NF	A1	2 200	4 100	
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		NF	A1	1 700	4 100	
R-454A	R-32/1234yf (35.0/65.0)	80.5	–48.4/–41.6			A2L	250	890	
R-454B	R-32/1234yf (68.9/31.1)	62.6	–50.9/–50.0			A2L	490	1 700	
R-454C	R-32/1234yf (21.5/78.5)	90.8	–46.0/–37.8			A2L	150	540	
R-455A	R-744/32/1234yf (3.0/21.5/75.5)	87.5	–51.6/–39.1			A2L	150	540	
R-456A	R-32/134a/1234ze(E) (6.0/45.0/49.0)	101.4	–30.4/–25.6		NF	A1	650	1 900	
R-457A	R-32/1234yf/152a (18.0/70.0/12.0)	87.6	–42.7/–35.5			A2L	150	520	
R-458A	R-32/125/134a/227ea/236fa (20.5/4.0/61.4/13.5/0.6)	89.9	–39.8/–32.4		NF	A1	1 600	3 900	
R-459A	R-32/1234yf/1234ze(E) (68.0/26.0/6.0)	63.0	–50.3/–48.6			A2L	480	1 700	
R-459B	R-32/1234yf/1234ze(E) (21.0/69.0/10.0)	91.2	–44.0/–36.1			A2L	150	530	
R-460A	R-32/125/134a/1234ze(E) (12.0/52.0/14.0/22.0)	100.6	–44.6/–37.2		NF	A1	2 100	4 100	
R-460B	R-32/125/134a/1234ze(E) (28.0/25.0/20.0/27.0)	84.8	–45.2/–37.1		NF	A1	1 300	3 000	
R-460C	R-32/125/134a/1234ze(E) (2.5/2.5/ 46.0/49.0)	105.3	–29.2/–26.0		NF	A1	730	2 000	
R-461A	R-125/143a/134a/227ea/600a (55.0/5.0/32.0/5.0/3.0)	109.6	–42.0/–37.0		NF	A1	2 700	5 300	
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	2 200	4 700	
R-464A	R-32/125/1234ze(E)/227ea (27.0/ 27.0/40.0/6.0)	88.5	–46.5/–36.9		NF	A1	1 300	2 700	
R-465A	R-32/290/1234yf (21.0/7.9/71.1)	82.9	–51.8/–40.0			A2	150	530	

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

Refrigerant Designation	Refrigerant Composition (Mass %)	Molecular Weight (kg/kmol)	Bubble Point/ Dew Point (°C)	ATEL/ODL (kg/m^3)	LFL (kg/m^3)	Safety Class	GWP 100 Year	GWP 20 Year	ODP
R-500	R-12/152a (73.8/26.2)	99.3	–33.6/–33.6	0.12	NF	A1	7 600	8 100	0.5
R-501	R-22/12 (75.0/25.0)	93.1	–40.5/–40.3	0.21	NF	A1	3 900	6 700	0.2
R-502	R-22/115 (48.8/51.2)	111.6	–45.3/–45.0	0.33	NF	A1	4 600	5 600	0.1
R-503	R-23/13 (40.1/59.9)	87.2	–88	ND	NF	A1	13 000	11 000	0.6
R-504	R-32/115 (48.2/51.8)	79.2	–57	0.45	NF	A1	4 100	4 200	0.1
R-507A	R-125/143a (50.0/50.0)	98.9	–47.1/–47.1	0.53	NF	A1	4 300	6 700	
R-508A	R-23/116 (39.0/61.0)	100.1	–87.4/–87.4	0.23	NF	A1	12 000	9 300	
R-508B	R-23/116 (46.0/54.0)	95.4	–87.4/–87.0	0.2	NF	A1	12 000	9 500	
R-509A	R-22/218 (44.0/56.0)	124	–40.4/–40.4	0.38	NF	A1	5 800	6 100	0.01
R-510A	R-E170/600a (88.0/12.0)	47.2	–25.2/–25.2	0.087	0.056	A3	1	1	
R-511A	R-290/E170 (95.0/5.0)	44.2	–42.18/–42.1	0.092	0.038	A3	1	1	
R-512A	R-134a/152a (5.0/95.0)	67.2	–24.0/–24.0	0.14	0.124	A2	210	710	
R-513A	R-1234yf/134a (56/44)	108.4	–29.2		NF	A1	600	1 700	
R-513B	R-1234yf/134a (58.5/41.5)	108.7	–29.2/–29.1		NF	A1	560	1 600	
R-514A	R-1336mzz(Z)/1130(E) (74.7/25.3)	139.6	29.0/29.0		NF	B1			
R-515A	R-1234ze(E)/227ea (88.0/12.0)	118.7	–18.9/–18.9		NF	A1	380	630	
R-516A	R-1234yf/134a/152a (77.5/8.5/14.0)	102.6	–29.4			A2L	140	400	

Note: Yellow highlights in Tables 2.I-1, 2.I-2 and 2.I-3 show data added after the RTOC 2014 Assessment Report.

Data sources for Table 2.I-1

Chemical Formula, Chemical Name, and Boiling Point: ISO 817 (ISO 817:2014) is used as first priority, ISO 5149 (ISO 5149:2014) as second priority and ASHRAE 34 (ASHRAE 34-2016) as third priority.

Molecular Weight: Calculated from the sum of atoms making up the molecule (based on the chemical formula). The atomic weights are from IUPAC (Wieser, 2013).

ATEL/ODL and LFL: Taken from ISO 5149 (ISO 5149:2014).

Safety Class: ISO 817 (ISO 817:2014) is used as first priority, ISO 5149 (ISO 5149:2014) as second priority and ASHRAE 34 (ASHRAE 34-2016) as third priority.

Atmospheric Lifetime: Values are taken from (WMO, 2018) where available, Table 5.1 and Table 5.3 in (WMO, 2014) is used as 2nd priority, (IPCC, 2014) is used as 3rd priority, (WMO, 2011) is used as 4th priority, and (IPCC, 2007) is used as 5th priority.

Radiative Efficiency: Values are taken from (WMO, 2018) where available, (IPCC, 2014) is used as 2nd priority (IPCC, 2007) is used as 3rd priority where (WMO, 2018), (IPCC, 2014) and (WMO, 2011) do not give radiative efficiencies. 3rd priority is (Patten, 2010) (HCC-1130(E)).

GWP 100 Year: Values are taken from (WMO, 2018) where available, Table 8.A.1 in (IPCC, 2014) is used as 2nd priority, (WMO, 2011) as 3rd priority the direct GWP values for hydrocarbons in (Colbourne, 2018), and Table 2.12 in (IPCC, 2007) as 4th priority (HE-E170).

GWP 20 Year: Values are taken from the same sources as for GWP 100 Year. Where values are not available from the above sources (HE-E170) the GWP 20 year is calculated from GWP 100 year using the same method as in the 2014 RTOC Assessment Report.

ODP: Values are taken from (WMO, 2014) where available, (WMO, 2011) is used as 2nd priority (for HCFC-123), (WMO, 2007) as 3rd priority (for HCFC-124), and the Montreal protocol as 4th priority (for CFC-13).

Data sources for Tables 2.I-2 and 2.I-3

Molecular weight, GWP 100 Year, GWP 20 Year, ODP: Calculated based on data for single components given in Table 2.I-1. The resulting GWP values are rounded to 2 significant digits, since, as mentioned in section 2.1.5, the uncertainty for the GWP values is on the order of ±20% and ±30% for GWP 20 Year and GWP 100 Year for very long lived gases and even larger for shorter lived gases (WMO, 2014 p.713).

Refrigerant Composition, Bubble Point/Dew Point (°C), Safety Class: ISO 817 (ISO 817:2014) 1st priority, ISO 5149 (ISO 5149:2014) in principle 2nd priority, ASHRAE 34 (ASHRAE 34-2016) 3rd priority. No information for these tables were simultaneously available in ISO 5149 and not in ISO 817, which is why ISO 5149 is in principle only the 2nd priority. Where dual safety classes are given in the standards, the higher is used.

ATEL/ODL, LFL: Values are taken from ISO 5149 (ISO 5149:2014)

Chapter 3

Domestic appliances

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3. Domestic appliances

3.1 Introduction

Under the domestic appliance category, the domestic refrigeration is a major sub-category and comprises appliances that are broadly used domestically, such as refrigerators, freezers and combined refrigerator/freezer products. Small beverage dispensing machines are similar products and are also commonly included in domestic refrigeration, but represent a small fraction of total units. For domestic wine coolers the same considerations as for domestic refrigerators apply. The other domestic appliance covered in this chapter is the heat pump clothes (laundry) dryer (HPCD), which is emerging in the market as an energy efficient alternative to the tumble dryers with electric heaters. Domestic dehumidifiers have not been considered in this chapter.

It is estimated that approximately 170 million domestic refrigerators and freezers are produced annually. Long product life and large annual production volume combine for an estimated 2.0 to 2.3 billion units inventory, globally installed. IIR (2015) estimated that domestic refrigerators and freezers consume almost 4% of global electricity. Globally, energy efficiencies of refrigerators have been increasing constantly, as evident from the evolution of the energy labels in many countries. For example, the energy consumption of typical household refrigerators has dropped by around 65% in the last 15 years (VHK, 2016).

The vast majority are used for food storage in residential dwellings, with a significant minority used in offices for domestic purposes and small businesses for commercial purposes. Typical storage volumes range from 20 to 850 litres. Various fundamental design approaches and consumer convenience features are included within the product offerings. A typical product contains a factory-assembled, hermetically sealed, vapour-compression refrigeration system employing a 50 to 250 W motor and containing 20 to 250 g of refrigerant. Some topics discussed below have been covered in earlier reports of this committee. They are briefly included here to provide a more comprehensive perspective.

The other domestic appliance covered in this chapter is the heat pump clothes (laundry) dryer (HPCD), which is emerging in the market as an energy efficient alternative to the electric heater dryer. The market for HPCD has been fast growing in the EU and has been introduced in the US and other parts of the world. There are manufacturers from EU, Japan, Australia and China. In North America, over six million clothes dryers are sold each year, with close to 100 million clothes dryers in operation and have reached 80% market saturation. These dryers are vented conventional tumble dryers. In a typical conventional tumble dryer, electrical heaters consume about 600 – 1,000 kWh per year and is one of the largest energy-consuming domestic appliances in North America. HPCDs consume only 40-50% of energy of North American conventional dryers.

The market share in Europe of HPCDs has increased to over 50 % of approximately 5 million shipments. Switzerland, with their minimum energy efficiency performance standard, effectively allows only HPCDs to be sold in that country. Some EU manufacturers have ceased their development of tumble dryers with electrical heaters. Therefore, it is projected that in EU, HPCDs would continue to gain market share in the next few years. Costs of heat pump driers have reduced substantially.

These HPCDs mostly use HFC-134a as the refrigerant, and charge amounts vary from 200 to 400 g. The continued use of HFC-134a is under discussion in several global regions. HPCDs using HC-290 have been just introduced.

The Super Efficient Dryer Initiative was formed in the US based on the European experience to replicate the European success. An American study has concluded that HPCDs have positive economic benefits only for households with high clothes dryer usage or with high electricity prices and moderately high utilization (Meyers, 2010). The current market share in Article 5 countries for this product is almost negligible.

3.2 Options for new equipment

Globally, new refrigerator production conversion from use of ODS was essentially completed by 2008. HC-600a (predominantly) or HFC-134a continues to be the refrigerant options for new production. Currently more than 1 billion domestic refrigerators use HC-600a. No other new refrigerant has matured to become an energy-efficient and cost-competitive alternative. Refrigerant migration from HFC-134a to HC-600a is expected to continue, driven by local regulations on HFCs. Excluding any influence from regulatory interventions, it is still projected that by 2020 about 75% of new refrigerator production will use HC-600a (possibly with a small share by unsaturated HFC refrigerants) and the rest will use HFC-134a (UNEP, 2010). North American domestic refrigerator manufacturing industry has announced a voluntary goal to phase out of HFC-134a in household refrigerators and freezers by 2024. HC-600a is their leading choice.

Besides the choice of alternative refrigerants, there are more aspects to consider with respect to the environmental impact of the equipment, such as energy efficiency improvements (see 3.2.5), recycling and end of life issues (see 3.4).

Domestic heat pump clothes dryers, which have recently entered the market use mostly HFC-134a, R-407C and HC-290 to a small extent. They do not have any significant historical use of CFCs or HCFCs. The refrigeration circuit differs from domestic refrigeration by its very high evaporation temperature (typical 10 to 30ºC) and high condensation temperature (up to 70ºC), requiring suitable refrigerants with relatively high critical temperature and high suction pressure compressors. Most systems employ rotary compressors.

3.2.1 Alternatives for domestic refrigerators

HC-600a: HC-600a is the main energy-efficient and cost-competitive alternative. Concerns with the high flammability, which existed at the introduction of the refrigerant in 1994 in Europe have been addressed with design features and safety standards, particularly as the charges required for domestic refrigeration are below 150 g. When the safety requirements are met (e.g. IEC 60335-2-24) and adequate risk assessment to address the flammable nature of the refrigerant, HC-600a is the ideal refrigerant for domestic refrigeration products, giving roughly 5 % higher efficiency than HFC-134a while at the same time reducing the noise level of the unit.

According to a study for a review of the European Regulation (EC) on fluorinated gases (Schwarz et al., 2013), the investment cost for a new manufacturing facility for domestic refrigerators using HC-600a is marginally higher than for HFC-134a. This is basically due to costs related to the requirements for safety systems. The report also mentions that annual running costs and lifetime cost of HC-600a equipment are lower, resulting in an overall negative life cycle cost differential in case of HC-600a.

Although product design changes are necessary to address safety and regulatory requirements for HC-600a, there are no significant technical barriers to the use of HC-600a, illustrated by the probable estimate of over 1 billion domestic refrigerators in the field to date. In North America, the use of HC-600a is still limited, but considerable progress is being made to convert from HFC-134a to HC-600a with the market introduction of freezers and small refrigerators that typically do not use electric defrost. During recent years, this conversion is progressing which is discussed in Section 3.2.2. The UL refrigerator safety standard (UL250) has been harmonised with IEC60335-2-24 and includes new safety requirements that abate the HC-600a safety and litigation risk. In 2010, HCs were approved with a charge limit of 57 g and in 2018 this limit was extended to 150 g. This reduces the product cost differential between manufacturers by imposing common safety requirements for HC-600a and other flammable refrigerants.

HC-600a was the standard refrigerant for European domestic refrigerators and freezers originally and proliferated into other regions, including Article 5 countries. Worldwide about 100 million appliances are produced annually with HC-600a. Increased energy efficiency and the negligible GWP of the HC-600a refrigerant reduce the climate impact of household refrigerators, due to mitigation of direct (refrigerant) and indirect (CO_2 associated with electricity consumption) GHG emissions, compared to HFC-134a.

HFC-134a: HFC-134a was the predominant alternative refrigerant for domestic refrigeration after the phase-out of CFC-12. There are no significant safety implications concerning its use. Energy efficiency is similar to that of CFC-12, although with continual optimization, the current HFC-134a refrigeration units are considerably more efficient than those that used CFC-12.

HFO-1234yf: It is feasible to use HFO-1234yf in domestic refrigerators and freezers and its application can be considered as some way between the use of HFC-134a and HC-600a, since the pressure and capacity are slightly lower than for HFC-134a and it has lower flammability characteristics than HC-600a. The lower flammability may make its application easier for North American industries that are concerned about the liability on the use of HC-600a.

According to some industrial sources, initial developments to assess the use of HFO-1234yf and blends in domestic refrigeration have begun (see Section 3.3.1), but it is not being pursued with high priority, as in automotive applications (see Chapter 10). Long term reliability tests for capillary tube blockage due to chemical degradation have not been completed. As such, product costs are estimated to be slightly higher than for HFC-134a technology due to the larger surface area of heat exchangers required (to account for poorer energy performance) and higher costs of the refrigerant.

Given the cost disadvantage, flammability and investment requirements for product development, HFO-1234yf suffers significant disadvantages. The lower flammability compared to HC-600a is an advantage but the global experience with HC-600a has shown that design changes and investment can abate the risk to an acceptable level. With the lack of activity by manufacturers, HFO-1234yf is not likely to displace HC-600a or HFC-134a in the foreseeable future.

HFO-1234ze(E): Although this refrigerant has been selected for some commercial applications, same considerations with respect to flammability as for HFO-1234yf hold. In addition, 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 foreseeable future.

R-744: Currently, experience on the use of R-744 is available from a large number of bottle coolers, which have been in use since many years, and are similar, low-charged applications. These are further discussed in Chapter 4.

R-744 applications imply additional costs, which can be attributed to the greater mass of materials necessary to achieve protection against the high-pressure level, in particular for the compressor. Availability of compressors with very small swept volumes at the needed efficiency levels poses a significant challenge due to the tight clearance requirements between the piston, cylinder and suction valve.

3.2.1.1 Safety of using flammable refrigerants: 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 appliance (washing machine, dishwasher or tumble dryer). 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.

Following design measures could be used by manufacturers to reduce the likelihood and severity of fridge/freezer fires. All of the following are addressed in the new UL harmonised version of 60335-2-24 with the exception of the fire retardant in the foam:

- Use of high quality standard components (e.g. capacitors)
- Contain potential ignition sources in metal boxes
- Use metal drip trays
- Use fire retardant added to insulation foam or applied to insulation surfaces
- Fit a non-combustible or fire retardant covering at the back of the appliances

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

Current industry dynamics include increasing migration from HFC-134a to lower GWP alternatives. Commercial conversion to date is restricted to HC-600a. European production of no-frost side by side refrigerators began conversion from HFC-134a to HC-600a in the early 2000's. Initial conversions of automatic defrost refrigerators in Japan from HFC-134a to HC-600a were discussed in the 2006 report of this committee (UNEP, 2006). Such conversions were motivated by global warming considerations, has progressed to include more than 90% of refrigerator production in Japan.

The North American appliance market is still dominated by HFC-134a, while the conversion to HC continues in the rest of the world. Several factors are uniquely weighted in the North American market that has caused this delay including:

- litigation costs
- increased intensity by the Consumer Product Safety Commission
- product cost differential for additional safety features
- investment cost associated with serviceability of a refrigerant.

In the EU, the producers follow the EU Directive 2001/95/EC on general product safety. North American manufacturers have opted to develop additional safety requirements in addition to third party standards prior to introduction of HC-600a to appliances.

Whilst legal concerns have so far limited the use of HC-600a in USA, a major U.S. manufacturer introduced an auto-defrost refrigerator using HC-600a refrigerant to the U.S. market already in 2010. US EPA has recently 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, subject to certain conditions. Additionally, UL250 has been harmonised with IEC 60335-2-24. With these developments, AHAM (2015) has volunteered to phase out HFC-134a in domestic refrigerators and freezers by 2024 with HC-600a as the leading alternative.

Since the previous report, significant progress has been made with the market introduction of freezers and small refrigerators in the USA. using HC-600a These products tend to be non-serviceable systems (as they include a second barrier to refrigerant leakage such as plastic liner). The required service infrastructure for HC-600a is being developed.

Concurrently, HC-based refrigerator models offered by manufacturers based in Central and South America are increasing as well.

The trend of new production conversion to hydrocarbon refrigerants will continue. Excluding any influence from government regulatory intervention, it is still projected that 75% of new refrigerator production will use HC-600a or any other alternative low GWP refrigerants and 25% will use HFC-134a by 2020 (UNEP, 2010). The estimated migration was presented in the earlier report.

Technologies to accomplish conversions are readily available, though it needs consideration as conversion costs of the production facilities are still significant. The rate and extent of conversion will be influenced by premium product cost to maintain product safety with introduction of flammable refrigerants. Premium costs are for modified electrical components, use of reduced voltage to avoid electrical arcing and any other safety devices. Cost pressures are more significant on models with lower profit margins. However, lower-end models include fewer components requiring conversions tend to receive priority.

3.2.3 Alternatives for tumble dryers

These dryers typically use HFC-134a as a refrigerant and charge amounts vary from 200 to 400 g. Products using R-407C are also being placed on the market and can potentially make use of the temperature glide, if heat exchangers are optimised for such refrigerant mixtures. Also, products using HC-290 with appropriate safety measures and refrigerant charges typically below 150g, are already in the market. Though the continued use of HFCs is under discussion at several global regions, it is also recognised that the use of heat pumps in a dryer leads to significant energy savings of 50% or more and to a substantial reduction in global warming impact of countries using fossil fuel for power generation. More low GWP refrigerant solutions including R-744, other hydrocarbons and low GWP HFCs and their blends are being explored (Belloemore and Minetto, 2015).

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 with subcritical refrigerants. The challenges faced are high costs of some components and the need of a high effective intercooler to reduce the gas temperature further after the gas cooler exit.
- Hydrocarbons: In principle various hydrocarbons are suitable. Safety hazards due to the refrigerant flammability need careful evaluation as laundry dryers pose additional risks compared to domestic refrigerators due to the high temperatures involved, the presence of dry textile materials, mechanically moving objects (drum, motor etc.) and the presence of static charges. It has been reported that tests on a HPCD, charged with propane, after proper compressor installation, showed that performances are very close to HFC-134a and that an energy saving around 5% can be obtained. Bellomare and Minetto (2015) studied a specific HPCD, designed for R-407C, retrofitted with HC-290 and R-441A, a HC blend. No modifications were carried out to the system except the compressor to match the capacity of R-407C. The expansion device was also adjusted for the new fluids. Increment of total energy consumptions were obtained with both refrigerants, +6% with HC-290 and +15% with R-441A. It is stated the increment of energy consumption was basically due to the compressor, which was not specific to the refrigerants used.
- Low GWP HFCs: Due to the similar characteristics to HFC-134a, this category may offer potential candidates. However, their flammability poses similar safety hazards as listed for the hydrocarbons, though some of these hazards may be easier to deal with due to the reduced flammability characteristic.

3.2.4 Not-in-kind alternative technologies

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 cost or efficiency competitive with conventional vapour-compression technology for mass-produced domestic refrigerators.

Absorption refrigeration equipment has been used in hotel mini-bar units due to low noise levels and for mobile, off-network applications such as campers or mobile homes for many years. Thermoelectric or Stirling cycle technologies are used for portable refrigerated chests in applications such as medical transport. Thermoelectric is also used for hotel units and wine storage units with moderate cooling temperature levels.

Magnetic refrigeration is one of the not-in-kind technologies with possible potential for commercialization. Magnetic refrigeration does not use a refrigerant and employs an active magnetic regenerator, comprising magneto-caloric materials exposed to an intermittent magnetic field. At lower cooling power, it possibly presents higher efficiency over conventional vapour compression. Based on recent R&D by different groups, it is considered that magnetic refrigeration is a promising technology; however, there are still a number of challenges (Sari et al., 2014). From the life cycle assessment of magnetic refrigeration, it has been concluded that when advanced design is accompanied by reuse of magnetic materials at end-of-life, the overall environmental impact may reduce (Monfared et al., 2014). To decrease the cost of the materials used, the use of an iron-based alloy to provide the magnetic charge has been considered as an alternative to the rare-earth magnets such as gadolinium used originally.

Stirling based systems have been explored in the domestic marker intensively, but have not been commercialised. Cost and energy reductions have not been achieved against available technologies. Stirling based systems in ultra-low freezing (-80 °C and lower) have become available in the market where the specific advantage of Stirling cycle for high temperature lifts (difference between condensing and evaporators) against vapour compression cycle is exploited.

The remaining specialty niche product areas cited above would each require high capital investment to establish mass production capability. These product technologies for domestic refrigeration will not be further discussed in this report mainly focused on options for mass produced markets.

Not-in-kind laundry dryer technologies are still in a very early exploration stage with only academic interest.

More details on NIK technologies can be found in Chapter 12 of this report.

3.2.5 Product energy efficiency improvement for domestic refrigerators

Domestic refrigeration consumes a significant percentage of the global energy production. Some market research reports estimated global domestic refrigerators and freezers market size at over USD 59 billion in 2015 and USD 72.43 billion in 2017 and was expected to reach USD 125.7 billion in 2025. It was further reported that an average refrigerator uses around 13.7% of residential energy and is the largest energy user next to air conditioners, which consume about 16%. The largest part of this consumption is in the high production volume, inexpensive, small to medium size refrigerators that are sold in emerging markets. The growth in installed base of refrigerators, driven by increased worldwide standard of living in the emerging markets makes it unlikely that any reductions in consumption are possible. However, reductions in the rate of growth of energy consumption are possible when refrigeration and insulating technologies listed below, that are currently in use in the higher end efficient products, are driven to the less expensive products to improve operating efficiency.

The energy efficiency of domestic refrigeration products is a topic of active consumer and regulatory interest. This topic is discussed at length in Chapter 11 of this report as well as in the TEAP Task Force Report on energy efficiency while phasing down HFCs (2018). This section contains only a condensed discussion on energy efficiency. A more detailed discussion of efficiency improvement options was included in the 2002 report of this committee. Additional information can be found in various sources, amongst others the reports under the Eco-Design Directive studies (VHK, 2016). These studies provided capability background used for updating European Commission minimum energy efficiency and labelling standards (EC 643/2009 and EC 1060/2010). It is also estimated that the use of more efficient refrigerating appliances will allow Europe to save up to 10 TWh of electricity per year by 2030.

Factors influencing refrigerant selection and product energy efficiency include local, regional and national regulation, Eco-labelling, and third-party standards. Globally labelling requirements and minimum standards are reviewed and upgraded on a regular basis, driving the product to reduced power consumption levels with corresponding reductions on global warming impact. Such standards for measurement of product sustainability provide transparency and credibility in the labelling of product impact on the environment, thus driving a more informed decision for the consumer. One example is the AHAM 7001-2012 Sustainability Standard for Household Refrigeration Appliances (AHAM, 2015), developed and endorsed by multiple stakeholders including environmental, industry, government and consumers. Similar to the EU F-Gas legislation (European Union, 2014), this standard provides a calculation for the net material GWP impact of a product as the mass weighted average GWP of the product component materials.

Significant technology options to improve product energy efficiency have already demonstrated mass production feasibility and robust, long-term reliability. Both mandatory and voluntary energy efficiency regulation programs catalysed industry product efficiency development efforts. A universal energy test protocol has been completed (IEC 62552-1, 2 and 3:2015) and this forms the basis of energy legislation in China and Japan. 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 new IEC test protocol in energy regulations updates (e.g. Europe, Australia/New Zealand). A number of improved energy efficiency design options are fully mature, and future improvements of these options are expected to be evolutionary. Examples of these options include efficient compressors, high efficiency heat exchangers, improved low thermal loss cabinet structures and gaskets, and less variable manufacturing processes. Extension of these to all global domestic refrigeration would yield significant benefit, but is generally constrained by availability of capital funds and related product cost implications.

Design options with less economic justification are sometimes introduced in premium-cost models having incentive subsidies. This provides the opportunity to mature new efficiency technologies and progress them through their individual cost/experience curves. This increases the likelihood for migration of the efficient technologies to more cost-sensitive model line segments. Options that presently have limited or newly introduced application include variable speed compressors; intelligent controls; system reconfigurations, such as dual evaporators; advanced insulation systems, EC fans, improved air circulation reduced anti-condensation heaters; and Demand Side Management (DSM) initiatives requiring interactive communication with energy providers in order to implement the Smart Grid concept. The premium-cost of these options currently restrict their application to high-end models and constrain their proliferation for general use. A further constraint is the fact that not all energy saving measures result in a reduced energy value during tests according the current test standards. The new universal test protocol mentioned earlier attempts to improve this situation.

- Variable capacity compressors avoid cycle losses and inertial losses through modulating compressor speed and/or swept volume. Use of higher efficiency permanent magnet or linear motors is also enabled by electronic commutation controls.
- Intelligent, adaptive controls allow variable control algorithms that avoid optimising at seldom-experienced worst-case conditions (e.g. variable defrost algorithms).
- Parallel dual evaporators can improve energy efficiency by effectively reducing required pressure ratios of the higher temperature evaporator. Cost–effective, reliable and stable system controls need to be demonstrated.
- Advanced vacuum panel insulation concepts have been selectively used for several years in Japan, Western Europe and the United States. Their premium cost has constrained extension to general use.
- Power line load management (Smart Grid) features of domestic refrigerators reduce energy service provider's peak load demands. Typically, such a feature on electronic models responds to the power company request for reduced energy consumption. . Consequently, the appliances may postpone heated defrost, delay ice harvests or delay the start of a compressor for short periods. The application of such load management features to domestic refrigeration market is ramping up very slowly since the consumer benefit is marginal.

3.2.6 Product energy efficiency improvement for tumble dryers

For HPCDs, the inclusion of a heat pump on 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.

3.3 Options for existing domestic refrigerators

Non-Article 5 countries completed conversions of new equipment production to non-ozone depleting substances (ODSs) more than 15 years ago. Later, a number of Article 5 countries also completed their conversion, e.g. India by 2003. Therefore, most products containing ozone depleting refrigerants are now approaching the end of their life cycle.

Field conversion to non-ODS refrigerants has significantly lagged original equipment conversion. The distributed and individual proprietor character of the service industry is a barrier to coordinated efforts to convert from ODS refrigerants. Field service procedures typically use originally specified refrigerants. Refrigerant blends developed specifically for use as drop-in service alternatives have had limited success. The interested reader is referred to the 1998 report of this committee for an extended discussion of field repair and conversion options (UNEP, 1998).

3.3.1 HFO-1234yf and HFO-1234ze as alternatives to HFC-134a

Several retrofit tests on HFC-134a based domestic refrigerators have been reported applying HFO /HFC blends (Allgood et al, 2014; Aprea et al., 2016a; Aprea et al., 2016b, Aprea et al. 2017a; Aprea et al., 2017b; Bellman-Flores et al., 2017).

From these studies, it may be stated that the use of HFO-1234yf, HFO-1234ze and blends of HFO-1234yf/HFC-134a and HFO-1234ze/HFC-134a is feasible as possible drop-in refrigerant and the energy consumptions may also be comparable. However, one has to consider all safety issues with respect to using flammable refrigerants, much more significantly for retrofits. Any

LCCP assessment based on such drop-in studies should only be performed in relation to optimised systems.

3.4 End-of-life disposal

The small unit charge and the geographically dispersed location of these units 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 countries. Chapter 11 of this report addresses this and related conservation approaches. Interest in conservation programmes is leveraged by the 1 to 2 kg of foam blowing agents typically present in a domestic refrigerator.

For HPCDs, 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.

3.5 Concluding remarks

HC-600a (predominantly) and HFC-134a continue to be the refrigerant options for new production. No other new refrigerant has matured to become an energy-efficient and cost competitive alternative. Conversion of new domestic refrigerator productions to non-ODS refrigerants in Article 5 countries occurred over a span of five to seventeen years ago. Migration to second generation non-ODS refrigerant from HFC-134a to HC-600a in new product production is occurring driven by local regulations and Kigali amendment. This migration is now occurring, not only non-Article 5 countries but also in Article 5 countries including Brazil, Mexico. With the maturing of this technology, this trend will proliferate. The North American domestic refrigerator manufacturing industries have committed to phase down HFC-134a in domestic refrigerators and freezers by 2024, with HC-600a as the leading candidate.

The heat pump clothes (laundry) dryer (HPCD) is rapidly growing in the EU. These are still predominantly based on HFC-134a. HPCDs using HC-290 are available in the market. Additional low GWP refrigerant solutions using R-744, HC-600a and HFOs are still in the exploration phase.

3.6 References

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Chapter 4

Commercial refrigeration

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4 Commercial refrigeration

4.1 Introduction

Commercial refrigeration is characterised by storing and displaying food and beverages at different levels of temperature within commercial stores with sales areas varying in size from approximately 10 m^2 to 20,000 m^2. The refrigerating capacities of equipment vary from hundreds of watts to as high as around 1.5 MW. Two main levels of temperatures are generated by refrigeration systems from around 0°C to 8°C for the conservation of fresh food and beverages, commonly referred to as medium temperature, and around -18°C for frozen food and ice cream, commonly referred to as low temperature.

Globally, HCFC-22 continues to represent the largest refrigerant bank within commercial refrigeration and is used at all temperature levels. The most used HFCs are HFC-134a for medium temperature and R-404A (blend) for all temperature levels. Traditionally, commercial refrigeration applications are prone to significant refrigerant leakage due to the fact that most of the large systems are field installed. In recent years, some progress has been made to improve leak tightness, especially for centralised systems, and the effort continues for better refrigerant management during the life of the equipment.

The progressing phase-out of HCFC-22 in developing countries, and the phase-down of high GWP HFCs in many countries, requires making informed choices on the best replacement options.

AHRI launched a Low GWP Alternative Refrigerant Evaluation Program (AREP) in 2010 (AHRI, 2013). A number of 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 three groups of commercial refrigeration equipment, comparisons were made in order to select amongst the most energy efficient options with the smallest environmental impact due to both refrigerant emissions and energy consumption. Additional studies have also been carried out or 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 parallel there has been a significant development of technology and concepts for using R-744 as refrigerant, especially for larger capacity systems (Hafner, 2018), and HC-290, especially for smaller capacity systems.

In commercial refrigeration, as in air-conditioning, high ambient applications require special consideration in selecting and designing components and equipment. However, designers of commercial refrigeration equipment choose components to design systems based on delivering the cooling required at the highest ambient condition.

For moderate and cold climate regions recovering heat from the refrigeration system for heating purposes in the cold season increases system efficiency. Considering the supermarket as an energy system, including the building HVAC, water use, lighting and the commercial refrigeration as a single “system” for which energy use should be minimised, may give considerable total energy savings.

4.2 Types of equipment and applications

Stand-alone equipment are self-contained refrigeration systems and comprise a wide variety of appliances: ice-cream freezers, ice machines, vending machines, and display cases. These systems are found not only in large commercial stores but also in restaurants, convenience stores, mini supermarkets and gas stations. In developing countries, domestic refrigerators and freezers can be found in small shops and used for commercial purposes. Stand-alone equipment are increasingly used in developed countries in medium-size supermarkets because of ease of maintenance of the fully-welded circuit. In Europe, and lately in other markets, this choice is also often related with the use of hydrocarbons or R-744.

Condensing units exhibit refrigerating capacities ranging typically from 1 kW 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 typically located external to the sales area. The cooling equipment consists of one or more display case(s) in the sales area and/or a small cold room. Condensing units are typically installed in specialty shops such as bakeries, butcher shops, and convenience stores. In a number of supermarkets, one can find a large number of condensing units (sometimes up to 20) installed side-by-side in a small machinery room. In most of the Article 5 countries, the use of systems using condensing units is very extensive. The global market of condensing units has a strong consequence in terms of refrigerant choices; they are developed based on the most used refrigerants: HCFC-22, R-404A, and HFC-134a.

Centralised and distributed systems are the preferred options in supermarkets. They operate with racks of compressors installed in a machinery room (as in the case of a centralised system) or on the rooftop while cooling coils are in the display cabinets or cold rooms. Distributed systems may be thought of as multiple smaller centralised systems which lead to lower refrigerant charge levels. A number of possible designs exist and will be addressed in Section 4.3 3. Two main design options are used: direct and indirect 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 utilise common discharge lines to the air or water cooled condenser (located on outside the store or on the roof) and common suction and liquid lines to the refrigerated fixtures. Specific 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 centralised 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 around 15% or more per year, and studies show that low leak rates are possible to achieve in supermarket applications to less than half the typical values, some even as low as 3.5% of the refrigerant charge per year.

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 located 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.

4.3 Options for new equipment

In this section, the different types of refrigeration equipment and the lower GWP refrigerant options for use in new equipment are presented. When using refrigerants that have higher levels of flammability such as class A3, A2 or A2L, the appropriate safety standards, building codes and safe design and handling practices need to be followed.

	Stand alone	Condensing Unit	Centralised
High GWP HFC (current)	DX	DX	DX
Lower GWP HFC/HFO	DX	DX	DX/with HTF
R-744	DX	DX	DX
R-717	---	With HTF	With HTF
HC	DX	DX / with HTF	With HTF

The table above summarises the different equipment types and indicates how the current high-GWP and the replacement lower GWP refrigerants are used – in the direct (DX) or indirect (with a HTF) formats. Flammability and toxicity are often the reasons why a refrigerant is used in an indirect system instead of a direct.

4.3.1 Stand-alone equipment

Several stand-alone equipment types are described in this section, in order to analyse the trends for refrigerant choices depending on the cooling capacity, the refrigerant charge, and the refrigerant circuit design. Typically, many of the stand-alone equipment types are owned and installed by global food and beverage companies. The companies develop their own environmental policy and choosing low-GWP refrigerants as well as energy-efficient systems are part of the green positioning of those companies.

Bottle coolers

Glass-door bottle coolers can be found in nearly every supermarket, gas station, and kiosk. The most common type is the one-door 400-liter type, but also bigger (2 or 3 glass doors) and smaller types are on the market.

Hydrocarbon (HC-290) bottle coolers as well as R-744 bottle coolers show good energy performances and with R&D developments in compression technology and insulation, even better compared to the HFC-134a base line. Often when such comparisons are made, one needs to note that the older HFC-134a bottle coolers may not have the same improvements in compression, insulation, heat exchangers and controls the newer hydrocarbon systems do. Hydrocarbon bottle coolers showed 28% reduced energy consumption compared to older HFC-134a bottle coolers, and for R-744 12% energy consumption reduction (Pedersen, 2008). The choice of HC-290 has been made by several European and US companies manufacturing those bottle coolers, including some that had originally chosen R-744 (Hydrocarbons21, 2016).

Within the AHRI/AREP test program, laboratory tests have been performed in order to evaluate the two low-GWP HFOs: HFO-1234yf and HFO-1234ze(E), and HFC-134a based blends designed to replace HFC-134a at nearly the same performance. Tests indicate that those low-GWP refrigerants are in the same range of performance but that refrigeration system optimization may be necessary to take advantage of the characteristics of the new refrigerants.

Ice-cream cabinets

R-404A and HFC-134a are the refrigerants used in ice-cream cabinets and are progressively being replaced with HC-290 by large food companies. The number of HC-290 ice-cream cabinets is expected to grow significantly in the next several years.

Vending machines

Vending machines require a significant cooling capacity to rapidly cool the beverage or food container. A Japanese company has developed a high-efficiency R-744 cassette that is compact and has passed the tests of energy efficiency defined by soft drink companies. HC-290 vending machines have also been developed to perform satisfactorily from an energy point of view. As for bottle coolers, the choice between R-744 and hydrocarbons is made based on conclusions drawn from risk analysis, codes and standards that apply to flammable refrigerants, and minimum energy efficiency requirements.

In some markets, e.g., Japan, “hot and cold” vending machines are popular, selling both cold and hot drinks from the same machine. These systems utilize both the hot and cold side of the refrigeration system. These applications are well suited for refrigerants such as R-744 due to its heat rejection characteristics, but, could be applied with any refrigerant.

Water coolers

A large number of water coolers for both bottled water and tap water are installed worldwide. The refrigeration capacity is small and the refrigeration circuit is fully brazed. Thus this equipment looks like a small domestic refrigeration system. Many companies have switched from HFC-134a to isobutane (HC-600a). The hydrocarbon charge is typically 40 to 50 % of the HFC-134a charge.

Ice machines

Ice machines 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. The usual R-404A charge can vary from 500 g to 2 kg. Within the AHRI/AREP program, an ice-machine dispenser has been tested with three new low-GWP HFC-based blend with a temperature glide of about 7 K at the evaporator (AHRI, 2014). The study yielded mixed results for ice production and power consumed when the new refrigerants were “dropped in” with no optimisation being done for any of the components. The study concluded that optimization of the equipment was necessary for getting equal or better performance. In Europe, and in other regions, small ice machines now use HC-290 and are sold as a standard option. More recently, equipment manufacturers have started introducing ice machines using R-744 as the refrigerant (R744.com, 2014).

Stand-alone plug-in display cases

The use of stand-alone cabinets of the plug-in type is increasing in Europe, especially in discounter stores. Many small- and medium-size supermarkets install such units instead of the cabinets cooled by a remote refrigeration system. The plug-in cabinets have lower installed cost, are more flexible and require less system maintenance, because of the fully brazed circuit. Plug-in cabinets are typically less energy efficient compared to display cases cooled by condensing units or compressor racks, because small compressors have lower energy efficiency than larger ones. However, small commercial compressors continue to improve in efficiency and combined with less losses for such systems compared to the larger central systems, this situation may be expected to change. Efficiency can be further improved by the use of variable speed compressors, and these along with other options are discussed later in this chapter.

The condenser heat is released into the sales area where the display cases are installed. For high outdoor temperatures, the heat released in the sales area requires higher cooling capacity for air conditioning the sales area. On the contrary, the heat released is a gain in winter in moderate and cold climates. Some installations of stand-alone display cases are designed with water cooled condensers allowing the release of heat outdoor, usually using a small water chiller; in this specific design, energy efficiency can reach acceptable levels. Increasingly, a version of this design where the water-cooled condensers are connected and heat is rejected through a single large chiller system, is becoming popular. This design combines the benefits of stand-alone low-charge systems with an air-conditioning chiller for the final stage of heat rejection to the atmosphere.

The refrigerant choice used to be R-404A. Since 2007, hydrocarbon display-cases using HC-290 have been proposed as a standard option in Europe and gaining acceptance elsewhere, with an energy efficiency gain of approximately10% compared to R-404A (a better low temperature refrigerant than a medium temperature one from an efficiency point of view). R-744 and even HFC-134a systems for display cases have also been introduced by several key suppliers. Low-GWP HFC/HFO blends are also being tested and can be expected to be more commonplace once the results are proven positive.

Summary for stand-alone equipment

The preliminary conclusions that can be drawn for stand-alone equipment are as follows:

- HFC-134a and R-404A will be phased down progressively in non-Article 5 countries. Due to multinational companies this phase-down is also beginning in Article 5 countries. There are several low-GWP refrigerant options such as hydrocarbons, R-744 and new low-GWP HFO based blends that can be used depending on commercial availability. Revision of safety standards is under way to increase the charge limit of flammable refrigerants which may allow larger quantities in stand-alone equipment.
- Addition of glass doors and LED lighting to display cases can reduce the refrigeration load thus enabling the use of flammable refrigerants for these display cabinets within the allowable charge limits and/or reduce the refrigerant charge in general.
- Minimum energy standards have been issued or updated in the last years in Europe, North America, and in many countries, making a new competition between manufacturers in order to reach higher energy efficiency stand-alone systems; the CLASP report (Waide, 2014) estimates the possible improvements for the different stand-alone equipment types between 30 and 40% compared to the current average energy consumption.
- Ecodesign measures, taking into account all impacts during the life cycle of the product (see Chapter 11) will be soon issued for commercial refrigeration in Europe, energy consumption being the main criterion to be addressed in order to lower significantly the environmental impact of those equipment. In addition, energy labelling schemes are being developed for certain types of commercial appliances. In parallel, the amended F-gas regulation has affected refrigerant choices in these equipment by setting quotas which has increased the price level of high GWP gases.

4.3.2 Condensing unit systems

Condensing units comprise one or several compressors, an air-cooled condenser (usually), a receiver, and a liquid line to be connected to the refrigeration circuit. Condensing units are designed for several capacities and are standardised equipment. They are commonly used in commercial refrigeration worldwide, especially in developing countries. The design is often a basic vapour compression cycle and the usual refrigerant is HCFC-22 in Article 5 countries, HFC-134a, R-404A and, to a lesser extent, R-410A in non-Article 5 countries.

Lower GWP HFC and HFC/HFO blends

For HCFC-22 and R-404A replacement, a number of “intermediate” refrigerant blends are proposed, such as R-407A, R-407F, R-407H, R-448A, R-449A, R-449B, R-452A and many others, including some that have not yet received their ASHRAE number. Their GWPs range from about 1000 to 1700. They are designed to replace HCFC-22 or R-404A and are 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.

A new set of low-GWP R-404A and HCFC-22 replacement refrigerant blends is also being introduced with GWPs ranging from less than 150 to 300, such as R-454C, R-455A and R-457A. Some have been tested and results are available in the public domain (Schultz, 2013) showing a volumetric capacity either identical or in the range of ±5%, with a COP from 2 to 7% lower compared to HCFC-22. Many low-GWP HFC/HFO blends contain HFC-32 and HFO-1234yf and/or HFO-1234ze(E), and they are classified as 2L low-flammability refrigerants in ASHRAE 34. For HCFC-22, HFC alternative-blend options that are proposed show performances close to the benchmark reference. The results indicate that soft optimization could lead to performances on the level of the baseline refrigerants. Nevertheless, equipment manufacturers have to take into account in the new equipment design that all these refrigerant blends have temperature glide varying from 4 to 7 K. In addition, A2L refrigerants are designated as Class 1 by the Pressure Equipment Directive (PED) and this has to be taken into account in the design of components and equipment.

Replacement lower GWP refrigerants for HFC-134a in this type of equipment include R-450A and R-513A. The HFOs are also being tested as possible replacements but the refrigerant amount is limited by the equipment safety standards.

R-717

R-717 is not commonly used in these systems for cost and safety issues. However, it is used in cascade systems with R-744 in the low stage of the equipment, especially in larger commercial application needs. Research into low-charge systems is being done that could make this refrigerant more attractive in these applications.

R-744

New R-744 condensing units are now commercially available in Europe and Asia. The market penetration is low at present but is expected to increase in the near future. R-744 condensing units require a double-stage design if high ambient temperatures occur frequently. Single-stage systems are designed for cold climates. The additional cost for a double-stage system is significant compared to usual HFC reference condensing units. The cost remains the main barrier for these R-744 condensing units in certain regions, but with increasing production capacity and financial incentives this barrier is expected to be overcome soon. Energy savings over HCFC-22 systems may provide incentives to use R-744. In a pilot program using R-744 condensers in 12 Indonesian pilot stores, energy savings of 20% compared to the existing older design HCFC-22 system was achieved (Santoso, 2016).

Hydrocarbons

Direct expansion condensing units using HC-600a or HC-290 or HC-1270 from 100 W to 10 kW (up to 1.4 kg charge) are commercially available from major manufacturers for temperatures ranging from -40°C up to 0°C. Costs for these HC-based systems can be up to 15% higher than HFC systems due to safety measures required for mitigation of risks.

Due to flammability concerns, indirect condensing units using HC-290 or HC-1270 with typical refrigerant charges varying from 1 to 20 kg, are beginning to be used in Europe. The HC systems can achieve up to 30% increases in energy efficiency (Garry, 2018).

Summary for condensing unit systems

The replacement of R-404A is underway primarily with lower GWP and low GWP HFC and HFC/HFO blends. Many of the newer low GWP replacement refrigerants for R-404A tend to be classified as A2L for flammability and toxicity. 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 improve leak mitigation and refrigerant charge limits. R-744 trials are underway but condensing unit systems are often focus on simplicity and cost which make it a challenge for R-744 to be applied. This could change as more research and trials yield positive results.

4.3.3 Centralised supermarket systems

Centralised systems are the preferred option in medium to large supermarkets, because they usually achieve better energy efficiency than plug-in cabinets and condensing units. This is mainly due to compressor efficiencies being higher for larger compressors (in the range of 60-70%) compared to smaller compressors (in the range of 40-50%) used in plug-in cabinets. The sales area of supermarkets with centralised refrigeration systems varies from 400 m^2 up to 20,000 m^2 for large supermarkets.

Generally, for large supermarkets, the reference design is a direct-expansion centralised system with several racks of compressors operating at the two evaporation temperature levels (-10°C ± 4 K and -32°C ± 4 K 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 using HCFC or HFC in direct expansion refrigeration systems. Usually, the compound compressors operate with a common condenser which provides a number of different evaporators with liquid refrigerant. Places to be cooled by the system include refrigerated cases and medium and low temperature cold rooms. Because all cabinets/evaporators are connected to all compressors in one compound system, refrigerant charges can be quite high – up to 3,000 kg for hypermarkets – with resulting high emissions in the case of component failure like pipe rupture, e.g. due to excessive vibration. In addition, the numerous joints of large systems are prone to frequent leakage (especially mechanical joints), hence such systems often have average refrigerant leak rates of 15 % of the refrigerant charge per year (Schwarz et al, 2011). Lower annual leak rates are possible through concerted effort; some successes have been reported in Germany and elsewhere with reduction of annual emission rates lower than 10% (Kauffeld, 2013).

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

- the choice of refrigerant(s),
    - HCFC or 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 carbon dioxide (MT and LT), and
- the method of cooling of the condenser/gas cooler
    - Ambient air cooled; in hot climates sometimes with evaporation of water in order to reduce air temperature
    - Water cooled; water cooling by ambient air, possibly assisted by water evaporation in cooling towers
    - Water based heat recovery; i.e. condenser is water cooled heating tap water or store
    - Air based heat recovery; heating store room air directly.

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

The evaporator of a direct expansion systems is located in the application (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. Direct expansion systems are common worldwide and is the dominant technology for supermarkets. The direct expansion centralised 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 of the sales area which the public may enter. Therefore, the refrigerant will be restricted to lower toxicity, non-flammable safety classification or charge limited if the refrigerant is flammable (i.e. class A1 per ASHRAE 34 and safety standards such as EN 378).

For cost reasons and for technical simplicity, commercial centralised systems have usually been designed with a single compression stage even for low-temperature levels down to -38°C. Two design options, cascade and booster systems, which are common in industrial refrigeration, have been introduced in commercial refrigeration in order to improve energy efficiency (see Figures 4-1 and 4-2). They can be used for all refrigerants, but the development has been especially made for R-744.

Cascade systems

The cascade system, as shown in Figure 4-1 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. In any case two-stage systems are more efficient than single-stage ones; the energy saved is typically of 15 to 20% and is more pronounced for high outdoor temperatures.

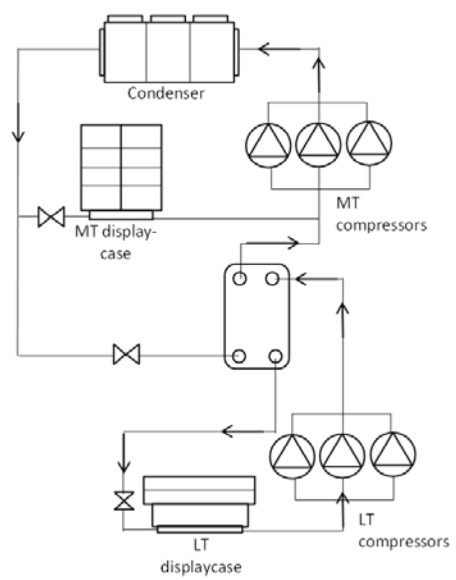

Figure 4-1: Cascade system

Booster systems

Another design, which is simpler and less costly, is also developed and now installed frequently in commercial refrigeration: the booster system presented in Figure 4-2. 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 further expanded by the expansion valve 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). The intermediate pressure level can also be used for comfort cooling purposes.

These two designs are now installed in several thousands of stores; cascade systems – with usually HFC-134a at the medium-temperature level and R-744 in the low temperature – in large supermarkets, and full R-744 booster systems in larger to smaller ones. These stores are currently mostly found in Europe, North America and Australia, but are gaining adoption in the rest of the world.

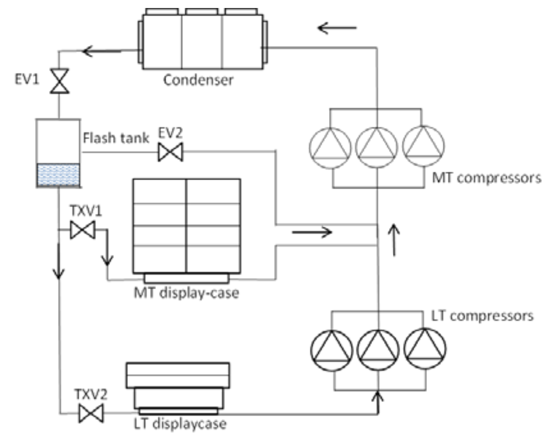

Figure 4-2: Booster system

Distributed systems

Distributed systems 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 (usually, compressors run cooler) 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 direct-expansion centralised system, while the energy efficiency is in the same range. 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.

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 heat transfer fluid (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 4-3.

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%.

As shown in Figure 4-3, the low-temperature direct expansion system can release the condensation heat to the HTF secondary loop, leading to better energy efficiency of the low-temperature system and allowing also 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 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 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.

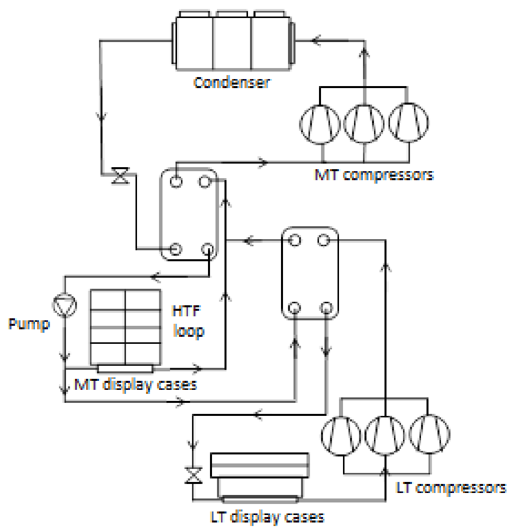

Figure 4-3: Indirect system at the medium-temperature level and direct expansion at the low-temperature level

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. are also possible where the condensation heat of the low-temperature system is directly released to the atmosphere.

The use of 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, has to 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.

In developing countries, supermarkets can be of very different sizes but also have a centralised machinery room as in developed countries. Often, for cost reasons, ease of installation and maintenance, many small supermarkets and convenience stores in developing countries use air-cooled condensing units. HFCs and HFC blends are common in both central, distributed and condensing unit systems.

Medium and high GWP HCFCs, HFCs and HFC/HFO blends

The dominant refrigerant for centralised systems in Article 5 countries is HCFC-22, while R-404A and increasingly R-407A, R-407F are common in non-Article 5 countries. In Japan R-407C is also used, and some stores using R-404A have switched to R-410A in the recent past. Pure HFC-32 is beginning to be used at the medium-temperature level and both R-744 and HFC-32 are under evaluation for the low-temperature level in Japan. The flammability of HFC-32 makes it difficult to be used in large direct expansion systems outside of Japan due to different standards and codes being applicable. The same could be said for other lower GWP HFC/HFO blends that are classified as flammable and field evaluations can be expected as standards and codes get developed. More recently, lower GWP non-flammable alternatives for R-404A, like R-448A, R-449A, R-452A and R-407H are undergoing field trials and starting production while HFC-134a alternative blends like R-450A and R-513A are also being evaluated. These and other similar lower GWP HFC/HFO blends are important not just for new systems, but also as replacements for existing systems that use R-404A and HFC-134a, as HFC phase-down regulations get implemented.

HC-290 and HC-1270

Refrigerant changes have begun since the early 2000 in Europe, and especially in Germany, where propylene (HC-1270) has been introduced in supermarkets, using a secondary loop. HC-290 is now the preferred option. For all HCs, the machinery room is located outside of the store. The number of these HC-systems is limited; however, charge reduction strategies can help in increasing the number of systems with such refrigerants.

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 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, cascaded together with R-744 at the low-temperature level. Research into low-charge R-717 systems are also underway and can lead to breakthroughs in the future.

R-744

The real breakthroughs 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 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 4-2). So far, more than 18.000 transcritical R-744 systems of different sizes have been installed, mainly in Europe (73%) (Skacanova, 2018). Due to the widespread use of R-744 in Europe and Japan, the cost of systems has been significantly reduced and they now compete with HFC systems.

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 a 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, 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).

Low-GWP HFCs and HFC/HFO blends for R-404A and HCFC-22 replacement

The AHRI/AREP Report # 21 (Shrestha, 2013) presents several low-GWP HFC/HFO blends (from 220 to 300) proposed to replace R-404A in condensing units that are the same as those proposed for centralised systems. The refrigeration capacities of these blends are slightly lower, energy efficiency slightly higher and temperature glides of 4 to 7 K are larger compared to R-404A. Several of the blends exhibit temperature glide and it is important to follow manufacturer recommendations for installing, commissioning and servicing systems when using refrigerants with glide.

Some of the low-GWP HFC/HFO blends are designed to replace HCFC-22. For the tested blends, the cooling capacity is 2 to 7% lower and the efficiency varies from -5 % to +10%. Some of the blends formulated to replace R-404A are the same as those formulated to replace HCFC-22.

The results of the AHRI/AREP reports show that soft optimization of refrigeration systems using those blends may lead to the same level of performances. Three issues are still to be finalised: safety rules for low flammability refrigerants, servicing of leaked systems operating with blends and commercial availability.

A new set of low-GWP HFC/HFO refrigerant blends is also being introduced with GWP around 150 or less. In general, these new refrigerants are flammable and could only be used in charge limited systems such as stand-alone, condensing unit, distributed and secondary equipment systems (de Larminat, 2018).

Summary for centralised supermarket systems

For centralised systems a number of options are available and proven; some of them require a higher technical training of contractors especially for two-stage R-744 systems.

The replacement of R-404A is underway and will lead to several families of 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 have a GWP lower than 2000 will grow in use, both in existing and new systems. Low GWP and mildly flammable HFC/HFO blends at all temperature levels will also be considered but flammability concerns might limit the types of systems due to the current standards. The change to flammable lower GWP alternatives is giving rise to innovations in systems architecture with the focus on using less refrigerant, with fewer or better joints, more electronics variable speed technology, and better control, all with the goal of reducing cost and complexity.

Regardless of the refrigerant chosen for a commercial refrigeration system, it is important that a whole system approach be taken to the design, selection, installation and commissioning of the equipment. Load reduction, either through addition of insulation, or location of refrigerated cases, use of doors whenever possible, can help reduce the size of the equipment and refrigerant charge. With a holistic approach to system design, commercial refrigeration systems should account for the presence and interaction with other equipment in the space, such as the heating, air conditioning, dehumidifying and even the heating of water, to name a few. Such an approach can also 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 commercial refrigeration system in the context of the use of the equipment.

4.3.4 Energy Efficiency in new equipment

Energy efficiency of commercial 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, to name a few. The efficiency of lower GWP refrigerants in new commercial refrigeration equipment is discussed in context in the sections above. A few additional points are made here which are particularly meant 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 power consumed; reductions in power consumption can come from efficiency improvement as well as reduction in cooling load. The latter often yields better results, e.g., the addition of doors which can reduce cooling load by as much as two-thirds, thus leading to significant energy consumption reduction.

Listed below are several energy reduction and performance improvement methods that can often be employed with any refrigerant and in both new and existing systems. 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. 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 centralised systems and condensing units and to a lesser degree in stand-alone equipment. 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.

System vs Component efficiency

In commercial refrigeration, more than in most other types of applications, it is important to take a holistic system approach to defining energy efficiency. In the case of stand-alone equipment, this is often the case; for condensing units, there are some countries that have established a whole system efficiency measure (AHRI 1250 2014). However, for centralised 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, when the outdoor ambient, the cooling load, and all components of a system affect the performance, leaves many energy savings opportunities unaddressed (Minetto, 2018). Some of these measures, that can only be realised through a whole system approach, are described below.

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, 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.

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 centralised systems, though this method of efficiency improvement is applicable to all refrigerants. Availability of water may however be a challenge in some areas.

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 centralised 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 contributes 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.

Mechanical subcooling

Mechanical subcooling is the process of cooling the refrigerant liquid out of the condenser or flash tank in order to increase the realised cooling capacity in the evaporator coil and improve the performance of the expansion device at the inlet to the evaporator. This is a commonly used method of improving system efficiency and is often overlooked, especially the part about the expansion device performance improvement, and can be applied to all refrigerants, but is often used with transcritical R-744 systems.

Ejector

An ejector can recover some of the energy released during expansion instead of only dissipating it as is the case when using a throttling valve. The most common use is to compress gas (and liquid) exiting from the evaporator. Two important effects are then: that 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 pressure lift. System efficiency may often be increased by 20% (Hafner, 2014b). This is a concept also being implemented for R-744 to achieve high efficiency for systems used in high ambient temperature conditions (Gullo, 2018).

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 the sytem's compressor (common in scroll and screw compressors).

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, and is discussed in section 4.3.3. This method of improving efficiency is most commonly used with R-744 transcritical systems.

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 evaporator coil through a simple heat exchanger. This has the dual effect of improving efficiency and preventing liquid from entering the compressor which can help improve reliability as well.

4.4 Options for existing equipment

This section covers the retrofit options for the installed base of equipment. Many of the new lower GWP refrigerant options are higher pressure, 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 “glide”. Therefore, it is important to make sure that the system design can accommodate this glide. 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, a few options for stand-alone equipment are: R-448A, R-449A or R-452A as replacements for R-404A; R-450A and R-513A for HFC-134a. These replacement refrigerants are classified as A1 and can be used for retrofit. This list can be expected to grow as more manufacturers release alternates 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 countries will be to find replacement options at acceptable costs, given the fact that Article 5 countries will lag the non-Article 5 ones in adopting these changes; the cost of these changes can be expected to be better when Article 5 countries 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 phase-down schedule. 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.

4.4.1 Energy efficiency in 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 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 refrigerant.

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. 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.

Proper refrigerant charge: A retrofit is a good time to confirm that leaks, if any, are identified and repaired. Filling the manufacturer recommended refrigerant charge is important for the performance of the system and its reliability. Too much or too little refrigerant charge will lead to poor performance and efficiency losses.

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 minimise energy consumption in the equipment.

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 of a system. Condensing 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 and power consumed. A refrigerant retrofit is a good opportunity to clean the coils and ensure that there are no barriers to free air flow over them as per manufacturer requirements.

Adequate defrost cycles: Too few or too many defrost cycles will lead to higher energy consumption, furthermore, getting the defrost start- and end-times as well as the frequency to recommended levels is important for efficiency.

Addition of doors and door heaters: 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 consumed, but, this can be mitigated through smart controls that take into account both ambient conditions and usage factors.

Conversion to LED lighting: This is another energy saving option that can be considered at the time of a refrigerant retrofit. Most existing display cases do not have low energy LED lighting and utilities and government agencies often offer incentives to retrofit the lighting as well. LEDs are more efficient and also put out less heat, thus making the refrigerated display case work better for maintaining the temperature.

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Chapter 5

Industrial refrigeration and heat pump systems

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5 Industrial refrigeration and heat pump systems

5.1 Introduction

The industrial sector has not changed significantly since the publication of the last, 2014 RTOC Assessment Report (UNEP, 2015). One has seen other trends that can seem marginal to outsiders but is a big deal in the industry. Low charge is one of these trends and the introduction of cascade systems and CO_2 trans-critical systems enforces the penetration of CO_2 in industrial systems.

Ammonia continues to be the preferred solution in many of the food and beverage industries, large industrial systems in most markets and new refrigerants have not gained any significant market share in this period. This can have many reasons and any guess can be as valid as the other. The new A2L refrigerants require the same attention to the design of the machine room as an ammonia plant. However, for large industrial process companies energy is of paramount importance. R-717 is a very efficient solution in most applications.

Many industrial systems have also been built using HCFC-22 and later R-404A/R-507A. In Europe many such installations were converted, due to the 2006 F-gas regulation, to the availability of other solutions such as R-422A, R-407C and others (see Table 5-1). Some of these solutions have GWP over 2500 and will be affected by the F-gas regulation of 2014. Some customers do not want to use R-717 under any circumstance.

Table 5-1: In Europe, refrigerants and blends with a GWP over 2500 are regulated by the F-gas regulation (EU, 517/2014). The refrigerants most used with these high GWPs are R-404A and R-507A, but also other blends fall in under the same category.

Refrigerant	GWP
R-404A	3922
R-507A	3985
R-422A	3143
R-422D	2729
R-428A	3607
R-434A	3234

There have been several major accidents involving R-717 especially in Article 5 countries resulting in multiple fatalities (Shanghai, 2013). These events have emphasised the need for system design to conform to recognised safety standards, as these levels of fatality are unprecedented in traditional market sectors using ammonia. Adherence to the standards might have helped reduce severity but not avoided entirely the accidents. A higher awareness and education level would have prevented some of these accidents.

Industrial systems can encompass systems such as ice rinks, large cold stores, freezing tunnels, ice production, and many other applications. Industrial systems are characterised primarily by the size of the equipment (physical size and heat transfer capability) and the temperature range covered by the sector. This chapter includes discussion on industrial heat pumps (heating systems similar in scale and application to industrial refrigeration systems) and industrial air-conditioning (systems for controlling air temperature in production factories, computer centres and other process areas). In addition to size of installation the distinguishing traits of industrial refrigeration systems are that the load is not primarily seasonal and the operation of the facility would be jeopardised by failure of the cooling equipment.

Such systems have special design requirements, including the need for uninterrupted service, which are not typically provided by traditional HVAC practices (ASHRAE, 2009). Large chillers used for air cooling in offices, hotels, convention centres, computer centres and similar installations are not covered by this chapter. Detailed information on those systems will be found in chapter 9 on chillers.

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.

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. In chemical plants one will send leaked ammonia to the flare which normally are available in such installations.

Most of the fluorinated alternatives available in the future are blends, which cannot be used in two or more staged systems due to fractioning issues of the blend causing various problems. It is therefore essential that the industry learns to work safely with ammonia. Kent Anderson, President Emeritus IIAR, said: "Most fatalities are to workers, not to responders or the public and are preventable." (Anderson, 2017)

5.1.1 Background

Thirty years ago, CFCs were widely used in the industrial sector in many European countries, particularly a blend such as R-502. The advantage of these substances was their low index of compression, which permitted single stage operation over a wider pressure ratio than could be achieved with R-717 or even HCFC-22. Other countries, notably the United States and Canada had not moved away from R-717 to the same extent as some European countries. In the heat pump sector, CFC-12, which has a critical temperature of 112ºC, was common for small to medium sized applications and R-717 was used in larger systems. Industrial air-conditioning was less common at that time, and tended to use standard chillers employing CFC refrigerant.

The move away from CFCs in the late 1980s, prompted by the Montreal Protocol, presented particular problems in the industrial sector because the replacement fluids with lower or no ozone depleting potential were not as suitable over the wide operating range required. In some places this resulted in a swift return to R-717 technology, for example in the United Kingdom (Brown, 1992). In other countries the re-adoption of R-717 was more widely resisted and the adoption of low ODP refrigerants was coupled with widespread use of secondary refrigerant systems. For example R-502 had been common in Japan. The industrial sector there responded to its removal by the development of compact, low charge R-717 systems and the use of secondary systems with a limited charge of the more expensive HFC fluids (Kawamura, 2009).

In Article 5 countries, where R-717 was already used for refrigeration, these systems were retained and extended (Tarlea, 2013; Gulanikar, 2013), but the designs used tended to be old-fashioned and not as efficient or safe as the new Japanese or European innovations. In countries with no history of R-717 use, or with no support infrastructure, the solution was often to use large numbers of smaller light commercial systems to satisfy a large cooling load (Pietrzak, 2011). This is expensive to install and maintain, and it is also much less efficient in operation.

5.1.2 Efficiency and Sustainability

With increased emphasis on climate change in recent years the importance of energy efficiency is now far greater than before (see further in Chapter 11). This has led to a reappraisal of previous policies, for example in the growing trend for central systems with R-717 rather than multiple commercial systems with HCFCs. There is also a greater focus on integration of industrial heating and cooling systems to make better use of waste heat recovery (Pearson, 2011).

In Europe, the regulation on the use of fluorinated gases has also encouraged users to consider R-717 and other developments such as the use of R-744 in cascade systems, similar to those shown in Chapter 4 of this RTOC report. The motivation seems to be primarily based on concern about restrictions on HFCs rather than the immediate effect of the current rules (Anon, 2010), which are mainly aimed at commercial and mobile air-conditioning. In the industrial sector it is likely that the adoption of R-717 and R-744 by users who previously deployed HCFC-22 and HFC blends, will reduce the energy-related GWP through increased efficiency as well as eliminating the direct global warming potential caused by refrigerant leakage. Especially outside Europe and warmer climates cascade make better sense than R-744 only systems in industrial applications energy wise, but other considerations may alter this in favour of an HFC solution on the high stage.

In some regions with hot climates (HAT, see chapter 13) new solutions using non-traditional solutions can come in to play when the cost of energy becomes a topic. In some cases you can use rivers or lakes with a flow as heat sink parts of the year or all year. What is also often neglected is the possible use of sea water as heat sink. Also machines for desalination can provide cooling while evaporating water for potable water production. The technologies are not new just not always connected to use all options. Cold water can be distributed from large tanks distributed strategically underground to avoid sun radiation.

A more wide spread use of cooling towers and evaporative condensers in warm and dry climates will give a great boost to the energy efficiency, because the condensing temperature can be kept close to the wet bulb temperature. In many parts of the world, it is possible to use sea-water for sea water resistant cooling towers. River and lake water not usable as a potable water source can also be used for cooling the condensers.

With a wider use of district cooling and heating systems the term waste heat will get a different meaning. What is waste heat in one place can be a precious heat source in other areas. In the future we cannot afford to throw away heat if it can be used by others if we are to achieve the carbon free energy future.

Further discussion of sustainable manufacture is provided in chapter 11.

5.1.3 Refrigeration

Industrial refrigeration systems are characterised by heat extraction rates in the range of 100 kW to 30 MW and in some cases even much more, typically at evaporating temperatures from –50°C to +20°C. There is some overlap at the lower end of the capacity scale with commercial and transport refrigeration for shops, restaurants and institutions: industrial systems in this sub-sector are characterised by the complexity of the design and the nature of the installation (NH_3 as working fluid). The size of the industrial refrigeration market is difficult to assess because it covers such a broad range of applications but look at the many market research companies' statements gives an estimate in 2023 to be in between US$ 38 and 41 billion.

Some useful insights can be gained from consideration of the market for evaporative condensers, as they are used for heat rejection in the majority of large installations. Data for 2009 was analysed for three global regions; Europe / Russia, North America and India / China. It is assumed that the value of the condenser accounts for 5% of the selling price of the refrigeration system – analysis of a wide range of projects showed that the value of the condenser is in the range 3% - 7% of the total refrigeration contract value.

Evaporative condenser manufacturers also report that 90% of the condensers sold in Europe, Russia, India and China are for R-717 systems. In North America the proportion is even higher, at 95% (RTOC, 2009). The balance is used on HCFC-22, R-404A, R-507A or occasionally HFC-134a. The results are shown in table 5-2.

Table 5-2: Estimated market value (2009) for large industrial refrigeration installations

	Total Condenser Sales (US$ M)	Estimated Total Market (US$ M)	Proportion of R-717 use
Europe/Russia	42	830	90%
North America	77	1,500	95%
India/China	45	900	90%

Smaller industrial systems more often use air-cooled condensers, and in these cases the refrigerant is more likely to be a fluorocarbon, although air-cooled condensers with stainless steel tubes are used in smaller R-717 systems. Table 5-3 shows the estimated value of the refrigeration market for the same regions with the split between R-717, HCFC-22 and HFCs.

Market research companies estimate the Industrial Market value to be worth US$ 23.22 billion in 2022 (Markets, 2016). It should be noted however that there may be significant variations within the regions from country to country or state to state due to legislation or tradition. For example the use of R-717 in small industrial systems is quite common in Germany, but not in France, and is virtually unknown in Canada and some states in the USA, such as New Jersey.

Typically, if HCFC-22 is still permitted, e.g., in Article 5 countries, it will be used for these smaller systems. If ozone depleting substances have already been prohibited then the likely refrigerants will be R-404A and R-507A for low temperature systems and HFC-134a for high temperature systems. Experience with the accelerated ODS phase-out in Europe showed that HCFC-22 systems continue to be deployed right up to the phase-out deadline. The same pattern of behaviour has been observed more recently in the United States which followed the Montreal Protocol phaseout schedule.

Table 5-3: Estimated 2008 market value for small industrial refrigeration installations

	Estimated Total Market (US$ M)	Proportion of R-717 use	Proportion of HCFC-22 use	Proportion of HFC use
Europe/Russia	200	25%	10%	65%
North America	300	10%	60%	30%
India/China	500	5%	90%	5%

This table shows that the transition in smaller industrial systems when HCFC-22 is removed is often replaced by HFC blends. For Article 5 countries it is possible that a different pattern will emerge. Concern about a "phase-down" of HFCs and associated price increases might result in a switch directly from HCFC-22 to R-717 for larger new systems provided trained staff are available and the inherent fear of R-717 is overcome. In many ways this is simpler than switching to HFCs and then to R-717 at a later date. For example, the traditional lubricants used with HCFC-22 can also be used with R-717, whereas alternatives (typically polyol ester) are required for HFCs and are not compatible with R-717. The use of R-717 as a replacement for HCFC-22 for small capacity systems will only be feasible if technician training is prioritised and system designs incorporate low refrigerant charge.

In the Middle East, Saudi Arabia and Egypt have a relatively large bank of refrigerants in industrial refrigeration applications. Saudi Arabia has an estimated bank of HCFC-22 of about

2,500 tonnes, in 2008. This constitutes 80% of the total refrigerant bank in Saudi Arabia for industrial refrigeration applications. The remaining 20% is distributed between R-717, R-404A, HFC-134a and some CFCs.

The phasing-out of R-502 and the harsh high ambient temperatures in the region for a large part of the year coupled with the scarcity of water have resulted in the use of small capacity air-cooled condensing units operating on HCFC-22 in many industrial systems. R-717 systems are few and are used for large applications such as food processing plants, large cold stores and large industrial cooling processes. There is now a growing trend to use CO_2 in cascade systems using e.g., R717 on the warm side of the system in warm climates. This enables the user to reduce the R717 charge to about 10% or less of the original charge by substituting it with R744. CFC refrigeration systems are still in operation although most are near the end of their operational life and need to be replaced.

In Southern Africa almost all large systems use R-717 and, although R-744 has been tested in some supermarkets, R-7444 has not been used in industrial applications. In smaller industrial systems HCFC-22 is almost universally used, and the most common alternative is R-404A.

In many Article 5 countries there is a big growth of the food chain lately, especially in India and China but also in the rest of Asia, Africa and South America generally. With the growth in economy there is a demand for fresh and safe food to be supplied through the supermarkets. This also puts pressure upstream all the way to the producer. In the seafood sector it will not be acceptable to sail out without some kind of cooling of the catch and the traceability and temperature records will become mandatory in the future to ensure food safety for the consumer.

5.1.4 Heat pumps

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 where you can recover surplus heat or waste heat and use it for heating a process or preheating process fluids.

Industrial heat pump systems have heat delivery rates from 100 kW to over 100 MW, with the heat source usually at ambient temperature or the waste heat temperature of an industrial process. These systems are usually required to deliver higher temperatures than domestic or commercial heat pumps used for space or water heating as described in chapter 8. Typical heating temperatures are in the range 60ºC to 90ºC, although, if the recovered heat is to be used for steam heating, then it needs to be at least at 130ºC level. Research on systems producing heating at more than 180ºC is going on with water as a working fluid using vapour recompression 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.

There is no single component of the system that can be identified and tracked to give an indication of the overall market size, because the compressors could equally be used in other industrial systems and the condenser will be a bespoke design suited to the heating application – most probably a fluid heater such as a plate and frame heat exchanger or shell and tube pressure vessel. The market is probably around 5% of the industrial refrigeration market in Europe, and less in North America, India and China.

Market Intelligence Company reports are mainly focused on smaller systems for domestic and light commercial applications. However, the company Technavio has estimated the global Compound Annual Growth Rate (CAGR) for industrial heat pumps to be 5% for the years 2017-2021 (Technavio, 2017).

Under others, one finds markets like district heating or other types of space heating e.g. multi apartment houses, hospitals, shopping malls, office buildings etc.

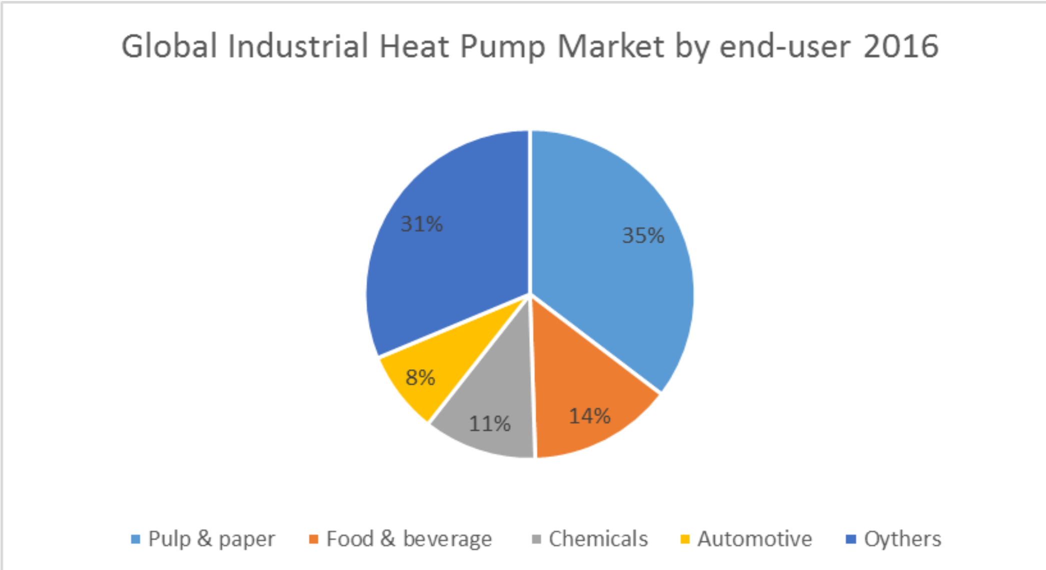

Fig. 5-1: The 2016 market share for industrial heat pumps by type of end-user

In some markets the focus on large heat pumps in industrial applications has been declining, Averfalk (Averfalk, 2017), shows how the annual heat generated by large-scale heat pumps in district heating grew from 1982 to 1986 from where it was very stable until 2003. Since then it has been falling steadily. Werner (2017) estimates that, globally, there are about 80,000 district heating systems, of which 6,000 in Europe. One of the benefits of district heating is that when the world market price for energy goes up district heating can keep the heating price down. But the challenge is the increasing amount of wind energy and how to get this worked into the grid. Here thermal storage can be an advantage for heat pumps. At the same time Gadd and Werner (Gadd, 214) report that the return and supply temperatures are becoming lower in the systems. This is also a benefit for heat pumps. Lund (2017) compares traditional district heating systems with new low temperature district heating systems (4^{th} generation district heating). The supply temperature should be reduced to about 55°C, it says in the conclusion, and then heat should be provided locally, if necessary.

David (David, 2017) has a list of installations. From this list one can take that the number of heat pumps based on HFC-134a outnumbers the alternatives based on R-717 or R-744. One of the reasons for this is that heat pumps with temperatures up to 80°C can be provided with capacities up to about 20 MW on one unit only. The survey includes a supplementary material with data for 149 heat pumps yielding a total capacity of 1580 MW where the average HFC-134a units have a capacity of 6 MW. HFC-134a has a GWP of 1430 and is therefore an unwanted substance in Switzerland and Denmark where their use is restricted or banned and highly taxed in others such as Spain, Norway, Sweden and France.

The difference between industrial and semi-hermetic compressors is that the industrial compressor is based on open-type compressors and the semi-hermetic compressors are using suction gas cooled motors. This internally cooled motor limits how high the suction gas temperature can be where the open type is less sensitive. This limits the efficiency for the semi-hermetic compressor when the suction gas has to be precooled before heated.

Also thermally driven heat pumps are attracting renewed attention. They are available in capacities from about 10kW to a few MW. The system is driven by heat that can come from both direct and indirect sources. Direct is in connection with a burner of oil or gas. Indirect is when heated with a hot liquid where the heat is generated in solar panels, electric heaters driven by wind power, waste heat etc.

5.2 Applications

5.2.1 Food processing

Refrigeration is used for chilling and freezing food during processing, in order to prolong shelf life, but it can also be used to make handling or processing easier. For example, hams are temporarily frozen to enable them to be sliced more thinly. Chilling also plays a part in the pasteurising process where the product is rapidly cooled after heat treatment to minimise spoilage.

A wide variety of chilling and freezing techniques are used, including immersion in liquid, air blast freezing in batches or in a continuous process and contact freezing on tables or in blocks between metal plates. The choice of process depends on the form that the product takes, whether it is wrapped or unwrapped, robust or fragile, processed or raw. Some fruits and vegetables such as potatoes, apples and most soft fruit are notoriously difficult to freeze as the expansion of water destroys the cell walls, leading to mushiness when thawed. Other produce, such as peas, corn and beans, can be frozen in very small pieces using a fluidised bed of air to allow each individual piece to freeze without agglomerating.

There is a negative public perception of frozen food, which is that thawed food will always be inferior quality to fresh. In fact if good quality food is frozen professionally immediately after harvest, catch or cooking it should offer increased shelf-life and superior quality when thawed. Spoilage rates could be substantially reduced if a greater proportion of food were frozen before shipment. If the public perception of frozen food is improved then there could be a significant increase in this sector of the market. Freezing food requires a lot of heat transfer compared to storage, so refrigeration systems are large capacity and require a large power input although the freezing chamber may be physically quite small. There is a trade-off between the time required to complete freezing and the operating efficiency. Running the system at very low temperature is less efficient but results in a shorter freezing time and a higher through put in the freezer per hour.

Some food processes require careful control of humidity and temperature to ensure product quality and in these cases a cooling system is not enough. Examples include bakeries producing cakes and bread, fruit and vegetable storage and fruit ripening. The rate of fruit ripening is controlled by maintaining low ethylene levels in the atmosphere through the use of high rates of ventilation with fresh air. In periods of high ambient temperatures, the cooling load for the incoming air can be substantially higher than the product-cooling load. Failure of the cooling system would cause the product to ripen too quickly resulting in a large loss of product value before it reached the point of sale. In some cases the air-conditioning system is connected to a central plant cooling system using R-717 or HFCs but in others a custom designed stand-alone system in an air-handling unit serves the humidity control requirement.

5.2.2 Cold storage

Cold storage facilities usually operate at two temperature levels, frozen (well below 0ºC) and chilled (above 0ºC). Frozen produce must be stored below -18ºC, and it is usual to maintain the store between -22ºC and -26ºC to provide a factor of safety in the event of major equipment failure. Some products require lower temperatures, for example ice-cream and similar produce is stored between -26ºC and -29ºC, and some niche market products such as some types of sushi must be kept significantly colder, even down to -60ºC, in order to retain product quality.

Chilled produce is typically held between 0ºC and 4ºC, although fruit, bakery products and vegetables are stored between 8ºC and 12ºC. Some stores offer long term storage contracts, in order to stock produce until it is "out of season" and therefore more valuable. Stock may be held for months in these warehouses. Other sites provide marshalling facilities in order to restock supermarkets on a daily basis; in these plants the product is not usually in the building for more than 24 hours. The cooling load on such a building is high because of the amount of traffic through the temperature controlled chambers, although product load is typically low because the residence time is not long enough for the air temperature to have any appreciable effect on the product.

5.2.3 Industrial heat pumps and heat recovery

Many industrial processes including brewing, dairies, food factories and chemical processes require large amounts of heat in addition to a cooling load. Even if the primary use of heat, for example for cooking food, cannot be achieved by heat pumps or recovery there may be many uses for lower grade heat, such as pre-heating boiler feed water or heating wash water for the production area. When the application is collecting and redirecting waste heat from a refrigerating system it is called heat recovery. When it is performing a non-productive chilling process on a source of heat, whether it is at ambient temperature or is the waste heat stream from another process such as a cooker flue, it is a heat pump.

Large heat pumps have also been used for heating public buildings, for example in Gardermoen Airport, Norway (8100 kW heating capacity) and Akershus hospital, Norway (8000 kW heating capacity). These systems are custom-designed, using R-717 as the refrigerant (Stene, 2008).

Even larger systems are used for district heating systems, with many examples in Scandinavia. The smallest of these systems are about 5,000 kW. Most installations use HFC-134a in centrifugal compressors, with some (up to 40,000 kW) using R-717. The largest is in Stockholm, with a total capacity of 180,000 kW (180 MW) using HFC-134a in centrifugal compressors. This system takes heat from sea water to provide the thermal source; other similar installations have used waste water from the sewage system (Bailer and Pietrucha, 2006).

It is perceived that this market will have a large increase over the coming years as countries turn to low carbon heating, with natural refrigerants having a smaller market share of this market than the main industrial refrigeration market it can lead to an increase in HFO use in the coming years.

Steam-fired absorption systems (as described in section 5.3.6) can be used to raise condenser water temperature in power plants to provide heat to district heating networks and some industrial processes. Absorption can also be used to boost the temperature of a proportion of a medium temperature process stream by cooling the remainder of the stream. In this way a small part of a stream at 70°C could be raised to 120°C by cooling the rest of the stream and rejecting its heat to atmosphere at, say, 35°C.

5.2.4 Leisure

The principal use of refrigeration in the leisure market is for ice rinks, extended also to indoor ski-slopes, outdoor snow-making for ski slopes (some with water as refrigerant), ice climbing walls and other ice features. Many older ice rink systems used direct CFC-12 or direct R-717. To change to an indirect system would require replacement of the floor slab, which is a considerable capital expenditure. Some CFC-12 systems have been converted to HCFC-22 despite the increased pressure. Similarly, some R-717 systems in Central Europe have been converted to R-

744. A few very large systems have been installed for bobsled and luge runs, typically associated with winter Olympics. These systems usually use pumped R-717. A recently installed cross-country ski track in Finland used R-744 for the track cooling, with circuits up to 1 km long.

5.2.5 Process refrigeration

Cooling is used in a wide variety of process applications (in addition to food industry applications covered in section 5.2.1). 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 9 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 or propylene 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.

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 raising steam which is fed to the chiller. Such systems require to be tailored 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 so saying R123 is the only solution is not true. Actually, HFC-134a is widely used in South African mines. Actually, an accident in SA was reported in Scanref using HFC-134a. Some of the new fluid blends currently under development for other applications (see for example chapter 2, chapter 4 and chapter 9) may also be suitable for this application but it is unlikely that a fluid will be developed solely for this use.

5.2.6 Gas liquefaction

Gas liquefaction is a growing market and involves industrial refrigeration equipment. The temperature levels reach down to -160°C, which is also defined as cryogenic. These temperature levels can be reached either by using 3 or 4 stage cascade systems or by using propriety blends using different compositions of gases. These plants are used at the production fields or on ships used for transporting the liquid gas. In the past some of the gas was burned off to cool the remainder. To reduce these losses as well as the CO_2 emissions the refrigeration system re-condenses the 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 in 4 or 5 cascaded systems using Helium and other noble gases in the lower stages and other gases on the following stages.

5.3 Options for new equipment

Where its use is still permitted in new systems, particularly in Article 5 countries, HCFC-22 is still common as an alternative to R-502. It has not been supplanted by HFC blends because it is cheaper than any of the blends and usually offers better system efficiencies. The most common alternative to HCFC-22 as a replacement for R-502 in new systems is R-404A, although it has a significantly higher global warming potential and is less efficient.

Table 5-4: The table indicates the requirements to handle safety. Yellow are the 2L refrigerants. The HC refrigerants are widely used in the chemical industry where the companies know how to handle the flammability. Green indicates that the refrigerants are perceived as being harmless. The red in the GWP indicates that the GWP for the fluids are not acceptable and yellow indicates that in the long term they will also be eliminated. There are concerns about the breakdown products of the HFOs – hence the yellow fields. Availability of systems based on R-718 (water) is due to their status. Water systems are going in field test or already available. R-32 is not available in all markets (2015)

	Safety	GWP	ODP	Breakdown by-products	Availability	Option in high ambient
R717	[yellow]	[green]	[green]	[green]	[green]	[green]
R718	[green]	[green]	[green]	[green]	[yellow]	[green]
R290	[red]	[green]	[green]	[green]	[green]	[green]
R600a	[red]	[green]	[green]	[green]	[green]	[green]
R600	[red]	[green]	[green]	[green]	[green]	[green]
R1270	[red]	[green]	[green]	[green]	[green]	[green]
R1150	[red]	[green]	[green]	[green]	[green]	[green]
R404A	[green]	[red]	[green]	[yellow]	[green]	[green]
R507	[green]	[red]	[green]	[yellow]	[green]	[green]
R134a	[green]	[yellow]	[green]	[yellow]	[green]	[green]
R1234yf	[yellow]	[green]	[green]	[yellow]	[green]	[green]
R1234ze	[yellow]	[green]	[green]	[yellow]	[green]	[green]
R32	[yellow]	[yellow]	[green]	[yellow]	[yellow]	[yellow]

5.3.1 R-717 (ammonia)

The analysis of evaporative condenser use shown in Table 5-2 indicates that R-717 is by far the most common refrigerant used in industrial systems. 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 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. It is at atmospheric pressure at -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 (Nielsen, 2000).

5.3.1.1 Low charge ammonia systems

Following recent accidents, there is more focus on the ammonia charge sizes. Safety is the main issue. It does not make sense to make regulations following accidents when standards and regulations have not been observed. 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, standard EN13313 deals with education and training, from design to disassembling of the system, and to the level of educational knowledge given. An ISO standard is now in development based on that standard.

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. Alternatively, one can use rooftop units with a water cooled condenser where the gas from the evaporator goes to the central compressor room and then back to the unit. In this way one avoids having liquid going forth and back, it is then concentrated around the evaporator.

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 CO_2. This is method has been used in all parts of the world for a variety of applications mainly within F&B. The low stage is most often working at about -45°C to -50°C and the medium temperatures are between -10C to -20°C. The ammonia charge is then limited to work from about -15°C on the evaporator and condenser to the ambient.

There is also some research and experimental work going on with direct expansion systems for smaller ammonia systems. The reduced charge can help installing smaller R-717 systems for the commercial market. (Hrnjak, 2014; Hrnjak, 2017). The results achieved are 18g/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 a number of years.

In future, condenser heat will be an energy source that can be circulated in district heating and cooling systems. This will enable to achieve the carbon free future that is being envisioned in many parts of the world.

If the system is installed near inhabited areas it is possible to install a scrubber that will bind the ammonia to water in the machine room preventing: 1. The ammonia to leave the room 2. Minimising the risk of reaching a concentration at which ammonia can ignite and cause an accident.

Figure 5-2 shows the principles of a wet scrubber where a spray system "washes" the air contaminated with ammonia out of the air quantities. The cleaned air can be re-circulated to the machine room or sent to the ambient.

Scrubbers can be designed to handle from the smallest charge to the largest charge in the room. One can absorb the ammonia in water, hence the name wet scrubber or in a solid called a dry scrubber.

The ultimate solution is to send the leaked ammonia to a flare and burn it away but this solution is mainly used in petrochemical sites where one has the flare already available for other purposes.

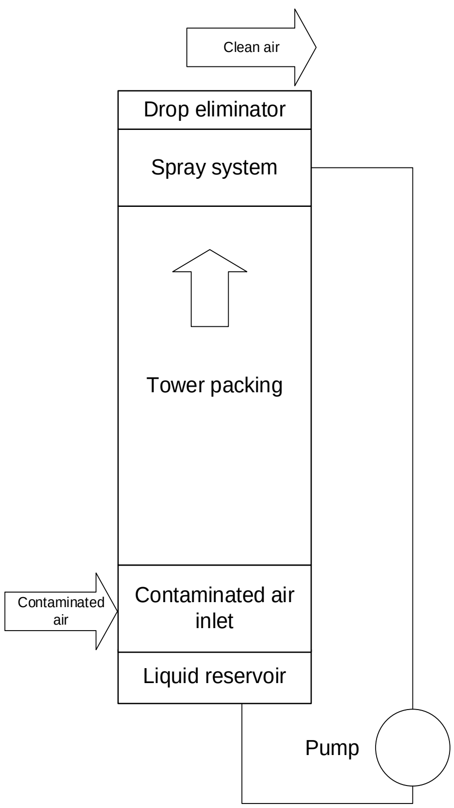

Figure 5-2: Principle of a wet scrubber

5.3.2 Hydrofluorocarbons

When the first HFC refrigerants, particularly HFC-134a, were introduced in the late 1980s to replace CFC-12, there was no obvious successor to the most common CFC blend in the industrial market, R-502 . This had been introduced to enable single stage compression plants to be used for low temperature applications without excessive discharge temperatures. When it became clear that R-502 could no longer be used, because it contained CFC-115, most system designers either used HCFC-22 or R-717, both of which produced higher discharge temperatures and therefore required additional cooling or two compression stages for freezer applications. In HCFC-22 systems, one would often see copper plating on the bearings if the system had increased air and water levels in the circuit, causing the formation of acids.

Saturated HFCs: saturated hydrofluorocarbons include fluids such as HFC-134a, HFC-143a and HFC-125 and blends of fluids, mixed to provide specific advantages for particular applications. HFC-134a is used in small high temperature systems; it is at atmospheric pressure at -26ºC, and it requires larger compressors than R-717. Sub-atmospheric operation is less common with HFCs because traces of moisture are liable to freeze and block the expansion valve. Also HFC refrigerants form acids in the presence of water and air in the system. Here the dominating acid is HF.

HFC-134a is also widely used in centrifugal compressors, including some very large systems used for district heating. A trial system using HFO-1234ze(E) as an alternative to HFC-134a in district heating has been tested in Norway (Nørstebø, 2013).

There is no single fluid alternative to HCFC-22 for use in industrial systems. HFC-125 has approximately the right pressure temperature relationship, but has an extremely low critical temperature of 66ºC, and would therefore be extremely inefficient if used in industrial systems, unless the condensing temperature would be very low. It is used as a component of several of the most popular blended refrigerants, where the deficiencies in its physical properties can be offset by careful selection of the other components of the blend. The most common blends used in the industrial sector are R-404A and R-507A, which are primarily mixtures of HFC-125 and HFC-143a; with the latter providing a higher critical temperature and hence improved efficiency. Many industrial systems use flooded evaporators, where the refrigerant boils in a pool. Zeotropic blends (with a temperature glide during evaporation) are not suitable in these systems because the blend components may fractionate, so R-407C and service replacement blends such as R-417A have not been much used in the industrial sector.

It is surprising that R-410A has not been more widely used in industrial systems because it has a low boiling point at atmospheric pressure (-51.4ºC), very low glide (less than 0.2K at -40ºC) and the critical temperature is almost the same as R-404A. The compressor swept volume required for R-410A is about 30% less than for R-404A, so equipment costs, including installed pipework should be less, although operating pressures are higher. This can be because of the high pressure, which has limited the use of R-410A and not the price of the refrigerant. The main barrier to its use is probably the high price of the refrigerant, particularly compared to R-717 and R-744. When the refrigerant inventory in a system is in tonnes the cost of the charge may be a significant part of the total cost of the installation. Typical installations are therefore low capacity, low temperature, for example blood freezing and small pharmaceutical systems. The introduction of rules and guidance for the use of “lower flammability” refrigerants (those that have a burning velocity less than 10 cm s^{-1} and therefore do not explode) might result in an increase in the use of HFC-32 as an alternative to R-717 in industrial systems.

Unsaturated HFCs, HFOs: unsaturated hydrofluorocarbons such as HFO-1234yf and HFO-1234ze(E) have not to date been used in industrial systems. The low global warming potential suggests that they may be a suitable alternative to R-717 and R-744, but it is very likely that they will be even more expensive than R-410A, with the further disadvantage of being flammable. It is therefore likely that none of this family of chemicals will achieve any significant market penetration in the industrial sector, even if blended with other compounds to reduce price or flammability. An exception may be found with centrifugal compressors for industrial chillers and heat pumps where unsaturated HFCs, i.e., HFO-1234yf or HFO-1234ze(E), might provide an alternative to HFC-134a (Nørstebø, 2013). HCFO-1233zd(E) might be a better solution but is seeing opposition to application in some countries due to its chlorine content.

5.3.3 Hydrocarbons

Hydrocarbons are not widely used in industrial refrigeration except where the additional safety measures required to ensure that leaking refrigerant cannot be ignited are required anyway, for example in a petrochemical plant. They offer excellent efficiency, and compatibility with most materials and lubricants. However the precautions required to prevent ignition are significantly more expensive than those required for R-717 systems, although the whole system cost may be comparable. HC- 290 is generally similar in performance to HCFC-22 and R-717 in terms of operating temperatures and pressures, and requires similarly sized compressors.

5.3.4 R-744 (carbon dioxide)

R-744 cannot be used in exactly the same way as other industrial refrigerants. It needs to be coupled with a higher temperature refrigerant in a cascade system due to the low critical temperature of 31ºC or else used in a transcritical system. Transcritical systems have been used in commercial and small systems, but there are no compressors on the market to provide the necessary high operating pressures to run an industrial R-744 system in this way. A medium-sized distribution centre with an installed capacity of 1500 kW has been operating in Denmark since 2008, using multiple commercial-sized compressors (Madsen, 2009).

R-744 is particularly suitable for use in freezer systems because it is liquid at positive pressure down to -56ºC and the gas is extremely dense, giving very high rates of heat transfer. The pressure drop characteristics are also very favourable at low temperatures, so R-744 freezer systems have been found to be significantly more efficient than any other alternative, even R-717 (Pearson, 2009). In slightly higher temperature applications, such as cold storage, R-744 cascade systems are likely to be slightly less efficient than two-stage R-717, but still on a par with a single stage economised system, and more efficient than any system using a secondary fluid due to the much lower pumping cost for R-744 compared to glycol, brine or other heat transfer fluids (ASHRAE, 2010).

In Article 5 countries, Saudi Arabia and Jordan (HAT countries) have cold store and processing applications where cascade systems utilise R-744 and R-717 as a working pair.

In higher temperature applications, for example IT cooling, R-744 is attractive as an alternative to chilled water because it is electrically non-conductive, does not cause fabric damage in the event of a small leak and enables use of smaller heat exchangers. The major challenge in these systems is that the operating pressure is approximately 50 bar.

5.3.5 R-718 (water)

Water and air are the two most used secondary refrigerants. In general R-718 is not suitable as a primary refrigerant for most industrial applications because the triple point is very slightly above 0ºC. The advantage of R-718 as a primary refrigerant is the very high latent heat, and the disadvantage is the swept volume required for a typical cooling duty is extremely high.

There are a few notable exceptions: R-718 has been used for a few deep mine cooling projects where a vacuum system is used to create a mix of solid and liquid water (ice slurry) at the triple point. Similar systems have been used for large plastics moulding coolers. Ice slurry is used routinely for fish cooling onboard larger fishing vessels.

Heat pumps based on R-718 are also emerging the market (Larminat, 2014). The advantage of water is the high critical point, which is much higher than any other refrigerant. Sakamoto (2017) shows a water vapour chiller that can match the capacity of a HFC based chiller and reduce the primary CO_2 emissions by 17%, claimed to better efficiency. Also Madsboell (2016) shows good results with water as refrigerant for positive temperatures. These water based chillers can be used as the high stage for e.g. R-744 or R-170 cascade systems. The systems can also be used for cooling plastic machines or other machinery.

5.3.6 Ice slurry

Ice slurry has been used for special applications and installations for many years. Especially in the deep mines in South Africa Ice slurry technology has been used as an alternative to having refrigeration systems in the mine itself. Ice slurry is being used for quick cooling of especially big fish like big types of tuna for which a quick cooling down is very critical. Circulating the ice slurry around the fish cools them down much faster than ice and consequently gives a much longer shelf-life.

5.3.7 Absorption

Absorption systems using aqua-ammonia 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 12 kW to 12 MW or more for process systems.

Water-lithium bromide (LiBr) systems can only be used above freezing because the water is the refrigerant, and the LiBr is the absorbent. Absorption systems are only 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. Also in many other Article 5 countries 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 at water or steam temperatures of 90°C to 120°C. The efficiency of those units is compared to those of vapour absorption in chapter 9. The lithium bromide-water chillers are all water cooled. .

5.4 Options for existing equipment

Systems using HCFC-22 have been converted to zero ODP refrigerants, but it is difficult to replicate the operating conditions of HCFC-22 and therefore conversions often involve an element of equipment replacement. Before committing to any large scale retrofit project, serious consideration should be given to the age of the plant, the cost of replacement with a modern, more efficient system and the risks to continued operation of retrofit.

A good approach is to calculate the systems as one would do with the new refrigerants and then see where the main differences are between the old system and the imaginary new plant. From this point one can then properly see what compromises are taken if one would just take out one oil-refrigerant pair and replace it with another. An overseen problem in many retrofit projects is the O-rings and other sealings that absorb the working pair. When one would change just one of the pairs one would also change the composition of the pair in the O-rings and sealings. If they have been in place for an long time, they will have lost their flexibility and one would need to replace them when retrofitting the system, otherwise one would end up with a leaking system within a few days.

When calculating pipe sizes one would most likely find the biggest differences in the liquid lines which then will need upsizing or additional pipes in parallel with the old piping.

One also has to be aware of chemical reactions if there are residues left in the system. This is most notable when converting systems from HCFC-22 or any HFC system to R-717. Reactions can occur between the refrigerants where a reaction between RHCFC-22 and R-717 will form prussic acid. If the oils are not compatible they can react to form different polymers that will cause them to form non-desirable substances e.g. one charges POE oil into a R-717 system they will form polymers comparable to wine-gums.

5.4.1 Conversion to HFC blends

There are numerous blends for the replacement of HCFC-22 in DX (superheat controlled) systems, but there is none that replicates the pressure temperature relationship of HCFC-22 without significant glide, and so these blends are much less common in flooded systems where fractionation of the blend is a major problem. The fractioning of the blend can cause the system to use more energy and in more severe cases it can fail or blow off refrigerant though the safety valves.

Where industrial systems are converted to a blend it may also be necessary to change from mineral or alkyl benzene lubricant to a synthetic polyolester oil (POE oil). Some blends are formulated with hydrocarbons in the mix so that, although still non-flammable, the lubricant is more miscible and less likely to accumulate in the evaporator of the system.

For a large flooded system it might be appropriate to convert the high pressure side e.g. compressors and condensers to an HFC blend, but convert the low pressure side to a secondary fluid e.g. propylene glycol or even to R-744, as a secondary volatile secondary loop. This can in many cases reduce the high stage part of the system by 90%. This type of system conversion is mainly done when the system is relatively new.

Retrofitting of HCFC-22 plants in Article 5 countries is very uncommon but it is a viable solution.

5.4.2 Conversion to R-744

The high operating pressure of R-744 systems makes it highly unlikely that an existing HCFC-22 system could be converted to operate on R-744. Conversion to a cascade system is possible, greatly reducing the inventory of fluorocarbon refrigerant in the system. It may even be possible to reuse the low pressure pipework and evaporators in the system if they are suitably rated and documented. A cold storage or freezing system operating as a cascade on R-744 could be limited to an allowable pressure of 25 bar gauge, however this is a complex retrofit and it may well be more economic to replace the whole plant, especially if it is already more than ten years old.

That said, in some regulations it is required that you in the documentation for the components, compressors, valves and system vessels can see that the manufacturer has considered the compatibility with the refrigerant and the lubricant. This can be an obstacle for old systems.

5.4.3 Conversion to R-717

In a very few cases a pumped HCFC-22 plant has been converted to R-717 (Jensen, 1996). In some cases the compressors and evaporative condensers are suitable for either refrigerant, and pipework is probably welded steel in large applications. If the evaporators are of the copper tube type then they need to be replaced. It is imperative that the system is carefully cleaned during the conversion because any residual traces of HCFC-22, for example in the lubricant, will react with R-717 to produce a solid foam which can block all internal components. Triple evacuation with nitrogen purging is probably necessary – this is time-consuming and expensive and again plant replacement should be considered. In the majority of cases, in all countries, equipment using HCFC-22 is not suitable for this conversion and this conversion cannot be generally recommended.

5.4.4 Conversion to hydrocarbons

Unlike R-744 and R-717 it is technically feasible to remove HCFC-22 from existing systems and replace it with HC-290, however it is highly likely that the resulting system will not comply with the safety codes on the use of hydrocarbons; this because the refrigerant quantity will not comply with charge restrictions (indoor installations) and the electrical infrastructure will not be suitably protected (intrinsicly safe). A conversion of this type was responsible for a fatal accident in New Zealand in 2008 (NZFS, 2008). A consequence of rapid phase out of HCFCs in Article 5 countries might be an increase of this type of conversion without adequate controls. There is however a case for a controlled conversion from HCFC-22 to HC refrigerant (propane or isobutane) where the system efficiency can be improved. In this case it is essential that suitable safety measures are ensured.

Conversion of HCFC-22 turbo systems on drilling platforms are not new. With a plant and plantroom upgrade, you can achieve close to the same capacity with better efficiency. Installing a gas tight wall isolating the panels is one of the changes, but not a problem on the platforms, where one more piece of equipment in ATEX execution makes no big difference.

5.5 Service requirements

Given the difficulty of converting from HCFC-22 to zero ODP refrigerants, many users with multiple systems have planned a replacement strategy to conserve their stock of refrigerant. Setting priorities for which system to replace or convert first includes consideration of age of the plant, likelihood of leakage and ease of conversion. Refrigerant which is recovered from converted systems can be recycled and stored on site to be used in the remaining plants.

In Europe, where service with "virgin" HCFC-22 has been prohibited from the beginning of 2010, some users have banked additional refrigerant by overcharging their plants with new HCFC- 22 prior to the end of 2009, and then recovering the excess refrigerant, which is then classed as recycled. This practice is not strictly outside the law, but it is not in the spirit of the regulation. It probably accounted for some additional sales of HCFC in the two years leading up to the prohibition, keeping sales artificially high at a time when many plants were being converted or decommissioned.

If other regions implement similar regulations for the phase out of HCFCs they should consider ways to plug this loophole, for example by limiting the time that recovered HCFC can be stored before it is used, and requiring it to be sent for destruction or reprocessing if it is not used within the timeframe. This was done in Ireland, and greatly improved the effectiveness of the restriction on virgin HCFC-22.

5.6 Education and training

Many accidents, near miss and dangerous situations could have been prevented by following current standards, industry guidelines and codes of good practice. It has been noted how some bad accidents in China in 2013 led the politicians to regulate on the basis of accidents caused by ill-informed or badly trained engineers and technicians. The introduction of new low GWP refrigerants will require more education and training. It is a misconception to think that one can work with any refrigeration system without any education and training, but it is also a misconception if one would assume that any engineer would be able to work with the design of an industrial refrigeration plant.

Many engineering schools and universities do a lot of good research and work with new technologies, but this rarely includes training in current standards and regulations for the use of different types of refrigerants. KTH in Stockholm started a web-site “Refrigerants with low GWP” in 2012 (KTH refrigerants, 2012). Here one can find a collection of information useful for an everyday look-up. But if one would be searching information about the practical use of refrigerants and standards this is more difficult to find. There is information about the European F-gas regulation etc. but when it comes to EN-378 and ATEX it is not easy to find adequate information. However, it should be part of the engineers’ education when they specialise in this field.

In some countries there exists an apprentice system where the candidate through his/her apprenticeship comes to learn about regulations with which they have to comply. It is only in rare cases that they learn about standards and how to use them efficiently. The next issue here is the cost of getting access to the standards; the price is a major barrier.

On industrial refrigeration and heat pump systems education and training is a prerequisite for a safe and efficient use of the system. One has to have an understanding of the process and what is ongoing in the system and what the function of the valves and components are. An understanding of safety is a must and also how to provide first aide in case of accidents. The better understanding and the better trained engineers will be, the more likely it is that one can confront critical situations without making mistakes.

5.7 Conclusions

The majority of large industrial systems in certain sectors world-wide use R-717 as the refrigerant and other sectors are using fluorinated refrigerants and blends. Where R-717 is not acceptable in direct systems, options include R-744 or glycol in secondary systems or HCFCs or HFCs in direct systems. For outdoor installations, HC refrigerants are used for the cooling of either a cascade system or a secondary refrigerant. Especially R-290 has gained a certain market-share around the world.

In countries where R-717 has not been the preferred solution, or in market segments with smaller systems, the transition from HCFC-22 is not straightforward. It requires acceptance of higher cost fluorocarbons in similar system types, or the adoption of more expensive systems with the cheaper refrigerants R-717 and R-744. This transition is slow and is constrained by lack of trained personnel and lack of experience of local end-users. It has been facilitated by corporate policy from multinational food and beverage manufacturers exemplified by the policy statement from the Consumer Goods Forum (Anon, 2010).

The industrial sectors covered in this chapter are too diverse to facilitate the level of development expenditure required to bring a new fluid to market. It therefore can be stated that, if any new development gains market share in industrial systems, it will be a fluid developed for some other purpose, either as a refrigerant in smaller mass-market systems or as a foam-blowing agent, solvent or other speciality chemical. Apart from absorption systems there is no significant growth of other not-in-kind cooling or heating solutions.

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Chapter 6

Transport refrigeration

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6 Transport Refrigeration

6.1 Introduction

Since 2015, the transport industry in Europe started to phase in lower-GWP refrigerant R-452A with a GWP of 2141 in new and existing systems instead of R-404A. In parallel research and development, field trials and limited production quantities on natural solutions (such as R-744 and R-290) continue. Flammability, efficiency and availability along the transport routes are the main concerns affecting the future refrigerant choices of the transport industry today.

6.2 Types of equipment and applications

The equipment described in this chapter includes refrigeration systems in trucks, trailers and reefer containers, refrigeration and air conditioning systems aboard ships, and air conditioning systems in railway cars. Transport applications have specific challenges such as shock, vibration, corrosion and extreme operating ambient conditions, this leads to design choices different from other refrigeration applications described in other chapters.

6.3 Options for new equipment

6.3.1 Truck and trailer

6.3.1.1 Non-flammable solutions

R-452A was introduced during 2015 as a customer option on new truck and trailer refrigeration units. R-404A continues to be offered widely elsewhere, but in Europe, concerns with R-404A availability have quickly made R-452A a preferred choice. By July 2015, one manufacturer had sold over 500 units with R-452A within the first three months on the market (TK, 2015). During 2016-2017, at least two large manufactures had started offering R-452A as standard in Europe. In 2017-2018 the vast majority of newly produced trucks and trailers in Europe use R-452A.

R-452A has similar cooling capacity, reliability and refrigerant charge as R-404A. The features supporting R-452A for use in transport refrigeration include non-flammability and low compressor discharge temperatures. The close property match of R-452A to R-404A gives customers the option to retrofit their existing fleets and operate on R-452A later, should they wish. The conversion does not require component changes and it can be carried out in the field during the life of the product.

The main limitation of R-452A lies in its GWP, 45% lower than R-404A, but higher than HFC-134a or flammable alternatives. Considering the phase down steps required by the EU F-gas regulation, it is possible that in the future R-452A availability may become a concern, and lower GWP solutions may need to be developed and introduced.

R-448A and R-449A are examples of refrigerants that stand out as “lower” GWP options (both approx. 1400, similar to HFC-134a). However, their discharge temperatures are higher, and require a significant system re-design in order to achieve comparable capacity, efficiency and reliability. This makes them unsuitable for retrofits. Furthermore, given that their GWP is only 30% lower than R-452A, it is unclear if the customer base will accept a change that may have a short life. HFC-134a is being used in small direct drive systems, and one manufacturer uses R-410A in their truck unit. Non-flammable alternatives to HFC-134a such as R-513A are being tested, but no commercial solution is yet available in road transport. R-404A continues to be used in new truck and trailer applications outside of Europe.

As described in detail in the 2014 RTOC Assessment Report, R-744 is a possible alternative refrigerant for both containers and truck and trailers. The challenges are: high pressure and lower performance in high ambient temperature. One manufacturer has released in Europe field trial quantities of a trailer closed loop solution based on CO_2. Specifically, a UK supermarket chain has continued carrying out trials of an R-744 refrigerated trailer since 2013 (UTC, 2013). They revealed that they have subsequently acquired a second R-744 trailer that can operate at different temperatures and this was joined by a third in 2016. Trials of R-744 trailers with two large supermarket chains in Europe are continuing (CP, 2016).

The efficiency of R-744 continues to prove higher than incumbent refrigerants at low to moderate ambient, but inferior, when compared to R-404A, at medium to high ambient temperatures (UNEP, 2014). For this reason, the first truck and trailer commercial applications of R-744 are located in moderate ambient regions in small numbers.
R-744 has been implemented using a semi-hermetic dual stage reciprocating compressor, where the issue of high pressures can be managed more easily. R-744 open shaft compressors have technological challenges in the transport refrigeration pressure range and continue to be unavailable today.

6.3.1.2 Safety considerations

Hydrocarbons continue to be examined due to their superior thermodynamic properties, but the possibility of leakage of the flammable refrigerant inside the box and other failure scenarios present a safety issue to be mitigated by design operation and servicing procedures.
Currently, no commercial solutions with hydrocarbons in transport are available. However, the number of relevant scientific studies presented at recent conferences (e.g. IIR Gustav Lorentzen series, etc.) to manage flammability risk on A3 and A2L fluids, is testimony of significant research and development going on in the area of flammability mitigation in transport.

One relevant paper describes the successful field test results of a small truck unit using HC-290 in South Africa (Colbourne et al., 2016). Other papers studied the energy efficiency of different replacement options in container and truck/trailer (Finckh et al., 2016; Poolman et al., 2016).

6.3.2 Containers

6.3.2.1 Non-flammable solutions

R&D activity is continuing to assess non-flammable (A1) lower GWP solutions that could replace the so far dominant HFC-134a and R-404A. R-513A, R-513B, and R-456A are potential candidates for HFC-134a replacement, and R-513A seems to attract most interest. One manufacturer announced a test of 100 units with R-513A together with 2 major shipping lines (MCI, 2017); shipping lines ordered approximately 10,000 R-513A compatible reefer units for potential later retrofit (MCI, 2018).

R-744 has been field-tested in container refrigeration applications since 2011. Its non-flammable characteristics make R-744 an attractive option, but the gap in efficiency at high ambient temperatures and the limited component supply base are limiting its market penetration. The efficiency of R-744 continues to prove higher than incumbent refrigerants at low and moderate ambient, but inferior at medium to high ambient (UNEP, 2014).
In the last 2 years, at least three shipping lines have purchased or leased a total of approximately 2,200 units operating with R-744 (Carrier, 2018).

6.3.2.2 Safety considerations

While no commercial solution with flammable or mildly flammable solutions are available, the number of relevant scientific studies presented at recent conferences to manage flammability for transport applications, is testimony of significant research and development. König et al. (2014) have shown that frequency of hazard and probabilities of fatalities for the global reefer container fleet would be below 10^{-6} if adequate design changes were in place and best practice guidelines were established. A second paper studies energy efficiency of the different replacement options in container or truck/trailer, and identifies 3 different design approaches to mitigate the flammability risks (König et al., 2016). The mitigation approaches are described in the paper, and can be (1) reduction of joints, use of leak proof components, addition of sensors, shut off valves, door interlocks and alarms; (2) multi-circuit solution, to reduce the amount of charge associated with leaks; and (3) indirect cycle using a non-flammable fluid in the second loop.

Two manufacturers of container units have announced an interest to use HC-290 and HFC-32 in the long term especially focusing on energy efficiency (WCN 2016a, b). Two other manufacturers have expressed concerns about safety.

In February 2016, the first meeting took place to develop the ISO 20854 (ISO, 2018a) safety standard for refrigerating systems using flammable refrigerants in marine containers. The ISO committee for thermal containers is currently working on revising one standard and drafting a new standard of safe operation of reefers with flammable refrigerant. Committee draft of ISO 20854 for flammable refrigerants for reefers was distributed for national voting in late 2016 with a positive result and the final standard can be expected to be published in the first half of 2019. The standard will include risk-based assessment for design and operation. In addition, the latest revision of ISO 1496-2 (ISO, 2018b) includes an energy efficiency test. Whilst R-744 is non-flammable, it operates at high pressure, safety precautions need to be taken in design, operation and service.

6.3.3 Ships

This sector was described in a special TEAP report (requested by Decision XXVII/4) in 2016. In the section below there is a summary and an update.

All vessels above 100 GT, of which according to International Maritime Organization (IMO) there are in excess of 180,000, have a cooling requirement for their provision rooms, air conditioning for cabin space, bridge and for the electrical equipment in the engine control room.

More specialised ships have greater cooling requirements, including cruise ships, ferries, refrigerated cargo ships, juice carriers, fishing vessels and fish factory ships, chemical/LPG carriers and nuclear fuel carriers.

IMO, FAO and the classification companies will consider the impact of the Kigali amendment on the marine sector once the CO_2 emission monitoring is rolled out (including engine emissions). As of 2018, during all voyages from and to EU ports as well as stays at EU ports, monitoring, reporting and verification for ship emissions are required. An emission report is likewise required for each ship annually. IMO already has minimum requirements regarding highest allowed GWP in new equipment (DNV-GL, 2016). CO_2 equivalent emissions are now monitored.

Despite the generally declining market for reefer ships due to the higher demand for refrigerated containers, several reefer ships have been delivered and further vessels including a juice carrier are currently under construction for delivery in 2018, with options for future deliveries. All of these ships use R-717 as the primary refrigerant with a secondary refrigerant circulating of calcium chloride brine. The fuel efficiency of these ships is said to be slightly superior to direct expansion HCFC-22 refrigerated ships due to the improved system design, greater efficiency of R-717, and the use of inverters on the pumps.

In fishing vessels, R-717 has already a significant presence. R-744 systems both as cascade and transcritical systems are used in this application too. Transcritical R-744 system are a good choice for small refrigeration systems and are being supplied from the commercial refrigeration sector.

There is also a demand for refrigeration equipment for provision rooms operating on low GWP refrigerants such as HC-290. However, these systems are likely to require a brine circuit and will therefore have a lower overall efficiency.

Cruise liners have extremely large AC systems and use large centrifugal systems now exclusively with HFC-134a (up to 10,000 t) and circulating chilled water. Systems using R-717 or flammable refrigerants are difficult to envisage without radical redesign. Indirect systems (where refrigerant is confined to a machine room and secondary coolant is distributed) are mostly used today and they could be redesigned for flammable refrigerants. Despite current concerns on GWP, a very large capacity (280,000cft) ultra-low-temp reefer ship (-50°C) was recently delivered (ULTR) designed to operate on R-404A, clearly indicating that further and more effective dissemination of information is required.

6.3.4 Railways

HVAC units for passenger trains commonly use HFC-134a or R-407C as working fluids. One manufacturer has proposed R-449C as a replacement to R-407C (Zankl and Crombie, 2017). HFC-134a could be replaced with R-513A based on the studies conducted in other industry segments.

The German and French railways have continued to look at air cycle systems as alternatives to vapour compression systems. In 2015, DB, a German railway company, has equipped an ICE train (Liebherr, 2015) while SNCF, the French railway company, has set up a 24-month demonstration program in a regional train (RG, 2015).

Several companies have presented units with R-744 but they have not been applied in commercial projects. Flammability is a major concern in public transport; therefore flammable solutions are unlikely.

6.3.5 Energy efficiency considerations

One of the challenges in the transition to lower GWP for transport refrigeration relates to the fact that some of the alternative refrigerants tend to have lower efficiency than incumbent refrigerants. For instance, R-744 is a valid non-flammable alternative in some applications, but medium to high ambient efficiency tends to be challenging for R-744 as opposed to conventional refrigerants not operating in a transcritical cycle. In a similar manner, some of the new HFO/HFC blends tend to lead to lower efficiency unless the systems are optimised for these fluids.

When assessing the environmental impact of new refrigerants, both the direct and the indirect effect are relevant. The indirect effect is often dominant, and closely related to the energy consumption. For this reason, energy efficiency as well as the type of energy source used are as important, or even more important, as the GWP itself with regards to environmental impact.

A detailed study on TEWI (total equivalent warming impact) and LCCP (life cycle climate performance) was presented to compare refrigerant options at different ambient temperature conditions operated in the US (Finckh et al., 2016). Figure 6-1 shows the estimated LCCP evaluation for the different replacement candidates for a climatic zone in the US.

The paper summarised that the biggest challenge for R-744 is efficiency, whilst for HC-290 it is safety. Both challenges require investment: for R-744 optimisation of processes and components, for HC-290 flammability mitigation. A similar conclusion was recently reported by Steddin et al. (2017).

Three different approaches are followed to reduce the environmental impact associated with the indirect effect:

1. Improve the application (example: better trailer or container insulation) in order to reduce cooling demand;
2. Optimize the system and introduce technology improvements in order to meet the cooling demand with the least amount of energy consumption (example: enhanced heat exchange surfaces);
3. Use a cleaner energy source.

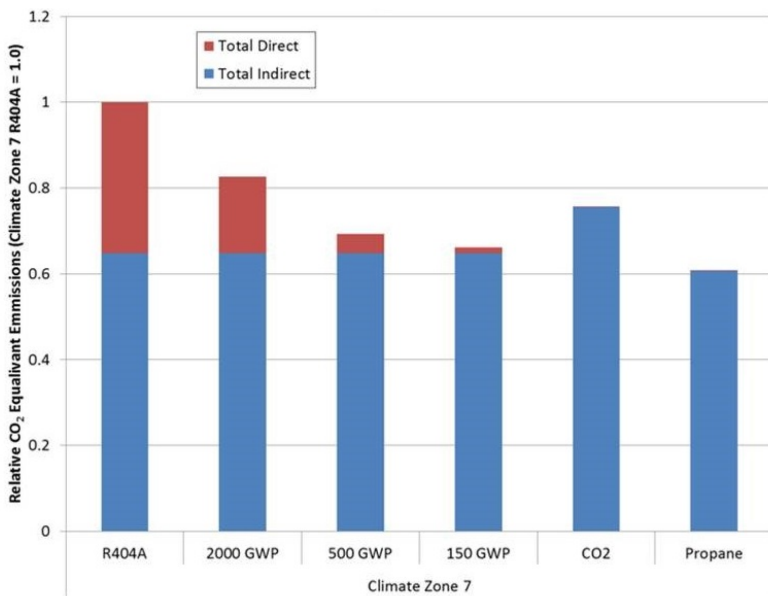

Figure 6-1: LCCP evaluation by refrigerant GWP and type for climate zone in the US (Finckh et al., 2016). According to the authors, the 2000 GWP, 500 GWP, and 150 GWP refrigerants are "fictional" refrigerants assuming the same efficiency (indirect emissions) as R-404A for comparison purposes.

Regarding the application, one area of research and development is a significantly improved insulation via composite material. Some trailer manufacturers have offered prototypes and solutions available in limited quantities that offer insulation 25% better than traditional trailers. These solutions also offer a weight advantage, leading to a secondary benefit (reduced tractor fuel demand).

Another path manufacturers and users are following to reduce energy demand is with improved control algorithms. Some manufacturers, for instance, offer solutions that widen the control temperature range depending on the type of load being carried, reducing cooling demand. Also, remote monitoring solutions are more and more common: the mode of operation of the container or trailer is monitored remotely, and changes are recommended to always use the system in an optimised mode.

Numerous technologies are being introduced to improve system efficiency. Most manufacturers have transitioned to enhanced tube and fin heat exchangers, and some manufacturers have migrated to microchannel heat exchangers: these type of heat exchangers improve system efficiency (reducing the indirect environmental effect) while at the same time reducing refrigerant charge (reducing the direct effect). Compressors represent an area of great improvement. Manufacturers are moving from single stage compressors to multi stage, and to variable speed, with significantly improved average energy efficiency. Finally, the introduction of new refrigerants gives an opportunity to introduce additional optimisation in the area of expansion and cycle control, discharge temperature control, heat exchange optimisation with regards to temperature glide of refrigerant mixtures.

A final trend can be observed in the area of alternative energy sources, particularly for truck and trailer. More and more non-diesel solution are being introduced. Eutectic, diesel free solutions are used in small refrigerated vans, as are various systems where nitrogen or CO_2 is injected into an open loop heat exchanger and exhausted to atmosphere. Other alternatives are for example battery powered systems and compressed natural gas engines.

6.4 Options for existing equipment

6.4.1 Trucks and trailers

Studies analyzing field alternatives to R-404A and HFC-134a are continuing, looking at both natural and non-natural solutions.

Retrofit of an existing R-404A system with natural solutions (such as R-290 or R-744) appears unlikely now and in the future, mainly because of the very substantial conversion system change necessary. Retrofitting R-404A with R-452A is much simpler and is already happening in the marketplace in Europe. The solution is a near drop-in; the GWP is significantly reduced and performance almost maintained.

With the progress of F-gas regulation it is reasonable to expect that availability of R-452A will be reduced, and new alternatives may be required. New refrigerants R-448A and R-449A stand out as lower GWP (approx. 1,400) options, requiring system changes with various degree of complexity (typically addition of liquid injection to limit discharge temperatures).

6.4.2 Containers

Similar to truck and trailer, retrofit of an existing, R-404A or HFC-134A system with a natural solution (such as R-290 or R-744) appears unlikely now and in the future due to the different design and complexity of the system changes.

Retrofitting R-404A with R-452A is much simpler and is already happening in the marketplace. In a similar way, trials on retrofitting HFC-134a systems with R-513A are ongoing. One manufacturer offers HFC-134a based reefer systems which can be used for operation with R-513A (MCI, 2017).

6.4.3 Ships

Ships are in operation for 30 years on average. Merchant and cruise ships are among the newer equipment. The average age of a merchant vessel has been decreasing from 18.9 years in 2008 to 16.7 years in 2012 (ISL, 2012). The number of cruise ships and their size has about doubled in the last decade (ISL, 2011).

HCFC-22 has been the dominant refrigerant in many marine applications and is still used in the majority of reefer ships. For most countries, despite their systems often incurring leaks, there is no difficulty in refrigerant supply and they continue to be replenished and used.

Approximately 70% of the global fishing fleet still uses HCFC-22 for all refrigeration applications (UNEP, 2016), mostly built before Montreal protocol requirements existed. Vessels built over the past two decades were designed for HFCs such as R-404A or R-507. Blends can usually be found for DX systems that enable a retrofit, but this can be costly due to relatively high leakage and lower overall efficiency. Flooded systems cannot be retrofitted and the option here is to refurbish with ammonia or ammonia/CO_2 cascade systems.

The use of HCFC-22 on cruise liners has been virtually eliminated. Some ships still operate with screw compressors and R-410A. Cruise liners operating with centrifugal chillers on HFC-134a have been successfully retrofitted to R-513A with a 1% reduction in energy efficiency. Leak rate for these systems is less than 0.5%/ annum. The storage rooms present a bigger challenge, (sometimes 50 or 60 in number on a liner). Indirect systems (where refrigerant is confined to a machine room and secondary coolant is distributed) can be retrofitted by either changing the refrigerant or changing the cooling system to R-744. Ships with direct systems are the most problematic, they have large charges (1000 kg) and are leaky due to pipe work length. HCFC-22 could be retrofitted to blends (for example R-407F) but lower efficiency could be a challenge due to temperature glide.

The IMO Study 2014 provided an estimate of refrigerant leakage. Refrigerant and air conditioning gas releases from shipping contribute an additional 15 million tons (range 10.8 million to 19.1 million tons) in CO_2 equivalent emissions. Inclusion of reefer container refrigerant emissions yields 13.5 million tons (low) and 21.8 million tons (high) of CO_2 emissions (IMO, 2014). DNV-GL demands no higher than 10% leakage (DNV-GL, 2012).

The ships' refrigeration systems have to comply with legislative requirements of their flag state. There is consequently more pressure to retrofit ships flagged within the EU where the F-gas regulations apply (Gluckman, 2016).

Reefer ships for this EU market for the carriage of fruit and frozen fish products have been retrofitted to alternate gases R-407C and R-404A respectively. This, though successful, has resulted in decreased reliability and an approximate increase in energy consumption of about 15%. Where flooded evaporators are employed using zeotropic refrigerants retrofits are considered probably not possible.

Provision or storage rooms have been successfully retrofitted from HCFC-22 to R-407F, though also now there will be a need to move from R-404A systems to refrigerants of lower GWP.

6.4.4 Railways

Non-flammability is of paramount concern in public transport systems operated frequently in tunnels or on bridges where fast evacuation is problematic. R-513A and R-449C are being considered as replacements for HFC-134a and R-407C going forward, but to date no such application has been reported.

6.5 Concluding remarks

Since the introduction of the European F gas regulations, high GWP refrigerants have received pressure to phase down. The first refrigerant to be affected was R-404A, as a technical option had become available (R-452A). In truck and trailer, R-404A has been completely replaced by R-452A in new equipment in Europe since 2015.

Other applications using HFC-134a, have shifted in limited numbers to low GWP alternatives such as R-513A. Some refrigerated containers have been produced and are in service operating on R-744.

Research and development continues on systems for R-744 as well as for flammable refrigerants in conjunction with their related safety standards.

While new ships use R-717/R-744, the majority of the global fleet of existing reefer ships and fishing vessels other than those trading in Europe are likely to continue to operate using HCFC-22.

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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

On a global basis, air conditioners (ACs), including reversible air heating heat pumps (generally defined as "reversible heat pumps") ranging in size from 1 kW to 1,100 kW comprise a vast majority of the air conditioning market (the bulk of which are less than 70 kW). In the remainder of this chapter the term air conditioning will be used to apply to both air conditioners and air-to-air heat pumps that directly heat air. This broad category is sometimes referred to as air-cooled or unitary equipment. These systems cool and/or heat enclosed spaces ranging from single rooms to large exhibition halls. Essentially, most are electrically driven vapour-compression systems using hermetic rotary, reciprocating or scroll compressors 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 1,100 kW. Air in or from the space is drawn over a coil containing evaporating refrigerant. With systems that provide heating and cooling, the role of the evaporator and condenser can be reversed to provide either heating or cooling. In the heating mode, air from the conditioned space passes over the same coil that contains refrigerant undergoing condensation thereby transferring heat to the air.

Nearly all air conditioners manufactured prior to 2000 used HCFC-22. [4] The transition away from HCFC-22 is complete in non-Article 5 countries[5]. The phase-out of HCFC-22 in the manufacturing and import of new products in the EU and Japan was completed by 2004 and 2010, respectively, whilst North America and Australia and New Zealand use of HCFC-22 in new systems was prohibited from 2010 and 2016, respectively. However, it is important to note that technical options available at the time of the phase-out in these countries were environmentally focused on the protection of the ozone layer and not on the mitigation of climate impact. Some non-Article 5 countries began the transition to zero-ODP alternatives ahead of the Montreal Protocol commitment dates (primarily within Europe and Japan).

In addition, certain Article 5 countries such as the Republic of Korea also pursued an accelerated phase-out similar to non-Article 5 countries. The Kingdom of Saudi Arabia had a phase out date of 2016 and 2017 in 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 countries are following the Montreal Protocol phase-out dates.

Globally, in 2018, about half of the installed unit population currently use HCFC-22 and approximately 60% of new units use non-ODP refrigerants, thus new HCFC-22 systems are on the whole unnecessary. An estimated 600 to 800 million HCFC-22 air conditioners were operating worldwide, representing approximately one million (metric) tonnes of HCFC-22. Global energy demand from air conditioners is expected to triple by 2050 and the global stock of air conditioners will grow to 5.6 billion by 2050. The energy efficiency of new units is thus of utmost concern (IEC, 2018).

The scope of this Chapter includes an overview of the common types of air conditioning equipment, their characteristics and where they are normally applied. Sections also highlight the alternatives refrigerants currently being used and anticipated for use, examining factors such as safety, climate impact, performance, cost implications and lubricants, commercial availability, operation and maintenance. In addition, issues related to refrigerant charge reduction and not-in-kind technologies applied to air conditioners are also covered. Alternative refrigerants for existing equipment, options for refrigerant replacement (only) and retrofit are summarised and implication

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[4] Details of HCFC phase-out schedules can be found in Chapter 1.

[5] Meaning of "Article 5 countries" is explained in Chapter 1.

of refrigerant choice for new systems used in high ambient temperatures is also addressed. The ODP and GWP values of the refrigerants mentioned in this chapter are given in Chapter 2 of this report.

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. Regarding the use of HCFC-22, in 2010 many non-Article 5 countries were approaching the final phase-out of HCFC-22 in new systems; this has now been completed and most major Article 5 countries have initiated their transition from HCFC-22. Previously, medium and low GWP alternatives were not being given major consideration (except hydrocarbons (HCs) such as HC-290) whereas now more manufacturers are proposing and adopting HCs and there is also considerable uptake of HFC-32 in several countries. Particularly in larger (commercial) systems manufacturers are also considering the variety of new HFC/unsaturated HFC blends. There are also new additions to information relating to refrigerant performance under normal and high ambient conditions. Otherwise, implications on the use of alternative refrigerants and design of systems suitable for high ambient temperatures are applicable to air conditioning as well as other applications; refer to Annex 1 for further details.

7.2 Equipment types

Air conditioners generally fall into four distinct categories, based primarily on capacity or application: small self-contained air conditioners (window-mounted, portables, packaged terminal air conditioners (PTAC) and through-the-wall air conditioners); non-ducted split residential and commercial air conditioners; ducted, split residential air conditioners; and ducted commercial split, multi-split (including variable refrigerant flow, VRF) and packaged air conditioners (commercial air cooled). In each of these categories, the term "air conditioner" includes systems that directly cool or heat the conditioned air.

Table 7-1 summarises the typical physical and installation characteristics of each type of air conditioner.

Table 7-1: Typical configurations of air conditioner type

Type		**Primary configuration**	**System layout**	**Capacity range (kW)**	**HCFC-22 charge range (kg)**
Small self-contained	Window	Small self-contained	Self-contained	1 – 10	0.3 – 3
	Portable	Small self-contained	Self-contained	1 – 10	0.3 – 3
	Through-the-wall	Small self-contained	Self-contained	1 – 10	0.3 – 3
	Packaged terminal	Small self-contained	Self-contained	1 – 10	0.3 – 3
Split (non-ducted)		Non-ducted split	Remote	2 – 15	0.5 – 5
Multi-split		Non-ducted and ducted split	Remote	4 – 300	2 – 240
Split (ducted)		Ducted split	Remote	4 – 17.5	1 – 7
Packaged rooftop		Ducted commercial	Self-contained	7 – 1,100	5 – 250
Ducted commercial split		Ducted commercial	Remote	10 – 1,100	5 – 300

7.2.1 Small self-contained air conditioners

Small Self-Contained (SSC) air conditioners are small capacity units in which all of the refrigeration system components are contained within a single package; see Figure 7-1, Figure 7-2,

Figure 7-3 and Figure 7-4. 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:

- Window Mounted Room Air Conditioner,
- Through-the-Wall (TTW) Air Conditioner
- Portable Air Conditioner [6]
- Packaged Terminal Air Conditioner.

Small self-contained air conditioners are designed to heat or cool single spaces, such as bed-rooms, small shops, restaurants and offices. Small self-contained air conditioners, 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, duct-free, split type room air conditioners are being selected more frequently as the first comfort air conditioning option in most countries resulting in a global decline in the demand for window mounted and through-the-wall air conditioners.

These systems have average 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. The majority use hermetic rotary compressors.

Most small self-contained air conditioners historically used HCFC-22. As non-ODP refrigerants have been applied to these products-the majority have used HFC blends, R-407C and R-410A. A small proportion of units are using HC-290.

Globally there are about 17 million SSC air conditioners currently produced annually (Gloël, 2014; JRAIA, 2018), split approximately equally between Article 5 and non-Article 5 countries. With service lives over 10 years, it is estimated that more than 200 million SSC air conditioners remain in operation globally.

Figure 7-1: Portable

Figure 7-2: Window

Figure 7-3: PTAC

Figure 7-4: TTW

7.2.2 Split (non-ducted) residential and commercial air conditioners

In many parts of the world, residential and light commercial air-conditioning is done with non-ducted split air conditioners. Non-ducted split air conditioners are widely applied in commercial buildings, schools, apartments and freestanding residences 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.

They 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 a fan-coil unit located inside the conditioned space, generally on the wall but also can be ceiling or floor mounted

[6] Portable air conditioners are a special class of room air conditioners 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 air conditioners use a separate outdoor condenser, which connects, to the indoor section with flexible refrigerant piping.

designs. Single splits often position the expansion device also within the condensing/outdoor unit. Compressors are typically hermetic rotary, scroll or reciprocating type; high energy saving potential comes from introducing inverter technology is currently used in about half of new mini-split units but only about 10% of others.

Reversible air conditioners (heat pumps) are gaining market acceptance in cool and cold climates where they are used primarily for heating but also provide cooling during summer operation. These units are designed to provide high efficiency and capacity at low ambient temperatures; typically down to -30°C. Reversible air conditioners are the way to reduce indirect CO_2 emissions by providing an efficient and cost effective alternative to electric resistance and fossil fuel heating. Heat pumps designed for cold climates utilize one or more technologies to improve their low ambient performance. These technologies include, multi-stage or variable speed compression, larger heat exchangers and enhanced control strategies.

The vast majority of mini-split residential and commercial air conditioners manufactured prior to 2000 used HCFC-22 refrigerant. Mini-split air conditioners have average HCFC-22 charge levels of approximately 0.25 to 0.30 kg per kW of cooling capacity. The majority of non-ODP refrigerants that have been applied to these products are HFC blends such as R-410A and R-407C, whilst HFC-134a has been more dominant in regions that experience high ambient conditions.

The current global market for these types of split systems is around 75 million units per year (Gloël et al, 2014; JRAIA, 2018), with approximately 20% going to non-Article 5 countries and 80% to Article 5 countries. The installed population is estimated to be around 1,000 million units.

Figure 1-5: Outdoor condensing unit

Figure 7-6: Indoor wall unit

Figure 7-7: Indoor ceiling cassette

Figure 7-8: Indoor floor/wall unit

7.2.3 Multi-split air conditioners for commercial and residential

Another type of products are multi-split; essentially the same as a single split (as described above) but a single condensing unit may feed two or more indoor units, although 50 indoor units can be used with over 1 km of piping; see Figure 7-9. Whilst dual indoor unit models may be used for residential applications, this category of split systems is more often used in commercial buildings. Specific refrigerant charges tend from around 0.3 kg/kW upwards, depending upon the installation characteristics. As with single splits, non-ducted and ducted multi-splits also offer reversible (heating) options.

VRF systems are a sub-category of the multi-split air conditioning systems and are distinguished from regular multi-split systems by their ability to modulate the refrigerant flow in response to the system demand. The outdoor air conditioning unit can adjust the refrigerant flow in response to the demand from each indoor unit. In some configurations, these systems can have independent cooling or heating functionality for each indoor unit thus simultaneously heat and cool separate indoor spaces. The outdoor unit modulates the total refrigerant flow using various compressor capacity control methodologies, with compressor types generally being rotary or scroll type. VRF systems have capacities ranging from 10 kW to over 150 kW, with an average (module) capacity of 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 a growing increase in the use of R-407C and R-410A even in A 5 countries, with typical charge levels of 0.30 – 0.70 kg/kW of cooling.

Approximately 1.2 million systems are produced each year (Gloël et al, 2014; JRAIA, 2018) of which one quarter go to non-Article 5 countries and three-quarters to Article 5 countries. The installed population is estimated to be around 7 million.

Figure 7-9: Example arrangement of multisplit equipment

7.2.4 Split ducted air conditioners (residential and commercial)

Ducted, split residential air conditioners 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 within commercial or institutional buildings. A condensing unit (compressor/heat exchanger), outside the conditioned space, supplies refrigerant to one or more indoor coils (heat exchangers) installed within the duct system or air handler Air in the conditioned space is cooled or heated by passing over the coil and is distributed to the conditioned spaces by the duct system. Systems can in principle be designed as reversible types, although for this category of ducted air conditioners it is done less frequently. An example is provided in Figure 7-10. Compressor types typically include hermetic rotary, reciprocating and scrolls. The most common refrigerant in these systems was HCFC-22 until the period 2005-2010, although over the past few years the majority has transferred to R-410A and R-407C. 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 capacity. For commercial systems, capacities range from 7 to 1,100 kW with a current annual output of about 12 million units (Gloël et al, 2014; JRAIA, 2018), with about one-third in Article 5 and two-thirds in non-Article 5 countries. The estimated installed population is around 150 million.

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

7.2.5 Ducted commercial packaged (self-contained) air conditioners

Ducted commercial packaged air conditioners and heat pumps ("rooftop" units) are single self-contained units, which comprise an integral fan and heat exchanger assembly which is connected by means of ducting to the air distribution system of the commercial structure; see Figure 7-11. The other part of the package is the condensing unit, normally with an air cooled condenser and compressors, which are often hermetic scrolls, although hermetic and semi-hermetic reciprocating and screw machines are sometimes employed.

The majority of ducted commercial packaged air conditioners and heat pumps are mounted on the roof or outside on the ground of offices, shops, restaurants or institutional facilities. In some GCC countries, units are installed on the roof of large single home residences providing easy access for service without going into the living space. Multiple units containing one or more compressors are often used to condition the enclosed space of low-rise shopping centres, shops, schools or other moderate size commercial structures.

They are offered in a wide range of capacities from around 7 kW to over 700 kW and have specific refrigerant charges of around 0.3 to 0.5 kg per kW of cooling capacity. Most ducted systems historically used HCFC-22, whilst in non-A 5 countries R-410A is mainly used and to a lesser extent R-407C, which is used more frequently in regions with higher ambient conditions and R-744 is offered in some Northern European countries. Annual market is currently about 1 million units (Gloël et al, 2014; JRAIA, 2015), with about one-third in Article 5 and two-thirds in non-Article 5 countries. The estimated installed population is around 20 million.

Figure 7-11: Example of ducted commercial packaged unit

7.3 Options for new equipment

As discussed in Chapter 2, there are several factors that should be considered when selecting an alternative refrigerant. Accordingly, this section provides a summary of the most viable HCFC-22 replacement candidates for new air-conditioners, based on the current information available to the RTOC.

Several single component HFC refrigerants have been investigated as replacements for HCFC-22, although previously, HFC-134a was the only single component HFC that has been commercially used in air conditioning systems to a limited extent. Air conditioners have become available with HC-290 and HFC-32 as single component refrigerants. A number of HFC blends have also emerged as replacements for HCFC-22 in air conditioning systems. Various compositions of HFC-32, HFC-125, HFC-134a, HFC-1234yf and HFC-1234ze are being offered as non-ODS replacements for HCFC-22. The two most widely used HFC blends to replace HCFC-22 are R-407C and R-410A. However, both R-407C and R-410A have GWPs close to that of HCFC-22 (Table 2-7 and 2-8) and are therefore considered to be too high for long-term use under the Kigali Amendment.

Considering the various R-410A alternatives with medium and lower GWP, the majority of these are flammable to some extent. Alternatives with capacity and pressure comparable to HCFC-22, those with a GWP lower than about 600 tend to be flammable whereas those with higher GWP tend not to be (see Chapter 2 for more details). Appropriate measures have to be applied in order to mitigate the risk, for example, minimising the amount of refrigerant that can leak into occupied spaces or removing the refrigerant from the occupied space, ensure that probability of ignition is greatly reduced through risk assessment and at a minimum, meet the requirements of national regulations and/or appropriate safety standards (where they exist); such rules are continuously under development and refinement. A more comprehensive overview of applicable safety standards and recent developments in the field of safety of flammable refrigerants is detailed in the recent Task Force (TF) report under Decision XXVIII/4 "Safety Standards for Flammable Low global warming potential (GWP) Refrigerants".

Within the discussion of the various refrigerant options, numerous studies on performance are 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. Broadly for results that are within ±5% of the baseline, performance can be considered to be comparable.

Measurements considering high ambient conditions are also reported upon, where available.

7.3.1 HFC-134a

Whilst HFC-134a is a potential HCFC-22 replacement in air-cooled systems in limited product categories, it has not seen broad use because manufacturers have been able to develop substantially lower cost air-cooled air conditioning systems with other alternatives. Although it is seldom a cost-effective alternative, it has been used widely in regions that experience high ambient temperatures for a variety of different types of air-to-air systems. Further discussion on HFC-134a is in (UNEP, 2015).

7.3.2 R-407C

Since R-407C requires only modest modifications to existing HCFC-22 systems, it has been used as a transitional refrigerant in equipment originally designed for HCFC-22. However, since around 2004 many of the 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 high ambient temperatures, such as above 40-55°C. Further discussion on R-407C is in (UNEP, 2015).

7.3.3 R-410A

R-410A can be an alternative to replace HCFC-22 only for new equipment production, since the operating pressures are around 50-60% higher than HCFC-22. Due to its thermophysical properties, the design of R-410A units can be more compact than the HCFC-22 units they replace. R-410A air conditioners are currently commercially available globally. A significant portion of air conditioners uses R-410A. System designers have addressed the higher operating pressures of R-410A through design changes such as thicker walls in compressor shells, pressure vessels (accumulators, receivers, filter driers etc.). In addition, the considerations for lubricant requirements are as described for R-407C; POE or PVE have to be used.

As concerns over GWP have increased, R-410A is becoming seen as a less viable alternative for HCFC-22 in the longer term, although it currently remains the first choice for new air conditioning equipment. In some product groups there is now a transition away from R-410A. 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 up to 52°C, the performance (capacity and efficiency) of R-410A air-conditioners falls off more rapidly than HCFC-22 systems at high ambient temperatures (above 40°C). There have been numerous studies examining the performance of R-410A and particularly with respect to performance change with increasing ambient temperature. Most results indicate 5% to 20% degradation in performance relative to HCFC-22 at higher temperature; these are described in detail in (UNEP, 2015).

Even with optimised designs, for systems that will operate a significant number of hours at high ambient temperatures, the system designer should take into consideration the reduced capacity at high ambient when sizing the equipment. For cases where the base capacity of the unit would need to be increased to meet the building load at extreme ambient temperatures the cost impact can be approximated as proportional to the respective capacity degradation.

7.3.4 HFC-32

HFC-32 is seen as a replacement for R-410A due to its medium GWP and similar capacity and similar efficiency. Due to lower density the specific refrigerant charge (per kW of cooling capacity) is around 10-20% less that R-410A (Piao et al, 2012, Yajima et al., 2000). Depending upon the product group and capacity, R-410A systems can be redesigned for HFC-32 with modifications and with additional safety measures given its class 2L flammability (see Annex to Chapter 2); appropriate design, application and service changes will be required for it to be safely applied. Another 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. The current POE and PVE lubricants used with R-410A have insufficient miscibility with HFC-32 (Ota and Araki, 2010), but some POE lubricants with poor miscibility with R-410A are already used and therefore the same oils are also 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, as reported in (UNEP, 2015). Overall, COP ranges from -3% to +10% compared with R-410A, whilst capacity is within -1% to +6%.

At high ambient temperatures it has a higher efficiency and capacity compared to R-410A, although worse than HCFC-22, where approximately the capacity is 2% less and COP 5% lower in theoretical cycle calculations (UNEP, 2015). Discharge temperature can be from 5 K to 30 K higher than R-410A or HCFC-22. However, this can be managed by injection technology or wet suction control, although this implies at a cost and/or performance penalty to the air conditioner. It can also be tackled by adjusting the viscosity of oil (Piao et al., 2012), although this impacts reliability. Again, several studies have compared performance at HATs and found COP ranging from -10% to +10% relative to HCFC-22 (UNEP, 2015).

Recently there have been several additional performance studies. In VRF systems, HFC-32 was found to have about 10% higher cooling capacity (expressed in terms of compressor speed) and cooling COP, compared to R-410A and in heating mode, improvements were in the order of 5% and 8%, respectively. However, taking partial loads into account, it was determined to give an annual performance factor (APF) of 3% more than R-410A (Naito et al., 2016). Pham and Monnier (2016) presented compressor calorimeter results comparing R-410A and HFC-32. Across the range of tested conditions, HFC-32 gave 3-7% higher cooling capacity and COP ranged between -3% and +1% relative to R-410A. Shen et al (2017) carried out measurements with various refrigerants to characterise performance of a rooftop system with HFC-32 relative to R-410A. Under "normal" conditions, COP and capacity were 2% higher and 7% higher than R-410A, respectively, whilst at high ambient conditions improvements were about 3% and 8% greater. Alabdulkarem et al. (2015) conducted a series of measurements to determine seasonal performance of a reversible AC-HP system. Compared to the R-410A baseline, HFC-32 gave a 9% lower seasonal cooling COP but a 3% improvement in seasonal heating efficiency. Wang and Amrane (2016) present results from a number of reports carried out under the phase II of the AHRI Low-GWP AREP programme. Of the six “soft optimised” units tested with HFC-32, one achieved the same capacity as R-410A but with 5% higher COP, four exhibited the same COP within ±2% but with 5-10% higher capacity, one showed about 7% greater COP and 10% more capacity and one had capacity reduced by 5% and a drop of 10% in COP. Four of the units were tested at “high ambient”, with two having higher performance at about 10% higher capacity and 15% higher COP, whereas one fell to 2% greater COP and 7% more capacity, relative to R-410A (at high ambient conditions). One unit remained with lower performance at 2% reduced capacity and 10% lower COP. Abdelaziz et al. (2015) report on a comprehensive series of measurements on charge-optimised single split air conditioner and under “normal” and high ambient test conditions. Compared to R-410A, HFC-32 gave a 1 to 4% improvement in COP and 2 to 5% higher capacity under “normal” conditions and 5 to 6% higher COP and 11 to 13% greater capacity at hot and extreme temperature conditions. PRAHA (2016) project managed by UN Environment and UNIDO testing units built specifically by manufacturers in high ambient countries at 46°C and 50°C showed results for HFC-32 similar in COP to R-410A and up to 15% higher in capacity.

As can be seen from these studies, there are a wide variety of relative results amongst different units and conditions. Broadly for results that are within ±5% of the baseline, performance can be considered to be comparable.

Currently, air conditioners using HFC-32 are produced in at least 13 countries located in Asia, Europe and Africa. Products are being marketed in Australia and the Middle-East, amongst others.

7.3.5 HFC-161

HFC-161 is also being evaluated as a replacement for HCFC-22 in air conditioning systems. It has similar thermodynamic properties to HCFC-22 and is flammable and therefore systems have to be designed, constructed and installed accordingly (see Annex to Chapter 2), as well as due consideration to reclaim and recovery requirements during servicing and at end of life. One potential obstacle exists in that the toxicity classification has still not been assigned under the relevant standards (see Annex to Chapter 2).

The 2014 RTOC Assessment (UNEP, 2015) reports on several studies that examine the performance of HFC-161 in comparison with HCFC-22, which show capacity of HFC-161 about -5% and COP from around +5% to +15% higher than HCFC-22.

7.3.6 HFC-1234yf

Since HFC-1234yf has a relatively low volumetric refrigerating capacity it is unlikely to be used widely as a replacement for HCFC-22. Further discussion on HFC-1234yf is in (UNEP, 2015).

7.3.7 HC-290

HC systems are commercially available in low charge air conditioning indoor applications, such as mini split, window and portable air conditioners and more recently in split and rooftop ducted systems. HC-290 is the most frequently used HC refrigerant in air conditioning applications. When used to replace HCFC-22, HC-290 has performance characteristics which tend to yield higher energy efficiency and slightly lower cooling and heating capacity. In terms of improvements in system COP in split type and window air conditioners with HC-290, values range from around -4% to +20% and capacity varies within -10% to +10%, as detailed in (UNEP, 2015). For HAT, capacity is around -4% and efficiency -3% to +3%, relative to HCFC-22. More recently, Abdelaziz et al (2015) reported on a comprehensive series of measurements on charge-optimised single split air conditioner and under “normal” and high ambient test conditions. Compared to HCFC-22, HC-290 gave a 7 to 11% improvement in COP and 5 to 8% lower capacity under “normal” conditions and 7 to 8% higher COP and 9 to 10% reduction in capacity at hot and extreme temperature conditions.

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. In addition, HC-290 has reduced compressor discharge temperatures and improved heat transfer due to favourable thermo-physical properties.

The main difficulty with HC-290 is its class 3 flammability, which creates safety concerns in application, installation and field service. European and international standards limit the indoor charge of HC-290 (see Annex to Chapter 2). Such charge size limitations can constrain the use of HC-290 to smaller capacity systems that need to achieve a certain efficiency level, depending upon the specific heat load (i.e., kW/m^2) of the application; in order to extend the capacity range, charge reduction techniques can be applied. Charge reduction technologies and correct oil selection can be used to minimise the amount of refrigerant, which can increase the capacity range. Similarly, 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). Furthermore, systems (such as centralised or packaged ones) can use two or more independent refrigerant circuits or a reboiler loop, although this implies a cost increase.

Leak, ignition and fire tests 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 (Zhang et al., 2013). Similar findings for developed concentrations were reported by Li (2014a). Risk analyses on the use of HCs in air conditioners suggest that when the requirements of safety standards are met, the probability of ignition during normal operation is extremely low (Colbourne and Suen, 2004). A recent study demonstrated that the flammability risk associated with split air conditioners is around 100 times lower than with HC-600a domestic refrigerators (Colbourne and Suen, 2015). The situation leading to highest risk is sudden leaks, refrigerant handling, and servicing activities, thus, installation and service practices must be modified to avoid exposing occupants and field technicians to the additional risks associated with flammable refrigerants.

Another 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. 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 A 5 countries, venting of HCs may be considered an acceptable option, but should only be done subject to a risk assessment.

Some major Chinese and Indian manufacturers have had commercially available HC-290 products since 2012 and systems have been available in Europe and Australia for several years. To date, whilst output is limited, conversion of production capacity from HCFC-22 to HC-290 of approximately ten million units per year has been completed in China (Zhou, 2014; Shecco, 2018) and manufacturers have published a formal schedule for increased production numbers of HC-290 split systems from 2018 (Li, 2018) . 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 are also being launched in South America.

7.3.8 HC-1270

HC-1270 has favourable characteristics from the point of view of both thermodynamic and transport properties. It is a class 3 flammable refrigerant. Its performance has been evaluated, where the cooling capacity is up to 10% higher than HCFC-22 and COP up to 4% higher. Further discussion on HC-1270 is in (UNEP, 2015).

7.3.9 R-744

R-744 has a low critical temperature, which results in significant efficiency losses when it is applied at the typical indoor and outdoor air temperatures of air-to-air air conditioning applications without adjusting the refrigeration system and adopting certain technologies accordingly.

Air-cooled R-744 air conditioning systems are available in capacities from about 3 to 300 kW. Experimental results show that R-744 systems may compete in energy efficiency with high efficiency R-410A systems for moderate climates in both cooling and heating mode; however, improvements are needed to significantly increase the capacity, efficiency and reduce the peak electrical power requirements during the cooling mode in high ambient conditions (Jakobsen et al., 2007; Okamoto, et al., 2016).

Work is still on going to try to improve performance of R744 systems for AC and HP systems. For example, Lee et al (2014) demonstrated that improvement approaching 10% can be achieved with optimised ejectors. One study (Calabrese et al., 2015) investigated the feasibility of R744 in "rooftop" ducted systems. Whilst not comparing experimental results directly against those for conventional systems, the authors determined that the COP is likely to be lower than for conventional HFC systems when the ambient is above 16°C, but could offer substantially better performance when temperatures are below 10°C.

Further to the previous 2014 RTOC Assessment Report, there have not been major developments reported. Further discussion on R-744 is in (UNEP, 2015).

7.3.10 New mixtures for air conditioners

There are a number of new mixtures emerging for potential use in air conditioning, which include: R-444B, R-446A, R-447A, R-447B, R-452B, R-454A, R-454B, R-455A, R-459A and R-511A. All have saturated vapour pressure and volumetric refrigerating capacity characteristics that approximately span the range between those of HCFC-22 to R-410A and are potentially feasible for use in many types of air conditioning systems. All except R-511A have class 2L flammability (except R-511A, which is an A3 flammable refrigerant) and thus have maximum charge sizes constrained according to the limits detailed in the Annex to Chapter 2. As with all flammable refrigerants, systems should be designed, constructed and installed with due consideration of their flammability, as well as due consideration to reclaim and recovery requirements during servicing and at end of life. For all these mixtures, cost implications should be comparable to those of HCFC-22 and R-410A, although likely slightly greater due to the present higher refrigerant prices. Currently manufacturers and institutes across several countries are testing and trialling these various mixtures.

R-444B

R-444B has efficiency comparable to that of HCFC-22 and the liquid density indicates that the charge should be about 10-15% lower than HCFC-22. Preliminary test results indicate that R-444B shows similar capacity and efficiency to HCFC-22 (Sethi et al, 2014) and is expected to perform similar to HCFC-22 systems at high ambient temperatures; theoretical cycle performance indicates that the capacity and COP are about 5% and 3% lower, respectively, relative to HCFC-22 (UNEP, 2015). Tests on a split air conditioner (with modified capillary tube and evaporator circuitry to account for the temperature glide) achieved identical capacity and COP as HCFC-22 at both 46°C and 52°C ambient (Sethi et al, 2014). The discharge temperature is also the same as with HCFC-22.

R-447B

Zou et al. (2016) reported on measurements of R-447B against R-410A in reversible systems across a range of conditions. For “normal” outside temperatures, capacity with R-447B was reduced by about 2-5%, but gave improvements in COP of 4-6% in cooling mode, whereas in heating mode capacity was about 7% below R-410A and COP about 2% higher. At “high ambient” conditions cooling capacity was about the same as R-410A although COP increased by up to 10%. Shen et al (2017) carried out measurements with various refrigerants to characterise the performance of a rooftop system with R-447B relative to R-410A. Under “normal” conditions, COP and capacity were 3% higher and 4% lower than R-410A, respectively, whilst at high ambient conditions COP reached 8% above R-410A with capacity equaling that of R-410A. Alabdulkarem et al. (2015) conducted a series of measurements to determine the seasonal performance of a reversible AC-HP system.

R-452B

In VRF systems, R-452B was found to have about 2% higher cooling capacity (expressed in terms of compressor speed) and 8% higher cooling COP, compared to R-410A and in heating mode, capacity was reduced by 3% with COP increased by 2%. Taking partial loads into account, it was determined to give an APF of 2% above R-410A (Naito et al., 2016). Hughes (2016) also compared R-452B with R-410A in VRF type systems, for which measurements showed both cooling capacity and COP to be within ±2% across a range of standard conditions. Zou et al (2016) reported on measurements of R-452B against R-410A in reversible systems across a range of conditions. For “normal” outside temperatures, R-452B typically showed a capacity reduced by around 1-3% and increase in COP of 2-5% for both cooling and heating. At “high ambient”, there was improvement in both capacity and COP of 3% and 5%, respectively. Pham and Monnier (2016) presented compressor calorimeter results comparing R-410A and R-452B. Across the range, R-452B gave 4-6% lower cooling capacity and COP from -1% and +1% relative to R-410A. Shen et al (2017) compared performance of a rooftop system with R-452B relative to R-410A. For both “normal” and “high ambient” conditions, R-452B COP was about 3-4% higher and capacities were about equal. Wang and Amrane (2016) present results from a number of reports. Two “soft optimised” units were tested with R-452B, where one had reduced capacity by 7% and COP by 4%, whilst another achieved the same capacity as R-410A but with 5% better COP. At high ambient test conditions, both units exhibited identical capacity as R-410A but with 4-5% better COP. Abdelaziz et al (2015) reported on a series of charge-optimised split air conditioners under “normal” and high ambient conditions. Compared to R-410A, R-452B gave 2 to 3% improvement in COP and a reduction of 3 to 4% capacity under “normal” conditions and 3% higher COP and equal capacity at hot and extreme temperature conditions.

R-454A

Shen et al. (2017) carried out measurements with various refrigerants to characterise the performance of a rooftop system with R-454A relative to HCFC-22. For both “normal” and “high ambient” conditions, COP and capacity were both around 15% below and about equal to HCFC-22, respectively. Abdelaziz et al. (2015) report on a comprehensive series of measurements on charge-optimised single split air conditioner and under “normal” and high ambient test conditions. Compared to HCFC-22, R-454A gave a 12% drop in COP and 3% lower capacity under “normal” conditions and COP was reduced by 11% and 3% lower capacity at hot and extreme temperature conditions.

R-454B

In VRF systems, R-454B was found to have about 5% lower cooling capacity (expressed in terms of compressor speed) and 2% higher cooling COP, compared to R-410A and in heating mode, performance was reduced by 5% and 8%, respectively. Taking partial loads into account, it was determined to give an APF of 1% more than R-410A (Naito et al., 2016). Hughes (2016) also compared R-454B with R-410A in VRF type systems, for which measurements showed cooling capacity to be within ±2% across a range of standard conditions, whilst COP of R-454B was up to about 5% higher than R-410A. Wang and Amrane (2016) present results from a number of reports carried out under the phase II of AHRI Low-GWP AREP programme. Four “soft optimised” units were tested with R-454B, where three matched the COP of R-410A but with about 5% lower capacity, whilst another achieved the same capacity as R-410A but with 5% better COP. Under high ambient conditions, all units produced a higher COP than R-410A, ranging from 1% to 7% and with three units having a capacity between 1% and 3% below R-410A and one with 3% greater capacity.

R-459A

Wang and Amrane (2016) present results from a number of reports carried out under the phase II of the AHRI Low-GWP AREP programme. Two “soft optimised” units were tested with R-459A, where both gave the same 8% reduced capacity whilst one matched the COP of R-410A and the other was about 4% higher. When tested at “high ambient” conditions, both units showed a notable improvement in performance, providing COP at 7% and 12% above R-410A and COP within -3% and +3%, respectively.

7.3.11 Energy efficiency considerations

Energy efficiency and power consumption is of course an important consideration for all RACHP equipment. Given that air conditioning though is so prevalent across many of the most populous countries and is anticipated to continue to grow substantially across many of the A 5 countries as affluence and global temperatures rise, it will increase national electricity demand accordingly. For instance, Davis and Gertler (2015) estimate that the fraction of households with air conditioning will increase from 13% to more than 70% by 2100 corresponding to around 83% increase in residential electricity consumption. Air conditioning use coincides with peak electricity demand and is a main driver for peak power plant use in many countries. Such significant demand on national power supplies would have serious implications on reliability of supply and CO_2 emissions.

Recognition of this scenario has led most countries to implement some form of mandatory or voluntary minimum efficiency and/or labelling rules. Smaller air conditioners (such as those used for residential applications) are more widely regulated than larger systems. These measures include single-point efficiencies and seasonal efficiencies, although more recently there is a tendency to adopt the latter. Across various countries minimum seasonal COPs range from about 3 to 6 and are continually being raised. Theoretically system efficiency can far exceed these minimum values, but ultimately the choice of minimum efficiency values represents a balance between capital cost of systems, life cycle costs, electricity supply costs and environmental benefit.

As discussed in Chapter 11, there are numerous techniques available to improve efficiency and reduce energy consumption. These include variable speed compressors (to provide high seasonal energy efficiency), improved heat exchanger design, use of electronic expansion valves (EEVs), advanced control systems (for example, to provide the whole system and also building supervisory control), advancements in compressor design, integration of evaporative cooling to condensers and accounting for the range of conditions associated with the target climates for specific products. In addition, systems should be matched to anticipated building heat loads and can be coupled with integrated and/or remote energy recovery systems such as economisers and moreover “free” cooling systems that utilise for instance outside air or ground water when the temperature suits. Chapter 11 discusses these matters in more detail and myriad dedicated publications can be found within the public literature.

For existing systems efficiency and energy consumption can be improved when regular maintenance practices include cleaning of condensers and airside filters, checking and maintaining refrigerant charge levels, replacing degraded oil, filter driers, etc. In most cases, it may be preferable to replace old inefficient air conditioners with new higher efficiency models.

7.4 Options for existing equipment

As the HCFC phase-out proceeds in non-Article 5 or Article 5 countries, 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[7]
- Retrofit (refrigerant change and system components)
- Conversion (to flammable refrigerant)

Most of these categories are likely to be important for Article 5 countries because systems are often repaired several times in order to extend their useful lives. There are a large number of Low Volume Consuming (LVC) countries, which import rather than manufacture air-conditioners where most of the HCFC consumption is used to service the installed base of air-conditioners. In these countries, HCFC consumption can be reduced by the use of service refrigerants or by retrofitting existing equipment to non-ODP refrigerants. An additional option would be to replace the existing equipment before the end of its useful life, provided that the new equipment has sufficiently high efficiency. In non-Article 5 countries, 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 a new higher efficiency are more attractive. The need for retrofit and replacement refrigerants will largely be determined by the size of the installed population of HCFC-22 products, HCFC phase-out schedule, allowed “service tail”[8], the availability of HCFC-22 and the recovery and reclaim practices in place leading up to the phase-out. The installed population of air conditioners and heat pumps has an average service life of around 5 to 20 years, depending upon 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.

[7] 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”.

[8] The term ”service tail” is used to describe the time between when a refrigerant has been phased out for use in new equipment and the date at which the refrigerant may no longer be produced.

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

For refrigerant replacement only, HCFC-22 is replaced with a blend, 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.

Retrofit refers to not only changing the refrigerant, but also system components such as lubricant (although not always necessary), filter dryer (if required) and more extensive modifications which 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, replacing the refrigerant without additional changes or even unit replacement; it is probably not cost effective if either the compressor or heat exchangers have to be replaced.

Conversion is where the existing refrigerant is replaced with another without necessarily having to address the refrigeration circuit components and lubricant in the same way as retrofit, but because the replacement refrigerant is flammable, the external aspects of the equipment, such as potential sources of ignition, have to be addressed. However, since this is a complex process and can lead to unforeseen safety risks, it is not normally recommended. Again, such a change in refrigerant can affect capacity and/or efficiency, operating pressures, temperatures, lubricity, etc., to HCFC equipment.

In the case of refrigerant replacement and retrofit in HCFC systems, the GWP of the new should also be given consideration as many blends have a GWP higher than HCFC.

In all cases, before changing the refrigerant it is recommended that the system manufacturer be consulted.

7.4.1 Replacement refrigerants only

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 a HFC-227ea), which are added to the blend to enable the refrigerant to work with the naphthenic mineral-oil-based and alkyl benzene lubricants which were historically used in nearly all HCFC-22 air conditioning systems. Thus these refrigerants attempt to mimic the performance of HCFC-22. However, they seldom perform as well as HCFC-22; having either lower capacity, efficiency or both. Examples of findings from earlier studies are reported in (UNEP, 2015), whilst noting that in the majority of cases the studied alternatives were found to exhibit worse performance (cooling capacity and COP) than HCFC-22.

In addition to the performance and efficiency impacts the blends may not perform the same for oil return. HCs are added to allow for the oil return, but it may not be as effective and problems could result at lower loads and extreme operating point seen during high ambient temperatures 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. 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 the equipment, whilst in other cases manufacturers explicitly warn against such replacements. Information on the application of these blends can be obtained from manufacturers.

However, recently HCFC-22 compressors were produced with synthetic oils thus enabling pure-HFC refrigerants, primarily R-407C, to be used as a direct replacement.

There are a number of criteria that should be achieved in order for a replacement only refrigerant to be selected and these are discussed in Chapter 2.

7.4.2 Retrofit refrigerants

A number of the HFC blends proposed for alternatives to HCFC-22 in air conditioners, are also deemed as suitable retrofit refrigerants for HCFC-22 systems; examples of such HFC blends include 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 (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 filter driers that are able to absorb breakdown products from synthetic lubricants 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 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 of <10 K will tend to have similar practical implications.

The criteria for selecting a suitable retrofit refrigerant are discussed in section Chapter 2.

7.4.3 Conversion 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). Some countries are including this approach in their HCFC phase-out strategies, whilst the practice is not legal in other countries (such as in the USA). While these refrigerants may provide capacity and efficiency close to HCFC-22 (see examples in section 7.3), this practice can create a significant safety hazard because of the flammability of these refrigerants. In general, HCs are not recommended for use in systems that have not been specifically designed appropriately. If HCs are being considered then the applicable safety standards and codes of practice should be strictly followed. The GIZ Handbook for Hydrocarbon Safety (GIZ, 2010) is one source of information on the utilisation of these refrigerants.

In addition to the above, there are also some other mixtures with class A3 flammability being marketed, which in addition to HCs also comprise R-E170 (dimethyl ether) and HFC-152a. Prior studies were described in (UNEP, 2015), which generally reported on improvements in performance of up to 10%.

7.5 Final remarks

HCFC-22 and R-410A are presently the most frequently used refrigerants in the air-to-air systems. The HCFC-22 refrigerant bank for unitary air conditioners is estimated to be in excess of 1 million tonnes. HCFC-22 is now only used in new systems in Article 5 countries, although certain countries 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 high ambient temperatures. HC-290 is being used in split systems, window and portable air conditioners and recently in small ducted systems. HFC-32 is being used in split systems and is planned for larger ducted and multi-split systems. R-744 is available in some moderate (MAT) and low ambient temperature (LAT[9]) regions. These various alternatives highlighted have also been found to achieve performance approaching, as good as or better than HCFC-22.

In cooler climates, R-744 is available for commercial sized systems and the technology is further being explored. R-410A is increasingly becoming considered unacceptable because its high GWP and so investigations into medium and low GWP alternatives are continuing. There are a large number of new mixtures being considered for air conditioning systems primarily consisting of HFCs and unsaturated HFCs, such as R-444B, R R-447B, R-452B, R-454A, R-454B and R-459A. Although there is concern over the use of R-410A in high ambient temperatures, appropriate design measures can be used to help remedy the relatively greater degradation in performance; nevertheless, work is underway to investigate this refrigerant and others further.

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 efficiency. 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 GWP flammable HFCs, HFC/unsaturated HFC blends and HCs for normal operating conditions as well as high ambient.

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[9] A low ambient temperature (LAT) country is one that would have an incidence of at least two months per year over 10 consecutive years of a peak monthly average ambient temperature below 20°C (MAT is between LAT and HAT.)

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Chapter 8

Water and space heating heat pumps

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8 Water and space heating heat pumps

8.1 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 for process heating. The heat sources are generally 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 grey zone indicated in Table 8-1). The products for industrial process heating, large capacity systems, typically in the order of MW capacity, are covered in chapter 5 "Industrial systems". Air-to-air heat pumps are covered in chapter 7 "Air-to-air air conditioners and heat pumps".

The temperature difference between the source and sink has a direct impact on the pressure difference the compressor has to deal with for a specific refrigerant applied. In general, heat pump systems will be less efficient under higher temperature difference (temperature lift) condition. 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 from the heat pump, the temperature difference between the source and sink, the effectiveness of heat exchangers and the compressor/driver efficiency. Required power input to water pumps and fans must 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 recent European standard EN14825 and the EU regulation 813/2013 are referring to a seasonal coefficient of performance (SCOP), defined as the annual useful heat delivered divided by the corresponding power input.

In most applications heat pumps are an alternative to fossil gas or oil combustion boilers or direct electrical heating, resulting in a significant reduction of CO_2 emissions and primary energy consumption. The cost of the equipment and the COP/SCOP are the most important factors in the competition with fossil fuel systems. The use of hybrid systems, where the lower temperature-lift (operation at high COP) of the heat demand is supplied by the heat pump, is becoming attractive in certain countries in Europe.

In 2017, the global air-to-water heat pump market increased to 2.66 million units, a continuous increase from 2016. The main increase is caused by the growth of the Chinese market (JARN, 2018).

Thermodynamic characteristics, as well as values for the Ozone Depleting Potential (ODP) and Global Warming Potential (GWP) of the refrigerants referred to in this chapter are given in chapter 2 of this report.

8.2 Heat pump types, implications and trends

8.2.1 Heat pump types

Heat pumps can be classified by heat source (air, water, and ground) and heat sink (air, water), resulting in the following definitions for the type of heat pumps used in this chapter as given in Table 8-1.

It is also possible to classify heat pumps by types, depending on their usage:

1) Heat pump water heaters (HPWH)

2) Space heating heat pumps

3) Combined water and space heating heat pumps

Table 8-1: Heat pump classification

			Heat source		
			Air	Water	Ground
Heat sink	Air		Air-to-air	Water-to-air	Ground-to-air
	Water	Water heater	Air-to-water	Water-to-water	Ground-to-water
		Space heating			
		Combined			

Note 1: This chapter covers only systems where water is the sink (the grey zone indicated in Table 8-1)

Note 2: heat pumps may utilise either direct expansion or indirect expansion systems (applying a secondary fluid circuit) at the evaporator side (heat source).

Fig 8-1: example of a heat pump water heater

Fig 8-2: Example of an air-to-water mono-block - space heating heat pump

Fig 8-3: Example of a water-to-water heat pump

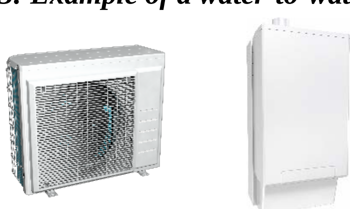

Fig 8-4: Example of a split type air-to-water combined water and space heating heat pump (this can be a hybrid system)

Heat Pump Water Heaters (HPWH)

Heat pump water heaters (HPWH) are a category of heat pumps designed to heat domestic and other service (hot) water to temperatures between 50 and 90°C. These operating temperatures must be considered when selecting the refrigerant to be applied.

Space Heating Heat Pumps

A space heating heat pump is normally optimised for comfort heating. Comfort heating heats the room by heating water for distribution to an air handling unit, a radiator or an under-floor panel. The required water temperature depends on the type of emitter:
- for under-floor heating the temperature is typically ranging from 25 to 35°C;
- for air handling units the temperature is typically around 45°C;
- for radiator heating the temperature is typically ranging from 55 to 65°C;
- for high temperature radiators the temperature is typically ranging from 65 to 80°C.

Combined Space and Hot Water Heat Pumps

Combined water heating and space heating heat pumps have two functions: supplying domestic hot water as well as 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.

Capacity Ranges of Water and Space Heating Heat Pumps

Table 8-2 shows the most common heating capacity ranges as offered by single units of each type of water and space heating heat pumps described above.

Table 8-2: Water and space heating heat pump capacity ranges

Heat pump type	**Capacity Range (kW)**
Heat pump water heater	1.5 – 50
Space heating heat pump	4 – 400
Combined water and space heating heat pump	6 – 45

8.2.2 Energy efficiency considerations

In Europe, Japan and the US, legislation is now in place to establish minimum energy efficiency values for water and space heating heat pumps. While this legislation limits the types of heat pumps that can be placed on the market (as some will fall below a required minimum efficiency), it has helped to increase the average efficiency of the units installed.

In the EU, energy efficiency requirements for space heating heat pumps (EU regulation 813/2013) are based on seasonal efficiency, for an "average" European climate with a design ambient temperature at -10°C, including standby losses. As of September 2017, all space heating heat pumps shall have an energy efficiency of 110%. For low temperature space heating heat pumps, it shall be 125%. For electric driven heat pumps, a "conversion coefficient" of 2.5 has been fixed, reflecting the estimated 40% "EU efficiency" of electricity generation, as referred to in directive 2012/27/EU. For electrically driven space heating heat pumps, this results in a seasonal coefficient of performance (SCOP) of 2.75 and 3.125, respectively (i.e., referring to the 110% and 125% efficiency). The seasonal efficiency is based on a specific temperature pattern and includes standby energy losses. For heat pump water heaters, the requirements are less restrictive, except for larger systems having restrictions as of September 2018. For the moment, there is no drastic impact resulting from energy efficiency requirements that could limit the refrigerants currently used.

In China, the government is strongly promoting a coal-to-electricity policy to reduce fossil fuel heating (JARN, 2017; JARN, 2018). There is a strong demand for heat pumps suitable to operate down to -25 and -30°C ambient temperature as well as heat pumps delivering water at temperatures up to 60°C, while maintaining good energy efficiency (JARN, 2018).

8.2.3 Safety considerations

The international standard IEC60335-2-40 specifies safety requirements for heat pumps including the use of flammable refrigerants. Toxicity requirements are covered by ISO 5149-1. Besides the safety issues as specified in the standard, regulations may be applicable that limit the use of refrigerant quantities both from a flammability as well as from a toxicity point of view. Certain countries have put in place specific building regulations prohibiting or limiting the use of flammable or highly toxic refrigerants. Some of these regulations are under revision with the aim of setting less restrictive requirements to the use of flammable or highly toxic refrigerants. Moreover, a new revision of IEC60335-2-40 was published in 2017 offering new options for the use of A2L flammable refrigerants. Under IEC61D, working group 16 is preparing new options for the use of A2 and A3 class refrigerants. This working group is mainly focusing its work on air-to-air air-conditioners, but some of these options may also be applicable to water and space heating heat pumps.

8.3 Refrigerant options for new equipment

In most non-Article 5 countries, the transfer to non-ODS refrigerants was completed several years ago. However, in some Article 5 countries, HCFC-22 is still in use for high and moderate temperature water and space heating heat pumps (JARN, 2018), based on its favourable thermodynamic properties that result in high efficiency for heat pump applications,

In the 2014 RTOC Assessment Report, the following refrigerants were reported as options for new water and space heating heat pumps: HFC-32, HFC-134a, R-407C, R-410A, R-417A, HFC-1234yf, new HFC/HFO blends, HC-290, HC-600a, R-744 and R-717. To date no additional options have been published, except that, in general, some new lower GWP HFC/HFO blends are proposed; however, their potential use for water and space heating heat pumps has not yet been clarified. The different options are described below.

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.

In Europe, there is a strong need to apply refrigerants that yield lower charges, resulting in a reduction of the CO_2 equivalent units, when weights are multiplied by the GWPs that apply. Due to the quota limitations in the EU, based on CO_2 equivalent units, the price and availability of high GWP refrigerants become important selection criteria. On the other hand, the change-over to lower GWP refrigerants generally requires a redesign of the equipment including the major components such as the compressor. The following items make it a difficult and time-consuming task to switch over to lower GWP substances:

- mitigation of flammability risks, as most low GWP refrigerants are flammable
- design changes required to maintain the same operating range and performance
- availability of components at a competitive price level.

8.3.1 HFC-134a and HFC blends R-407C, R-417A and R-410A

HFC-134a, R-407C and R-410A are widely used in water and space heating heat pump systems and are well commercialised globally. R-417A is considered as a replacement for HCFC-22 in air conditioners, however, it is used in both existing heat pump applications and in new equipment.

In the countries where HCFC-22 consumption reduction started in advance of Montreal Protocol requirements (i.e., mainly in Europe), these 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 used to mainly replace HCFC-22 in existing product designs because of the minimal design changes that are required. However, the use of R-407C is declining in favour of the higher efficiency and lower system cost when applying R-410A (UNIDO, 2016). In order to adequately use R-410A, design changes are necessary to address its higher operating pressures and to optimise the system taking into account its properties, thereby achieving higher performance.

Air-to-water split cascade systems are put on the market, using R-410A for low temperature circuits and HFC-134a for high temperature circuits. They both guarantee high seasonal COP in case of colder climates, even at high water sink temperatures approaching 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., 2018).

The energy efficiency of R-407C systems is typically lower than that of HCFC-22, although similar COPs can be achieved with a careful design of the system. In practice, R-407C shows a pronounced temperature glide during evaporation and condensation, which can lead to operational difficulties (Linton et al., 1996).

R-417A has been used by some manufactures for heat pump water heaters. R-417A provides lower capacity than HCFC-22, however, has demonstrated effectiveness at higher temperatures.

As the cost of the refrigerant itself is minor in comparison to the total system cost, small differences in the costs for the refrigerant therefore have minor effects. The cost of the components has a major impact. A more compact design generally results in lower costs. 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.

At the moment, there are no significant barriers to the use of these refrigerants, but their high GWP may put them under pressure, requiring a change towards lower GWP fluids.

8.3.2 HFC-32

The use of HFC-32 in water and space heating heat pumps is already commercialised on a larger scale. Moreover, applying HFC-32, similar units operate with a higher COP than with HCFC-22 or R-410A (Shigehara, 2001).

HFC-32 has saturation pressures slightly higher than the one 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 better thermodynamic properties and heat transfer performance than R-410A. Since HFC-32 has higher 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 substance is lower than that of R-410A, but this has limited impact on the system cost. HFC-32 space heating and combined water and space heating heat pumps have been introduced on the market with the same performance as for R-410A units, however, delivering 5 K higher temperatures up to 65°C. Recently, hybrid versions of a water and space heating heat pump using HFC-32, combined with a natural gas supplementary heater, have been developed as well; when introducing them on the market, they were characterised as "new systems".

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 2. The standard ISO-5149 was updated in 2014 and IEC-60335-2-40 was updated in 2017 in order to accommodate this new class. Generally, safety aspects during the lifecycle of the equipment are of limited importance. However, some building codes do not allow the use of flammable refrigerants in certain type of buildings. If the refrigerant water heat exchanger is placed in an outside occupancy, the safety issue is easier to resolve, however, in that case frost prevention becomes an issue.

8.3.3 HFO-1234yf and low-GWP HFC/HFO blends

HFO-1234yf is similar in thermophysical properties to HFC-134a, thus yielding comparable performance and no need for substantial modifications compared to an original R-134a system (Nawaz et al, 2017).

A number of other HFOs are studied and being identified in the patent literature as possible low-GWP refrigerants for heat pumps (Arpagaus et al, 2018) with special attention on HFO-1234(E) and HFO-1234(Z) (Fukuda et al, 2014) for high temperature applications. The latter is related to their favourable heat transfer coefficients in comparison to other refrigerants used so far in heat pumps (Longo et al, 2014). Blends of HFOs with HFC-32 or HFC-125 may make it possible to approach the properties of HCFC-22 or R-410A, but it results in higher refrigerant GWP than for pure HFOs. It is too early to judge whether any of these chemicals will be commercialised here, because of acceptable performance and competitiveness in water and space heating heat pump systems.

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. Some of the required changes include larger displacement compressors, larger diameter interconnecting and heat exchanger tubing, as well as additional heat exchanger surface in order to offset both lower heat transfer and higher flow resistance.

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 high temperatures that are typical for heat pump water heaters.

Component costs will be similar to HFC-134a system components, but the flammability will affect larger systems, due to the pressure vessel codes that need to be taken into account.

The same restrictions as for HFC-32 apply for these refrigerants (see Annex to Chapter 2).

8.3.4 R-744 (carbon dioxide)

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, 2017; 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; approximately 5 times higher than HCFC-22 and 3.5 times higher than R-410A. This is actually an advantage that enables more compact system designs. The low critical temperature of R-744 results in trans-critical operation. R-744 refrigerant has been primarily used in 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 use in colder climates. 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 space heating requirements (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 and minimum energy efficiency requirements.

R-744 as refrigerant enables domestic water heating up to temperatures as high as 90 ºC without use of auxiliary electrical heaters. R-744 may give a high performance if used at low temperature source and high temperature sink conditions, together with a high temperature difference between inlet and outlet water temperature (Stene, 2008). This makes it well suited for use in 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 applying R-744 for space heating alone (Nekså, 2010). It is challenging to achieve high efficiency for domestic space heating applications, if the difference between the high and low water temperature of the heat sink is low. In that case, system designs enabling a low water return temperature are required (Nekså, 2010); otherwise, the introduction of work recovery components, e.g., ejectors or expanders, may overcome energy efficiency barriers, however, their costs may make the product less competitive.

The cost of the working fluid is low. However, because of its high pressure, certain types of systems will require more robust designs for pressure safety, which adds cost; however, the specific tube dimensions to be applied are much smaller compared to current technology, which gives the advantage of compact tubing and insulation material.

The main barrier is the cost of the system and the energy efficiency in some applications. Based on investigations of manufacturers catalogue data, 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 to the market in 2001. The market volume has expanded steadily and cumulative shipments are now at 5.79 million units, status January 2018 (JARN, 2018). Since the Great Earthquake in eastern Japan in 2011, the annual sales volume has remained stable, but a continuing increase is expected to as a means of reducing future global warming impacts. Unit sales are subsidised by several programmes (JARN, 2018).

8.3.5 Hydrocarbons

Hydrocarbons (HCs) include three main refrigerants used in water and space heating heat pumps, i.e., HC-290 (propane), HC-1270 (propene) and HC-600a (iso-butane).

At present, a limited number of low charge level heat pump water heater installations are sold in Europe applying HC-290. While, for water and space heating systems, with ventilated enclosures configuration, larger refrigerant charges are allowed and introduced in the market.

Their use in Europe has declined, due to introduction of the Pressure Equipment Directive (Palm, 2008), but some compressor manufacturers are now offering 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, using 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 direct cost of the refrigerant is favourable. Based on the HC refrigerant properties, the equipment cost is comparable to HCFC-22 equipment cost, where mitigation devices for safety are supposed to add certain costs.

The main barriers are related to the 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 is being done on charge minimization in order to increase capacity for a given charge of the system (Andersson, 2018). The necessity to ensure that technicians are appropriately trained to handle hydrocarbon flammability is a main barrier. For equipment manufacturers, the liability aspects, combined with costs for safety measures, are the main barriers to extend the use of hydrocarbons.

8.3.6 R-717 (ammonia)

R-717 is mainly used for large capacity systems. 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 (see Annex to Chapter 2) during the life cycle of the equipment and the minimal capacity required for cost-effectiveness and certain national regulations controlling installation, even though it has been shown that small capacity water and space heating heat pump systems can be designed to operate with very low charge of ammonia (100 g of ammonia for 9 kW heating capacity (Palm, 2008)).

The main obstacle for the commercialization of small capacity water and space heating heat pump systems is the limited supply of components. Hermetic and semi-hermetic compressors are available for medium and larger size water and space heating heat pumps. In this context, it can be mentioned that a scroll compressor for an ammonia unit has been presented several years ago (Kawamura, 2009); based on that compressor type, a 15 kW input (Plus+HEAT) unit for water and space heating is now commercially available in Japan.

8.3.7 Overview

Table 8-3 gives an overview of the emerging refrigerants next to the refrigerants presently in use. Both categories are commercially available. The refrigerants used at present have matured in the market; emerging refrigerants are refrigerants that are currently used in certain full product ranges and that show clear potential for growth in the coming years.

Table 8-3: Emerging refrigerants used in water and space heating heat pumps

Product	Refrigerants Presently Used	Emerging Refrigerants used
Heat pump water heaters (HPWH)		
Air source heat pump	HCFC-22[1] HFC-134a R-407C R-410A R-417A	R-290 R-744 HFC-32
Water or ground source heat pump	HCFC-22[1] R-407C R-410A	R-290 R-744 HFC-32
Space heating heat pumps		
Air source heat pump	HCFC-22[1] R-407C R-410A R-417A	R-290 HFC-32
Water or ground source heat pump	HCFC-22[1] R-407C R-410A	R-290 HFC-32
Combined water and space heating heat pumps		
Air source heat pump	HCFC-22[1] R-407C R-410A	R-744 HFC-32
Water or ground source heat pump	HCFC-22[1] R-407C R-410A	R-744 HFC-32

[1]*Still in use in Article 5 parties*

8.4 Options for existing systems

There are no changes compared to the options described in the 2014 RTOC Assessment Report and the preferred method for continuing equipment operation remains a total equipment replacement. Larger equipment manufacturers may provide retrofit solutions for installations where the replacement of the total unit is difficult.

8.5 Concluding remarks

Based on the issues dealt with in this chapter (taking also into account the statements made in the 2014 RTOC assessment report), it can be concluded that most water and space heat pumps commercialised today, make use of non-ODS refrigerants. The refrigerants used at present are R-410A, HFC-134a, R-407C, HC-290, HC-600a and R-744. The majority of new equipment still uses R-410A, however, for new equipment there is a growing tendency to use lower GWP refrigerants (see for this the emerging refrigerants, listed in table 8-3). From all the options reported in the 2014 RTOC Assessment Report, only a limited number of refrigerants are now commercially in use, with the potential to grow further in use.

In some Article 5 countries, HCFC-22 is being used since it has favourable thermodynamic properties and high efficiency. There are no technical barriers in case HCFC-22 needs to be replaced by a non-ODS refrigerant, Replacements are commercially available, technically proven and energy efficient and have a similar or lower environmental impact.

The potential technical issues involved in the use of air-conditioning equipment for high ambient temperatures are of lower or no importance to water and space heating heat pumps.

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Chapter 9

Chillers

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9 Chillers

9.1 Introduction

What distinguishes chillers from other air-conditioning and refrigeration systems is the cooling of a secondary coolant that is then distributed and used to cool air or another substance. The critical distinction is *indirect cooling* contrasted with *direct cooling* of air (as in packaged air conditioners, Chapter 7) or other substances (common in industrial refrigeration, Chapter 5).

Chillers are employed in a wide range of sectors. Comfort air conditioning in large commercial buildings and building complexes is commonly provided by chilled water systems that use chillers. District cooling, large data processing and communication centers, medical facilities, large entertainment complexes, and university campuses are other examples of applications that use large chillers. Mission critical cooling for mines (particularly in deep mines with high thermal gradients) and large marine vessels are also noteworthy applications. Chillers also are widely used for process cooling in commercial and industrial processes and facilities such as electronics fabrication, precision machining, pharmaceutical manufacturing, and molding (see also Chapter 5 for industrial refrigeration applications). The chillers that serve these systems provide chilled water or other secondary heat transfer fluids. The fluid typically is pumped through a variety of heat exchangers within a process, or in coils within central station air handlers, air terminal devices mounted in the ceiling and/or ductwork, or packaged terminal products that heat, cool and dehumidify the air. While chillers are commonly associated with large cooling loads and facilities, smaller chillers are also used for some commercial applications such as schools and office buildings, and multifamily residences. Air cooled chillers are the dominant configuration for these types of applications, whereas water cooled chillers are generally associated with larger cooling loads and facilities.

Chillers covered by this chapter employ a vapour compression cycle using reciprocating, scroll, screw, centrifugal compressors (see Chapter 12 for absorption chillers using non-vapour compression technology). Heat typically is rejected through air-cooled or water-cooled heat exchangers, evaporative condensers or dry coolers.

Chillers are designed for high reliability and long service life, key customer requirements. They are likely to stay in service for long time periods. Though there is some variation in publicly available information, small air cooled chillers have a life of 15 to 20 years depending on the severity of the outdoor conditions. By contrast centrifugal water cooled chillers typically last 30 years, and not uncommonly even 40 years, with routine maintenance. The point is that whatever refrigerant is used in any generation-of chillers, it is likely to remain in service for a long time. As an example, CFC-11 and CFC-12 were widely used in chillers until the Montreal Protocol banned them due to their ozone depleting characteristics. Even though production of new equipment was stopped in mid-1990 in developed countries, CFC-11 and CFC-12 are still used in many countries for service, nearing 30 years later! And it should be noted that Article 5 countries may still use ODP refrigerants in new chillers until 2030. Chillers using ODP refrigerants are not widely produced in these countries, though there is some small production of using HCFC -22.

The change-over to non-ODP refrigerants required a very high investment and was a lengthy process. This resulted in the current generation of chillers, which has proven to be highly reliable and has resulted in higher performance. Still the majority of refrigerants in use today generally have GWPs greater than 1000 (a notable exception is centrifugal chillers that use HCFC-123 - banned in 2020 due to non-zero ODP despite is low GWP). Climate change concerns are driving efforts to seek lower-GWP refrigerants to replace them, mainly HFC-134a and R-410A. The process of selecting of new refrigerants began some years ago. This process was characterised in the 2014 report. At that time there were a number of leading low GWP candidates, but no refrigerant had been selected for commercialization.

Four years later we find that significant progress has been made and products using lower GWP refrigerants are available today in the market place, albeit only a small fraction is being sold. The refrigerants used in this early market phase may not be the final choice. Another major investment is required by equipment manufacturers who completed a changeover to the current generation of refrigerants only a few years ago. It will take time to change full product lines, and discontinue existing product lines. Refrigerant and product availability and cost, competition among manufacturers, government regulation and incentives, and safety codes and standards relating to the use of flammable refrigerants may hasten or retard the adoption of low GWP refrigerants.

All other considerations aside, to be acceptable, new refrigerants must result in products with energy efficiencies that are equal to or better than the refrigerants replaced. There are two reasons for this. First, customers are demanding higher performance from chillers, driven by the ever-increasing cost of energy and government regulations in many regions. Secondly, the global warming effects from chillers are dominated by their energy consumption over the life of the equipment. Total Equivalent Warming Impact (TEWI), Life Cycle Climate Performance (LCCP) and Life-Cycle Warming Impact (LCWI) models typically show *that more than 95% of the climate effect is due to energy consumption, not refrigerant emissions* (Calm, 2006). It follows that the use of higher performing chillers is more important to climate change than prematurely changing to another refrigerant with lower efficiency.

In all regions, there is a demand for higher performance chillers and the systems that use them, at both full and partial load. Manufacturers continue to refine their designs by offering newly designed compressors, some with advanced impellers, screw rotors, and scroll involutes, along with the use of variable speed drives, permanent magnet motors, suction line heat exchangers, increased subcooling, economizers, and more sophisticated control systems. There also continues to be expanded offerings of oil free centrifugal compressors that use magnetic or ceramic bearings. This is notable as it may avoid some of the issues associated with moving to alternative refrigerants and the lubricants that are needed in conventional compressors.

The ozone depletion potential (ODP), global warming potential (GWP) and other refrigerant properties are given in Chapter 2. Chapter 2 includes a description of the issues associated with changing refrigerants, including safety aspects

9.2 Types of equipment and components

9.2.1 Air and water cooled chillers

Figures 9-1, 9-2, and 9-3 shown below represent several common chiller types. While a change in refrigerants is now becoming more certain than ever, a change in technology is not. Mechanical vapour compression technology using centrifugal, screw, scroll and reciprocating (piston) compressors dominates all chiller types. Major improvements in compressors, heat exchangers, controls and other components are common, thanks to the R&D efforts by manufacturers and suppliers, and research efforts that they may sponsor with third parties. There has been little substantive progress towards commercialization of magnetic refrigeration, thermo-acoustic or other not-in-kind technologies that may have the potential for significant displacement of vapour compression in chillers (see Chapter 12). With the exception of absorption chillers (see Chapter 12), most remain in the R&D stage. Absorption chillers have been commercially applied for decades. They are part of the global mix of chillers particularly where there is a low cost source of high temperature waste heat, favourable gas-to-electric prices or utility incentives. There are a number of products that use vapour compression technology, but use non-fluorinated refrigerants, namely HC-290 (propane), R-717 (ammonia), R-718 (water), and R-744 (carbon dioxide). Though popular in some countries, the total production of these chiller products is small when compared to the global production of all chillers. See Section 9.3.4 for additional detail.

Large or small, air cooled or water cooled, and regardless of the refrigerant, the vast majority of chillers use some form of vapour compression using 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 is the refrigerant and is used on a very limited basis. The positive displacement category includes reciprocating (piston), rotary, screw, and scroll compressors. Not all refrigerants can be used with all compressor types because of cost, design and manufacturing considerations and because compressors are designed for specific refrigerants and applications.

Figure 9-1: Small Capacity Air Cooled Chiller

Figure 9-2: Medium Capacity Air Cooled Chiller

Figure 9-3: Large Water Cooled Chillers in a Mechanical Equipment Room

See Figures 9-1, 9-2 and 9-3 for examples of air and water cooled chillers. 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. Large chillers above 700 kW typically 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 (see Section 9.3.2) (ASHRAE Terminology). Accordingly refrigerants with high temperature glide cannot be used in flooded or falling film evaporators, the types used for larger chillers.(Technical Information ART 41, Du Pont)

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.

9.2.2 Chiller capacity ranges

Table 9-1 lists the cooling capacity range offered by single packaged units of each type of chiller. Within the product categories**,** higher capacity is typically achieved by adding multiple compressors and additional heat exchanger surface within the packaged product, as may be noted in Figures 9-1 and 9-2**.** For large cooling loads, it is common to use multiple chillers as can be seen in Figure 9-3.

Table 9-1: Chiller capacity ranges

Chiller Type	**Approximate Capacity Range (kW)**	**Dominant Refrigerants Presently Used**
Scroll, rotary, and reciprocating water-cooled	10 - 1,200	R-410A, HCFC-22, R-407C, Less common HC-290, R-717, R-744
Screw water-cooled	100 – 3,800	HFC-134a, HCFC-22, Less common R-717
Screw, scroll, rotary, and reciprocating air-cooled	10 – 1,900	HFC-134a, R-410A, HCFC-22, R-407C, Less common HC-290
Centrifugal or axial-turbo water-cooled	200 - 21,000	HFC-134a, HCFC-123, Less common HFC-245fa, R-718
Centrifugal air-cooled	200 – 1,600	HFC-134a

9.3 Refrigerant options for new equipment

9.3.1 Emerging low-GWP refrigerants

The 2014 RTOC Assessment Report gave a complete discussion of the trade-offs and research efforts associated with use of lower GWP refrigerants. At that time, there were a number of leading low GWP candidates, but none of them had been-commercialised and were available in the market. The pace and intensity of the work is typically governed by competitive forces, and the availability of capital and manpower to conduct major R&D and product development programs, and government regulations or financial incentives.

Government regulations can change the timing and intensity of the changes to lower GWP refrigerants. Two noteworthy developments concerning government regulations occurred since the 2014 RTOC Assessment Report, one in the US and the other one in Europe. On December 1, 2016 a significant event occurred in the United States. The United States Environmental Protection Agency (US EPA) adopted a phase-out of January 1, 2024 for chillers using higher GWP refrigerants, namely, HFC-134a, R-410A and R-407C, the most common refrigerants in use today (US EPA Final Rule 21, 2016). One other major refrigerant for chillers, namely HCFC-123, already has a phase out of 2020 predicated on its (very low) ODP, despite its very low GWP. Several states like California and New York are in the process of adopting similar regulations. While the EPA ruling has been challenged in court and likely will not to be implemented, when coupled with state activities has had the effect of encouraging US compressor manufacturers to accelerate the use of lower GWP refrigerants in new product development. And since the major manufacturers in the US sell products in most international markets where consumer interest may be higher than in the US, it signals a possible accelerated timeline for broad availability of chillers that use low GWP refrigerants.

For countries in the European Union, the 2014 EU F-Gas Regulation (517/2014) controls the use of certain fluorinated refrigerants in Europe and it has significant impacts for users of HFC refrigerants in chillers, namely HFC-134a and HFC-410A. By 2030, only 21% of the quantity of HFCs that were sold in 2015 will be available. The reduction scheme occurs in a series of steps and is based on "GWP-weighted" quantities (GWP x kg), meaning that higher GWP refrigerants will get the greatest pressure for reduction. The first really big cut in HFC supply occurred in 2018 when there was a cut of around 40%. The industry is obliged to manage the reduction. The chemical industry uses price and availability as the two main measures. Consequently there are reported shortages of refrigerants in some EU countries, and the cost of refrigerants increased dramatically in 2017. For example the cost of HFC-134a rose by approximately 500% from 2016 to the present. The natural consequence is that the transition to lower GWP refrigerants may be accelerated if manufacturers cannot pass along the refrigerant price increases for refrigerants currently used to consumers. Additionally, governments can use taxes, tax credits, and other financial incentives to accelerate the transition to lower GWP refrigerants. For example Norway, Denmark, Poland, and Spain have taxation schemes and there are discussions in other EU countries, notably France. There are no recent regulations related to refrigerants currently used in chillers from the Middle East, Africa, or the Asia Pacific region with the exception of Japan. A 2017 Japanese regulation prohibits the use of refrigerants with a GWP more than 100 after the year 2025 when used in centrifugal chillers.

Regardless of changes in government regulation, after years of research, a more certain array of choices is emerging and chiller manufacturers seem to be moving steadily towards lower GWP alternative refrigerants. Announcements of products using lower GWP refrigerants is becoming common, see Table 9.2. It should be noted that chillers have traditionally used an array of refrigerants due to the economics associated with high performance compressors as well as physical size and manufacturing constraints over the range of capacities provided by chillers. Table 9.2 is an abbreviated table that is meant to show the dominant refrigerants that are currently used in production chillers and the refrigerants that may replace them. It may not include all niche products that may be found in all regions.

Table 9-2 does not show CFC-11, CFC-12, or HCFC-22 that are banned in developed countries but may be found in Article 5 countries. Of special note is the expected phase out of widely used HCFC-22 in China in 2030. Absorption chillers are not included in the table as they are not vapour compression based chillers and as such are covered in Chapter 12.

Table 9-2 is intended to show that an industry wide change to lower GWP refrigerants is underway. To be clear, the term *'Emerging Refrigerants Used in Chillers'* means that the research and refrigerant selection process is sufficiently well along that one or more manufacturers are proceeding with product development and initial market launch. In other words, chiller products are being offered for sale, not just the refrigerant itself.

Product offerings typically change rapidly as manufacturers launch new products, and position and price them to gain market acceptance. Government regulation or financial incentive can also accelerate adoption of new refrigerants. In the absence of these types of incentives, product lines are typically changed over to the new refrigerant over time, while existing products remain available in the market. It does not mean that complete product lines are available to the customer at first product launch. This is not unusual since it typically takes several years to introduce a complete new product line. However, it may also reflect the uncertainty in a final selection of the refrigerants, the longer term concerns over the supply of new refrigerants and their cost, the application cost pursuant to safety considerations, and customer acceptance in view of the complete array of competitive offerings as well as the pricing and positioning of them.

Table 9-2: Emerging refrigerants used in chillers

Product	**Dominant Refrigerants Presently Used**	**Emerging Refrigerants Used**
Large chillers with centrifugal or axial-turbo compressors using low pressure refrigerants	HCFC-123 [1] HFC-245fa (less common) R-718 (much less common)	HCFO-1233zd(E), R-514A, R-718
Large chillers with centrifugal compressors using medium pressure refrigerants	HFC-134a	R-513A, HFO-1234yf, HFO-1234ze(E), HCFO-1224yd(Z)
Mid-size chillers with positive displacement (screw) compressors	HFC-134a, HC-290[3] R-717[2]	R-513A, R-450A, HFO-1234yf [2], HFO-1234ze(E) [2] HC-290 [3], R-717 [4]
Small chillers with positive displacement (scroll, rotary or reciprocating) compressors	R-407C, R-410A	HFC-32 [2] R-452B [2] R-454B [2] R-454B, R-290 [3] R-744

[1] Phase-out in new equipment in 2020 for Article 2 countries, 2030 for Article 5 countries

[2] Classified as safety group A2L (lower flammable) means there are special considerations contained in product or safety code and standards for safe application.

[3] Classified as safety group A3 refrigerant (highly flammable) currently available in air cooled chillers installed outdoors

[4] Classified as safety group B2L refrigerant (lower flammable and toxic), means there are special considerations contained in product or safety code and standards for safe application

If a refrigerant is shown in both columns (e.g. R-717) this means that with continued market acceptance, expanded product offerings are becoming available. It is impossible to predict the market mix that may emerge, especially in view of future government regulations or incentives. But it will certainly change over time.

9.3.2 Continuing evaluation of experimental refrigerants

The emerging refrigerants shown in Table 9-2 may not be the final selections. While the basic technologies used in chillers are adjusted for a new refrigerant and are seemingly simple, in truth the technical and economic obstacles to move to lower GWP refrigerants are far from trivial. After all, one is at the beginning of another wholesale change in refrigerants, the third since the late 1980's or early 1990's.

There are a number of reasons why there will be continuing evaluation of experimental refrigerants, even though we are in the early market phase of products with lower GWP than those currently in use.

1. It may be that yet another round of refrigerant changes will be necessary as the result of government regulation. The refrigerants that are being commercialised in chiller products have a GWP above 100 (excluding water, ammonia, hydrocarbons, and CO_2). There is disagreement within the technical and political communities over what GWP level will ultimately be acceptable, but refrigerants with a GWP above 150 will be questioned and possibly regulated. There are potentially useful refrigerants with a GWP less than 150, among them are HFO and HC refrigerants, as well as blends of them.
2. A change to another new generation of refrigerants will not automatically result in better energy efficiency. At equivalent capacity, synthetic fluids from various families (CFC, HCFC, HFC, HFO) have nearly equivalent energy efficiency, though there is a well-known tendency that lower pressure fluids (used in large centrifugal chillers) have generally higher thermodynamic efficiencies than higher pressure fluids (used in small scroll chillers) (de Larminat and Wang, 2017). In a world that expects ever increasing energy efficiency, there may be a belief that a refrigerant change is needed. It is not true, and the issue of improved energy efficiency must be dealt with through cycle changes or improved performance of compressors or heat exchangers at the cost of product redesigns. Still, refrigerants that avoid efficiency penalties are highly desirable and so exploration of alternatives will occur.
3. The movement to new refrigerants takes years of product development and involves a high cost for design engineering and manufacturing tooling changes. Lower GWP refrigerants that reduce the product development and tooling cost, and the time it takes to launch a new product, are highly desirable.
4. As with previous refrigerant changes, suppliers will attempt to recoup their R&D and capital investments. Accordingly, new refrigerants typically cost more than their predecessors. Lower cost alternatives are desirable, especially in products that carry high refrigerant charges, such as large centrifugal chillers.
5. And finally, a number of refrigerants listed in Table 9-2 are safety group A2L (lower flammable), safety group A3 (highly flammable), or safety group B2L (both toxic and lower flammable). In these cases, special product application requirements will apply to safely use these refrigerants as determined by the codes and standards, and government regulations applicable to the specific country. In any case, the application cost will be higher than conventional safety group A1 refrigerants that are-widely used today. So manufacturers will continue to explore alternatives to avoid higher product application costs.

The following information is taken from the 2014 RTOC Assessment Report, but is included here in order to present a complete picture of the ongoing work. Lower-GWP refrigerants have been tested and evaluated for quite a number years and new candidates will continue to be explored driven by the reasons given above. As stated in Chapter 2, the perfect, inexpensive, energy efficient, non-toxic, non-flammable, and broadly applicable refrigerant does not exist and is unlikely to come into existence (Mc Linden et.al, 2017). There is a complex selection process where the industry evaluates the proposed new refrigerants that are appropriate for each type of chiller system. The selection process is a trade-off among GWP, energy efficiency, safety, applied cost, and limiting the need for costly redesign and tooling (Calm and Didion, 1997). More detail on the search and selection process can be found in published works (Domanski et.al., 2017; Mc Linden et.al. 2017). Although some of these studies exclude refrigerants suitable for use in centrifugal chillers, the same search and selection process is applicable to all types of chillers, regardless of the compressor type.

In 2011, the U.S. Air-Conditioning, Heating, and Refrigeration Institute (AHRI) launched an industry-wide cooperative research program to identify and evaluate promising alternative refrigerants for major product categories including chillers (Johnson, 2012). The program, referred to as the Low-GWP Alternative Refrigerants Evaluation Program, gave a technical basis to accelerate industry's response to environmental challenges raised by the use of high GWP refrigerants, and avoid duplicative work. Many refrigerant blends as well as single-component refrigerants were candidates for chiller applications. A number of the proposed alternatives have vapour compression cycle characteristics that are close to those of the chiller refrigerant being replaced, namely HFC-134a, R-410A, HCFC-22 (and R-407C), and HCFC-123.

Test results from the Low-GWP AREP program are available from an AHRI website (AHRI, 2013). Tests of alternative lower-GWP refrigerants also have been conducted in Japan under the auspices of the Ministry of Economy, Trade and Industry (METI), and in China. The emerging refrigerants used in chillers shown in Table 9-2 are the leading candidates and some degree of commercialization has occurred..

Additional information on non-fluorinated and low-GWP refrigerants for chillers is given in Section 4 of the TEAP XXIV/7 Task Force Report (TEAP, 2013). The energy efficiency, efficacy, costs, cost effectiveness, and extent of commercialization are presented for a number of selected refrigerant alternatives.

When evaluating a new refrigerant there are many characteristics to consider beyond operating pressure levels, cooling capacities, and energy efficiencies. Chapter 2-presents these characteristics. -Chapter 2 includes application and safety standards for refrigerants and systems employing them. Flammable refrigerants, safety groups 2L, 2, and 3, are part of the mix of potential choices. Safety group 2L is a classification that was defined in 2010 with the idea that lower flame speed refrigerants could be treated differently by safety codes and standards than flammability groups 2 and 3. Timelines for introduction of safety group A2L refrigerants will vary by country, driven by changes to building and safety codes and standards, and local government regulations. ISO 5149 (ISO, 2014) has provisions for use of group 2L refrigerants. ASHRAE 15 (ASHRAE 15, 2016) and EN 378 (EN, 2016 b) is currently proposing new rules. They are in the public review process and subject to change.

Several limitations for refrigerant selection, unique to chillers, are important to note. A limitation on the application of blended, non-azeotropic refrigerants exists in large chillers where flooded evaporators and shell-and-tube condensers are commonly used. “Glide” in heat exchangers is a change in refrigerant temperature at constant pressure during evaporation or condensation. Flooded evaporators are essentially isothermal and isobaric, so the "glide" tendency is exhibited as a composition change between the liquid and vapour phases in the evaporator. Glide also occurs during condensation. Glide can be at least partially accommodated in the traditional cross-flow air-side condenser heat exchangers of air-cooled chillers. Refrigerants with little or no temperature glide (1 K or less) are required for use in shell and tube heat exchangers with refrigerant on the shell side. Refrigerants with temperature glides up to around 5.6 K can be used in direct expansion systems (e.g. those chillers using coils or brazed plate heat exchangers), but designs must be modified to account for glide which otherwise may handicap chiller efficiency and tends to increase heat exchanger size. Zeotropic refrigerants with glide also require special consideration of service practices that avoid composition changes resulting from separation and differential leakage of blend components.

Other unique refrigerant parameters that chiller designers must take into account in choosing a refrigerant include heat transfer coefficients especially in large pool boiling evaporators and compressor discharge temperatures, particularly at low suction temperature or high ambient conditions. Heat recovery and heat pumping applications for chillers are increasing. A refrigerant's performance in these higher-temperature conditions will be important for these applications. Another consideration is operating pressure level and the related need for pressure vessel code redesign

Unlike small systems that predominately use coils, refrigerant cost is an additional important factor. Centrifugal chillers of an average size (e.g., 1400 kW) hold a refrigerant charge of the order of 500 kg. Refrigerant cost may be affected favourably by increased production volumes stemming due to higher use in new chillers, retrofits or other applications.

9.3.3 Energy efficiency considerations

As noted previously in this report, in order to be acceptable, new refrigerants should result in products with energy efficiencies that are equal to or better than the refrigerants replaced. There are two major reasons. First, chillers are a major user of energy and customer demand for higher performance is ever-present due to the cost of energy. Additionally, there is pressure for higher efficiency products in most regions, including the Middle East, the Asia Pacific Region and many Article 5 countries, stemming from energy standards and government regulation. One example is ASHRAE 90.1-2016, "Energy Standard for Buildings Except Low-Rise Residential Buildings" (ASHRAE 90.1, 2016) widely used by building codes and regulations in the US. Secondly, there is a realization that global warming effect from chillers is dominated by their energy consumption over the life of the product. Total Equivalent Warming Impact (TEWI), Life Cycle Climate Performance (LCCP), and Life-Cycle Warming Impact (LCWI) models typically show that more than 95% of the climate effect is due to energy consumption, not direct emissions (Calm, 2006). As noted in the 2014 report, the direct global warming effects from refrigerant emissions are much smaller since direct emissions have been significantly reduced in recent years through lower charge systems, low-leak designs, manufacturing and testing improvements, and improved service practices. The use of higher performing refrigerants and the chillers that use them is more important to climate change than prematurely changing to another refrigerant with lower efficiency (Calm, 2002, Calm 2006). Additionally, the direct global warming impact from refrigerant emissions are significantly smaller today than 10 years ago, as manufacturers have been reducing direct emissions through low-leak designs coupled with manufacturing and testing improvements, and chillers requiring less refrigerant per unit of capacity.

Customers can make confident, intelligent choices when efficiency alternatives are explored, considering 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 2015) and EN 14825 (EN, 2016 a) are among the rating standards in use 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 and test standard. 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 modeling can provide systems and chiller solutions that minimize total energy consumption. Arguably the tools available to the customer to insure what is purchased matches what is delivered is more extensive that with other air conditioning products. 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.

Several items seem to be frequently overlooked in the discussion of energy efficiency. First, chiller application, piping, unloading and staging controls will dramatically decrease the overall energy consumption of the installation. Accordingly, it 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 great array of choices especially for large, multiple chiller systems, and a direct comparison of these systems involves extensive computer modelling. Though large multiple chiller application and control strategies are frequently the subject of various technical articles, it is not clear how to stimulate further use of them. For small systems such investigations are typically cost prohibitive.

A comparison of the choice of air cooled vs. water cooled chillers and the energy consumption of the system is an interesting problem. Generally, water cooled chillers are typically more energy efficient than air cooled chillers for any geographic location (Sharma, 2017), notably so in larger capacities. However, since air cooled chillers are the dominant chiller type globally, factors other than energy efficiency may drive the choice to 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.

Another overlooked item 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. This in turn reduces the overall energy consumption of an installation.

The previous discussion concerns the emergence of higher performing chillers and chiller systems through normal market dynamics. However, government regulation stimulates the market place by requiring certain minimum efficiencies for various chiller products. This increases the efficiency requirements for lower performing machines and ultimately eliminates them from the market. It is important to realise that such regulations run in a completely separate channel than do regulations concerning refrigerant changes. So both of these events can occur independently and represent significant challenges to equipment manufacturers, who must run R&D programs in parallel, causing a competition for resources. In fact, mandatory refrigerant changes can retard implementation of efficiency changes and therefore have a negative environmental impact.

An important example of this is the European Commission Regulation (EU) 2016/2281. This regulation establishes minimum energy efficiency requirements for chillers used for process cooling and comfort cooling for the European Union countries. Important aspects of the regulation related to the comfort cooling application of chillers are as follows:

1. All performance for comfort cooling is measured in terms of Seasonal Space Cooling Energy Efficiency (SSCEE), a new metric which reflects both full and part load performance and standby energy consumption.
2. Tier 1 requirements take effect in 2018, and Tier 2 take effect in 2021. Tier 2 requires higher SSCEE for all sizes of chillers of approximately 2% to 12%. Clearly the regulation is designed to make efficiency improvements mandatory over time.
3. Any refrigerant change stemming from other government regulations or market dynamics, must be accomplished, while still complying with the efficiency regulations of (EU)

2016/2281. Again, energy efficiency regulations and refrigerant regulations are completely separate.

Other methods used to describe the environmental effects of chiller operation are Total Equivalent Warming Impact (TEWI) or Life Cycle Climate Performance (LCCP) and Life-Cycle Warming Impact (LCWI). These methods are defined in Chapter 2, *Refrigerants*, and further discussed in Chapter 11, *Sustainable Refrigeration*.

9.3.4 Non-fluorinated refrigerants

There is no 'perfect' or universal refrigerant (Calm and Didion, 1997). Each refrigerant has characteristics that must be dealt with to be successfully sold in a competitive product. Products using non-fluorinated refrigerants with near zero GWP have gained momentum in the market place, notably in Europe, even as the use of new low GWP refrigerants is emerging.

- *R-717 (Ammonia)*

Chillers employing R-717 as a refrigerant have been available for decades in positive displacement compressor systems, and are used in industrial and central chiller plant systems. There are a number of installations in Europe, the Middle East, China, and the US. R-717 chillers are available with open drive screw compressors in the capacity range 100-7000 kW. Chillers with open drive reciprocating compressors are available in the capacity range 20-1600 kW. R-717 is classified as safety group B2L. It is both toxic and flammable, so safety considerations must be addressed for any installation.

R-717 chillers are manufactured in small quantities compared to ~~HFC~~ chillers using fluorochemical refrigerants of similar capacity. Different materials of construction are used because R-717 causes rapid corrosion of copper, the most widely used material for heat exchanger surfaces in chillers using fluorochemical refrigerants. Plate-and-frame steel heat exchangers are common in R-717 systems.

R-717 is better suited to water-cooled chillers because of higher costs of air-cooled R-717 condenser coils. Information on R-717 chiller applications in building air conditioning is given in (Pearson, 2008a; Pearson, 2008b) and in (Pearson, 2012). R-717 is not a suitable refrigerant for centrifugal chillers because it requires four or more compressor stages to produce the pressure rise ("lift" or "head") required.

If the use of R-717 refrigerant in chillers is to expand in the capacity range served by positive displacement compressors, particularly outside Europe, several impediments must be addressed:

- R-717 chiller costs typically are higher than for HCFC and HFC chillers.
- Safety concerns with R-717 in comfort cooling applications can increase installation costs. Building codes in some countries heavily restrict applications.

None-the-less, the market for R-717 chillers is accepted in regions where concerns about the control of high-GWP refrigerants are strong and safety considerations are addressed.

- *HC 290 (Propane)*

Propane and other hydrocarbon refrigerants are highly flammable and classified group A3. A discussion of safety aspects is given in the Annex to Chapter 2. Simply put, the use of highly flammable refrigerants in *an indoor space* poses significant safety issues that must be dealt with. However, chillers employing hydrocarbons as a refrigerant have been available and successfully applied in *outdoor locations* for many years, though typically only in small capacities (up to 200 kW) per refrigerant circuit. HC-290 is used in chillers in air conditioning and industrial applications. HC-290 and another hydrocarbon, HC-1270, are used in a limited number of small (<1200 kW) air-cooled chiller installations in Denmark, Norway, the United Kingdom, Germany, Ireland, the USA, and New Zealand. Some Article 5 countries such as Indonesia, Malaysia, and the Philippines are applying hydrocarbon chillers to large space cooling needs. The current market for hydrocarbon chillers (in outdoor air cooled installations) is larger than for R-717 chillers (in indoor water cooled installations) on a global basis but still very small compared to the market for HCFC-22 and HFC chillers.

HC-290 and HC-1270 have thermodynamic properties similar to those of HCFC-22 and are compatible with mineral oil lubricants typically used with this refrigerant. This allows their use in new equipment of current design after appropriate adjustments for safety aspects. Chillers employing hydrocarbon refrigerants are somewhat higher in cost than HFC chillers due to safety considerations, though modification of equipment originally designed for HCFC-22 is straightforward.

All safety codes impose strict requirements on hydrocarbons in large refrigerant charges in chillers, particularly for indoor chiller installations in machinery rooms. Accordingly, hydrocarbon chillers have not been adopted in all regions. In regions supporting hydrocarbon solutions the safety concerns have been addressed by engineering design, technician training, and changes in building codes and safety standards. If experience is successful, the use of hydrocarbon chillers may grow in the future. However, in countries such as the USA and Canada, regulations, building codes, and legal environments make it unlikely that hydrocarbons will be used in commercial chillers in the foreseeable future, apart from small capacity chillers located outdoors.

Hydrocarbon refrigerants are in limited use in centrifugal chillers in petrochemical plants where a variety of very hazardous materials are routinely used and the staff is highly trained in safety measures and emergency response (see Chapter 5). Hydrocarbon refrigerants have not been used in centrifugal chillers for air conditioning due to safety code restrictions, and safety concerns with large charges of flammable refrigerants, liability, and insurance issues.

- *R-744 (Carbon Dioxide)*

R-744 air-cooled chillers have been introduced in the northern European market. Both air- and water-cooled gas cooler versions are available, albeit at higher costs than chillers using conventional refrigerants. The higher operating pressure of carbon dioxide accounts for much of the difference. Models with cooling capacities from 40 to 500 kW are offered. In climates where the dominant cooling requirement is at an average ambient temperature of 15^0C or less, these systems can be equivalent in energy efficiency and LCCP with systems employing HFCs, R-717, or HCs. R-744 chillers are less attractive at higher ambient temperatures due to decreasing efficiency.

Where heat recovery to generate hot water at temperatures of 60 ^{0}C or higher can be employed in a total energy strategy for a building, R-744 chillers offer the advantage of being able to use waste heat to raise water to higher temperatures with higher efficiency than other refrigerants. Chilled water can be used to sub-cool the refrigerant before expansion. For this application, R-744 heat recovery chillers provide good efficiency.

- *R-718 (Water)*

The use of water as a refrigerant poses significant technical and economic barriers, though there are some limited applications in desalination plants, deep mines, and ice and snow making. The very low pressures, high compression ratios, and high volumetric flow rates required in water vapour compression systems require high volumetric flow axial compressor designs that are uncommon in the chiller field. However, several research projects remain active and developmental companies have moved towards commercialization. A product was announced in 2014 and again in 2015 using water as the refrigerant and additional product development has followed. Applications for water as a refrigerant can chill water or produce an ice slurry by direct evaporation from a pool of water. R-718 systems carry a cost premium above conventional systems. The higher costs are inherent and are associated with the large physical size of water vapour chillers and the complexity of the compressor technology, which includes both axial and multi-stage centrifugal compressors. Several developmental chillers and commercial vacuum ice makers have been demonstrated in Europe, the Middle East, and South Africa including deep mine refrigeration (Jahn, 1996), (Ophir, 2008), (Sheer, 2001), (Calm, 2011). They also are used in desalination plants (Calm, 2006) and-ice making.

9.4 Options for existing chiller equipment

The preceding sections cover the options for new chillers, and gives a view of the changes that are occurring in chiller markets. Chillers that are already installed and employ CFCs, HCFCs, and HFCs have to be supported in one of the following ways

Retain/Contain: continued operation with stocked and/or reclaimed inventories in conjunction with containment procedures and equipment modifications to reduce emissions.

Retrofit: modification to allow operation with alternative refrigerants (lower GWP HFCs where permitted) depending on applicable regulations.

Replace: early retirement/replacement with new chillers (preferably having higher efficiency which reduces energy-related climate impact) using allowed refrigerants or not-in-kind alternatives,

The retrofit options depend on the specific refrigerant for which the chiller was originally designed. When any retrofit is performed, it is recommended that the machinery room be upgraded to the requirements of the latest edition of safety standards such as ASHRAE 15 (ASHRAE a, 2016), and EN 378 (EN, 2016 b) or international standards such as ISO 5149 (ISO, 2014). It is also recommended that the manufacturers of the equipment be consulted in any retrofit program.

Retrofit of chillers that use a non-flammable refrigerant with a flammable refrigerant is especially problematic, if not unlikely, especially if the chiller is located indoors. Substantial modifications to the equipment and to the machinery room would be needed. For example, the pressure vessels and piping codes, such as the Pressure Equipment Directive (PED) in Europe, places additional requirements on the equipment design, materials, construction and inspection. Machinery rooms must be modified to deal with the potential of large charges of a flammable refrigerant as per the local building codes. These issues add significant cost and clouds the economic feasibility of a retrofit. Therefore non- flammable alternatives are highly desired for retrofits.

9.4.1 Positive displacement chillers

A positive displacement compressor inherently can be applied to handle a number of different refrigerants and pressure ratios in a chiller if its motor has adequate power, the compressor, tubing, heat exchangers, and other components can meet pressure codes and regulations with the refrigerants, and the system materials and lubricant are compatible with the refrigerants. Despite this flexibility, there remain a number of issues in retrofitting positive displacement chillers to operate with new refrigerants. These issues were discussed in the 2014 RTOC Assessment Report.

However, larger capacity screw compressor installations can represent a large capital investment for the owner. So despite the potential technical difficulties, several manufactures are offering retrofit programs that replace HFC-134a in some screw compressor products using a lower GWP refrigerant, namely R-450A or R-513A.

9.4.2 Centrifugal/axial turbo chillers

Centrifugal and axial-turbo compressors by nature 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 easily. In the past this has been accomplished by gear changes in open drive chillers and with variable speed drives in both open and hermetic compressor chillers. The compressor surge margin must be checked using the properties of the substitute refrigerant.

However, centrifugal and axial-turbo chiller installations can represent a very large capital investment for the owner. So despite the possible technical difficulties, several manufacturers are offering chiller retrofits using a lower GWP refrigerants, namely R-450A, R-513A and R-514A.

9.5 Concluding remarks

- Chillers using low GWP refrigerants have been commercialised and are emerging in the market. This comes after years of research and screening of alternative refrigerant candidates. It is expected that the transition to low GWP refrigerants will take some years owing to the high investment and the large product development effort to convert the huge array of product types and sizes. It is also noted that non-fluorinated refrigerants are available in some chiller types, albeit in select sizes, rather than broad, complete product lines.
- The refrigerants that are being commercialised may not be the final choices. Chemical producers and chiller manufacturers will continue to focus their efforts on refrigerant candidates that provide energy efficiencies that are equal to or better than the refrigerants being replaced and reduce product development cost and time.
- Global warming effects from chillers are dominated by their energy use during their operating life, rather than direct emissions. The direct global warming impact from refrigerant emissions are minimal, because emissions have been significantly reduced in recent years through lower charge systems, low-leak designs, manufacturing and testing improvements, and improved service practices.
- Customers and regulators alike are interested in less energy consumption, which results in lower climate impact. There continues to be consumer and regulatory pressure to improve full and part load or seasonal energy consumption which will have a positive climate impact. Various application and control strategies exist, especially those involving larger multiple chillers. Since chillers are a major user of energy, the additional benefits of lower energy cost, and potentially lower power production and transmission infrastructure are also noteworthy.

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Chapter 10

Vehicle Air Conditioning

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10 Vehicle air conditioning

10.1 Introduction

Road vehicles (i.e., cars, trucks, and buses)[10] built before the mid-1990's mostly used CFC-12 as the refrigerant with some HCFC-22 use in buses in a vapour compression cycle. From that period onwards the evolution is characterised by legal constraints and regulations. Since then and until recently, in response to the Montreal Protocol's phase-out of controlled substances with significant Ozone Depletion Potential (ODP)[2], new vehicles with air conditioning (AC) have been equipped with systems using HFC-134a, with the use of some R-407C in buses.

By the year 2000, the transition from CFC-12 to HFC-134a as an Original Equipment Manufacturer (OEM) refrigerant, for factory installed AC systems, was complete in all non-Article 5 countries. The transition to HFC-134a in Article 5 countries was completed around 2007. In addition, since the mid-1990's, development and deployment of refrigerant alternatives have been underway due to replace HFC-134a because of its high Global Warming Potential (GWP)[11]. Today, nearly all light duty vehicles in Europe and a significant portion in the United States and some other countries are delivered with HFO-1234yf mobile air conditioners (MACs). In addition, as of the year 2017, two German OEMs have started to deliver some of their premium models with R-744 (carbon dioxide) equipped MACs.

This chapter covers the new developments since the RTOC 2014 Assessment Report including the evolution related to the vehicle electrification (e.g., the adoption of the heat pump mode). Details on system design and history of refrigerant system development are included in preceding RTOC reports.

Even though railway (train) air conditioning falls within mobile mass transit because of the similarity of technology, this sector is covered in Chapter 6 (Transport Refrigeration)

10.2 Types of equipment and future trends

Light duty vehicles use from 0.3 kg to 1.4 kg refrigerant charge, while for buses the charge could be from 8 kg up to 16 kg as a function of the vehicle category (e.g. simple bus, articulated bus). Currently there are approximately 1,000 ktonnes of refrigerant in vehicles considering that there are about 1.3 billion road vehicles circulating (see https://www.statista.com/statistics/281134/number-of-vehicles-in-use-worldwide/).
Estimating that 75% of circulating vehicles are equipped with MAC, and assuming a yearly renewal rate of 8% (e.g. 100 million units approx.), the refrigerant demand (excluding service) is about 75 ktonnes/year.

After the switch from CFCs to HFCs in the mid-1990's, HFC-134a has been the refrigerant of choice for new equipment as well for retrofits worldwide. In the mid-1990's the evaluation of lower GWP refrigerant started, as an alternative to HFC-134a. Several synthetic and natural working fluids (e.g. R-744, R-290) have been evaluated and at the end HFO-1234yf has been identified as the preferred candidate by most OEMs because it is almost a drop-in solution in spite of its flammability.

[10] Trains applications are covered in Chapter 6

[11] Ozone depletion potential (ODP) and Global Warming Potential (GWP) of the refrigerants here are given in chapter 2 of this report.

In 2013 OEMs started the transition to lower GWP refrigerants that was forced or accelerated by the European and U.S. EPA regulations.

Meanwhile, MAC systems tightness has improved mainly in Europe, US and Japan, adopting new hose materials and technologies and more effective coupling designs as well as the energy efficiency has increased thanks to the development of heat exchangers, compressors, and control strategies. In US the peak age for vehicle service increased in recent years.

There is the opportunity to further deploying these technologies beyond the above-mentioned countries.

This evolution has been, once again, driven mainly by regulations (US light-duty vehicle regulations, European MAC Directive, Japanese regulatory prohibitions) and supported by non-regulatory initiatives (e.g. the "Improved Mobile Air Conditioning " (I-MAC), SAE Cooperative Research Program (CRP)) as well as four SAE 1234yf CRPs and the SAE Interior Climate Control Committee).

The refrigerant replacement opened the door for counterfeiting that started to become an issue after the 1987 Montreal Protocol and the 1997 Kyoto Protocol. This was due to the higher cost associated with new and more environmentally friendly refrigerants than the ones they are replacing (Velders, 2009). Hence, counterfeited HFC-134a is infiltrating the refrigerant bank, particularly in Asia, but also affecting other countries.

Currently, even though the cost of HFC-134a is low, i.e. 5 US$/lb or 11 US$/kg (or even less), counterfeit HFC-134a is still appearing in the automotive market. Counterfeit HFC-134a is containing multiple chlorofluorocarbons and hydrofluorocarbons, among which there are toxic or corrosive components, and is a serious threat because it destroys equipment and injures end-users. It also has an increasing opportunity to enter the supply chain. The issue is even more relevant in countries where the refrigerant supply is less regulated (Coll, 2012).

This issue is expected to become even more relevant as HFC-134a is partially being replaced by the more expensive HFO-1234yf. In 2013 the commercial price of HFO-1234yf (Weissler, 2013) was estimated at US$ 40-45/lb or US$ 88-99/kg (retail prices are usually 2 to 3 times higher). Cost and availability are crucial issues that have to be considered in identifying replacement(s) for HFC-134a, currently widely adopted in car air conditioning systems.

10.2.1 Regional regulations and influencing factors

The regulations for reducing the global warming (often climate change) are becoming more stringent in every domain, globally. In the automotive field, this trend is strongly influencing the vehicle design by promoting the electrification of the drivetrain as well as the on board thermal system and the heating and air conditioning system.

Europe

In the European Union the F-Gas regulation (EU 517/2014) is in force, establishing rules on the use of fluorinated greenhouse gases and quantitative limits for the placing on the market of hydrofluorocarbons, and the MAC directive (EU 2006/40/EC), prohibiting the use of fluorinated greenhouse gases with a global warming potential higher than 150.

In addition, the European Commission will include the Air Conditioning system efficiency improvement (EUCOM, 2017) in the list of technologies/functions eligible for the Eco-Innovation scheme in the next CO_2 reduction regulation framework for light duty vehicles, in this way opening the door for a further technology evolution.

The current scenario shows that almost 100% of sold passenger cars primarily use HFO-1234yf and in some cases R-744 (which are the two relevant alternatives), while for light commercial vehicles, heavy duty trucks and buses HFC-134a is still the primary option used.

U.S.A.

The U.S. EPA GHG regulations (USEPA, 2012b) for light-duty passenger vehicles establish credits for using refrigerants with a GWP lower than 1430 and for tighter systems and includes measures to grant CO_2 credits for MAC systems adopting more efficient components. For commercial trucks and buses, regulations require tighter air conditioning systems but do not mandate or offer credits for lower-GWP refrigerants (USEPA, 2017a). The fuel-efficiency (miles/gallon, liters/100 km) and total emission (g CO_2eq./mile, g CO_2 eq./km) reduction regulations steer towards more efficient on-board systems including MACs and towards the containment of high GWP fluids and/or their replacements with lower GWP substances.

Japan

Japanese regulatory prohibitions require the weighted average GWP target for MAC refrigerants to be designed at 150 or less by 2023 (METI), which drives the replacement to low GWP refrigerants in vehicles. In the Japan domestic market, currently nearly 100% of all sold vehicles is equipped with HFC-134a, while for a few and for exported vehicles to the USA or Europe, HFO-1234yf is the primary choice.

China

China has not updated any new regulations regarding the future application of refrigerants in vehicles. In the present Chinese regulations, HFC-134a is the only refrigerant recommended for vehicles. The current scenario shows that almost 100% of the sold vehicles is equipped with HFC-134a, while for some newly developed electric vehicles, R-410A has been adopted as the refrigerant for the heat pump system.

Other countries

Other countries, such as Korea, do not have any official publications regarding an HFC phase-out in MACs and still use HFC-134a in all vehicles sold.

10.2.2 Light duty vehicles and electrification aspects

Usually a vapour compression cycle in combination with a ventilation system is adopted to provide the passenger compartment cooling. The system also includes a coolant circuit and heat exchanger to use the waste heat of the engine to heat the cabin. The combination of cooling and heating functions ensures the dehumidification of the air that improves the fogging prevention function. The worldwide regulation to reduce GHG emission is driving towards an increase of vehicle electrification (e.g. the European Union is on its way to fully de-carbonize the light duty vehicles) that will impact the MAC design and requirements.

Conventional internal combustion engine (ICE)

The MAC system is based on a mechanical, belt-driven compressor, while engine waste-heat is directed into the passenger compartment for comfort and safety (i.e. de-icing and de-fogging) purposes. In highly-efficient and hence low heat generating vehicles, and for operations in very cold ambient conditions, additional heat is typically provided by electric-resistance e.g. Positive Temperature Coefficient (PTC) heaters. Such additional heat systems come at a low capital cost but are not very efficient.

Hybrid Electric Vehicle (HEV)

The Hybrid Electric Vehicle applies both a combustion engine and an electric motor, used to recuperate the kinetic energy of the vehicle which is stored in a battery. The electric motor is also used to support the conventional engine and to enable the vehicle to travel short distances in a pure electric mode. These vehicles usually adopt an electric hermetic compressor while the rest of the system remains unchanged.

Plug-in Hybrid Electric Vehicle (PHEV)

The Plug-in Hybrid Electric Vehicle usually has larger batteries that can be charged while connecting the vehicle to the electric power network (plug-in), in this way enabling the vehicle to drive longer distances (e.g. 50 km) in a pure electric mode. The MAC system is based on an electric compressor and is usually used also to thermally control the battery especially during charge phases, although, in some instances, two separate systems may be employed. The system loop 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. The refrigerant charge of such a system is usually about 30% to 50% higher than that of a conventional system. The cabin heating is ensured by the engine waste heat or, when operated in a pure electric mode, by an electric heater or a heat pump. The heating and air conditioning function may substantially affect the pure electric driving range reducing it by up to 50% (Denso, 2017, Koehler, 2018; Westerloh, 2019).

Battery Electric Vehicles (BEV)

The Battery Electric Vehicles MAC system is very similar to the system adopted for PHEV with the exception that there is a very low amount of waste heat produced. To overcome this fact, a larger electric heater was used in the past. For newer BEVs, the MAC system is usually designed to also include the heat pump function. On such a vehicle, the heating and air conditioning functions are even more relevant in determining the “real world” driving range that can be reduced by up to 40% here (Denso, 2017, Koehler, 2018; Westerloh, 2019).

Similar to PHEVs the MAC system loop integrates a chiller (refrigerant to coolant) or a direct expansion evaporator, integrated in the battery pack to enable the battery cooling. The refrigerant charge is usually about 30% to 50% higher than the one used in a conventional system, due to use of technology selected to cool the battery (indirect or direct expansion). Dual loop systems (with liquid cooled condensers and liquid heated evaporators) can be adopted to reduce the refrigerant charge and enable higher flexibility, lowering the risk of dispersion in case of an accident. To date, secondary loop systems have started to be applied on some premium cars additionally to the pure presentation as a viable technology option (see e.g., Menken, 2016).

Heavy-duty trucks

The heavy-duty trucks adopt a main system that is based on the same concept as used in light duty vehicles, albeit with a slightly higher refrigerant charge, due to the longer distance between the compressor and the cabin. To ensure comfort when the truck is parked, an auxiliary air conditioning system is very often adopted. This system is usually quite similar to domestic air conditioning systems with an external condenser, an internal cooling and ventilation unit as well as an auxiliary electric compressor. At present, heavy-duty truck MAC systems rely on HFC-134a, although HFO-1234yf is allowed for some truck classes (see e.g., USEPA, 2016a).

Buses and coaches

Buses and coaches are mass transit vehicles with air-conditioning systems that are larger in size with a higher cooling capacity and larger refrigerant charges than passenger cars. They also operate over a wide range of ambient temperatures, from -30ºC to 50ºC. These systems are typically packaged type roof or rear mounted units with a compressor belt driven by the vehicle engine. The predominant refrigerant is HFC-134a with R-407C for high ambient temperature applications in some instances (ASHRAE, 2015), while R-744 has also been introduced in small volumes in Europe (Sonnekalb, 2017). Typical refrigerant charge sizes were around 10 kg in the past, which amount has been reduced by 50% and more in recent years, due to the implementation of microchannel condensers.

10.3 Options for existing systems

10.3.1 Retrofit of CFC-12 systems

There are 13 blend refrigerants that are approved by the USEPA under the SNAP regulation for the retrofit of CFC-12 systems (USEPA, 2015a); however, many of these have only seen minimal use and some were never fully commercialised. The retrofit to HFC-134a was approved by the OEMs; it was applied more often if a retrofit was deemed to be required. The result of a 2013 MAC survey was that about 6% of all cars were still operated using CFC-12 and that about 10% of all cars had been retrofitted to R-134a (Atkinson, 2014). However, the retrofit of CFC-12 vehicles has decreased significantly, primarily due to the declining fleet of vehicles equipped with CFC-12 MACs and partly due to the continued availability of reclaimed CFC-12. In the USA, the sale of CFC-12 and many of the aforementioned blends is restricted to certified technicians only. The USEPA has proposed similar restrictions for HFC-134a and blends containing hydrofluorocarbons, with an exception for small cans (two pounds [0.9 kg] or less) of refrigerant intended to service MACs, as long as the cans are equipped with a self-sealing valve (USEPA, 2015b). However, the USEPA has indicated they will revisit these rules and hence changes can be expected in future (USEPA, 2017a).

10.3.2 Hydrocarbon retrofits

Retrofit of HFC-134a and CFC-12 systems to hydrocarbons is still occurring in various regions, particularly in Australia and to some extent in North America, even though vehicle OEMs and some regulatory bodies do not approve this process due to inadequate risk mitigation.

10.4 Options for new and future mobile air conditioning systems

As already mentioned in the introduction, this report concentrates on vapour compression refrigeration cycle technology for vehicle air conditioning.

10.4.1 Improved HFC-134a systems

Efficiency-improving technologies are now being used: e.g., an Internal Heat Exchanger (IHX), oil separators in compressors, as well as externally controlled compressors.

10.4.2 HFO-1234yf systems

As of January 2017, owing to the MAC Directive in Europe, in almost 100% of new passenger cars the low GWP refrigerant HFO-1234yf is applied, while in the US the current rate of adoption of HFO-1234yf is larger than 20%. Due to the lack of restrictions or incentives given by legislation, the adoption rate of HFO-1234yf is lower in the rest of the world (China, India, Japan). HFO-1234yf is designated as an A2L refrigerant, meaning that it is flammable under prescribed testing conditions, however, it exhibits a lower burning velocity than other flammable refrigerants designated as class 2 or 3 flammability refrigerants (ASHRAE, 2013). The flammability potential led to high scrutiny surrounding the safe use of the refrigerant and possible ways to mitigate any risks (USEPA, 2011a).

The US EPA has studied the potential use of HFO-1234yf as a MAC refrigerant under the US Clean Air Act's Significant New Alternatives Policy (SNAP) Program and has SNAP-listed HFO-1234yf as an acceptable refrigerant under certain use conditions (USEPA, 2011a). The HFO-1234yf MAC systems must meet the requirements of the 2011 SAE J639 standard version and manufacturers have to conduct and keep records of a risk assessment and Failure Mode and Effects Analysis according to the SAE J1739 standard for at least three years from the date of creation. Further requirements outside the US are based on ISO 13043:2011.

HFO-1234yf systems either need an IHX or a condenser with a 10% larger degree of sub-cooling (Zilio, 2009) in order to achieve the same performance as HFC-134a and a slightly larger charge of HFO-1234yf (up to 10%).

The effects of the HFO-1234yf decomposition are covered in Chapter 11.5.

In October 2017, the European Commission closed its antitrust investigation concerning the cooperation between two companies, owing to the HFO-1234yf patents. On 21 October 2014, the Commission adopted a Statement of Objections against those Companies voicing its preliminary concerns that they may have limited the product's availability and technical development. The closure decision has been taken after careful assessment of all the evidence in this case, together with the various submissions of the parties and other interested third parties. Furthermore, the complaints were withdrawn. The Commission will continue to monitor closely the whole chemicals market, including the HFO-1234yf refrigerant.

10.4.3 Carbon dioxide (R-744) systems

With appropriate system design and control, R-744 systems have been shown to be comparable to HFC-134a systems with respect to cooling performance and total equivalent CO_2 emissions from MAC systems, and they qualify for use in the EU under the current regulation (see e.g., Strupp, 2011). As of the year 2017, two German OEMs have started to equip some of their premium models with R-744 MAC systems (Daimler Press Release, 2015; Jung, 2017). The US EPA has studied the potential use of R-744 as a refrigerant and has SNAP-listed R-744 as an acceptable refrigerant under certain use conditions (USEPA, 2012a).

R-744 heat pumps are especially interesting as cooling and heating systems for application in particularly hybrid and battery driven electric vehicles. In comparison to electric resistance heaters (PTC heaters), R-744 heat pumps operate at a substantial higher level of efficiency (Steiner, 2014, Koehler, 2018, Westerloh, 2019).

10.4.4 Other refrigerants

HFC-152a

HFC-152a was suggested as an alternative to HFC-134a in MACs, however, because of its flammability, it requires additional safety systems. Most development activity has been focused on the use of this refrigerant in a secondary loop system or possibly in a double secondary loop system (i.e., both an evaporator and a condenser loop, usually defined as a dual loop system). To date, nothing is known about the adoption of HFC-152a for use in MAC systems (Lemke, 2014; Malvicino, 2012; Leighton, 2014).

At present, one car manufacturer has expressed interest in the adoption of HFC-152a as refrigerant with a secondary (evaporator) loop system for the Indian market (Andersen, 2013, 2018). The US EPA studied the potential use of HFC-152a as a refrigerant under the US Clean Air Act's Significant New Alternatives Policy (SNAP) Program and has SNAP-listed HFC-152a as an acceptable refrigerant under certain use conditions (USEPA, 2008).

Blends containing unsaturated fluorinated hydrocarbons

Some zeotropic blends with R-1234ze(E) were considered as possible candidates in vehicle air conditioning systems by many researchers (see for example, Schulze, 2015). Two mildly flammable A2L blends, R-444A and R-445A, were introduced by a large chemical company, and some application studies were conducted. However, even though the two blends are equivalent to HFO-1234yf with respect to flammability and performance, they have a high temperature glide which poses additional challenges in servicing. Therefore, these blends have not received any further interest and have not been introduced in MAC systems.

Hydrocarbons and blends containing hydrocarbons

In Australia and the USA, hydrocarbon blends, sold under various trade names, have been used as refrigerants to replace CFC-12 and to a lesser extent HFC-134a. Retrofits with HCs are legal in some Australian states, however, illegal in others, and in the USA. The US EPA has forbidden the use of HCs for retrofit. The use of HCs for new MAC systems could in principle be possible but requires proof that safety issues have been mitigated (USEPA, 1994). HCs or HC-blends, when correctly chosen, present suitable thermodynamic properties for the vapour compression cycle and allow achieving high energy efficiencies. Similar to HFC-152a, HCs would most likely be employed in indirect (secondary loop) systems only. Nevertheless, even with the use of indirect systems, the vast majority of vehicle manufacturers does not consider HCs as replacement fluids for mass-produced MAC systems due to safety concerns.

10.4.5 Bus air conditioning

Mass transit vehicles include buses and coaches (discussed in this chapter) and rail cars (discussed in Chapter 6). As compared to passenger cars, their air conditioning systems are larger in size, have a higher cooling capacity, and generally use modified commercial components. Usually, they are specifically packaged for each application.

The mass transit vehicle fleet is smaller than that of passenger cars. Available statistical data for Europe show that, per 1000 inhabitants, there are approximately 1.6 buses and coaches, and 477 passenger cars (Statistical Handbook, 2012). The number is assumed to be different elsewhere (in the North America and Japan, there are more passenger cars per person and less mass transit vehicles per person; in many developing countries it is the reverse). It can be assumed that, on average, at least 50% of the current EU mass transit vehicle fleet is air-conditioned. Both climate and economic conditions would determine the likelihood of air conditioning in transit vehicles in other regions. At present, most buses and coaches have the entire air-conditioning system mounted on the roof, except for the compressor, which is driven by the vehicle engine. Bus MAC systems may also be self-contained and electrically powered. The self-contained concept reduces both the charge and the leakage rate.

The predominant refrigerant used in new buses and coaches is HFC-134a, although R-407C has also been employed and may constitute a significant portion of the market in some regions. Several years ago the refrigerant charge used to be in excess of 10 kg per unit (Schwarz, 2007), however, the introduction of microchannel condensers as well as component downsizing has reduced the current refrigerant charge to less than 5 kg in some new systems.

In China, heat pump systems are used for thousands of electric buses, which exclusively use R-410A. Older systems in Article 5 countries still utilize HCFC-22. According to the European statistics, the average age of a European bus or coach is 16.5 years, indicating that the stock of HCFC-22 MAC systems in buses is likely to remain for decades to come. Although limited by the volumes, the mass transit vehicle industry closely follows the developments in passenger cars and other fields. Since 2003, a large German manufacturer has on-going fleet tests of R-744 systems in buses (see e.g., Eberwein, 2011, Schirra, 2011, and Sonnekalb, 2012). In the year 2012, a

Polish bus manufacturer started selling battery-driven electric buses with reversible R-744 heat pump systems for heating and cooling (Solaris, 2012).

In 2018, Daimler launched an electric city bus with a R-744 charged MAC system; the first units will be handed over by the end of 2018 (Daimler, 2018)

Environmental and fuel price concerns lead bus and coach manufacturers to pursue development of hybrid and battery driven electric vehicles. The concept makes traditional engine-driven compressors obsolete and favours self-contained hermetic systems, where the refrigerant charge and leakage rate are lower. The electric power is either supplied from on-board sources, or from engine-driven generators. These systems are not limited to electric vehicles, but can also be applied in traditional buses and coaches. Installations can be found in trolleybuses.

10.5 Energy efficiency in MAC applications

Based on average annual values, HFO-1234yf as well as R-774 systems exhibit efficiencies comparable to HFC-134a for cooling and heating (Koehler, 2018; Westerloh, 2019).

To achieve these performance levels in case of the use of HFO-1234yf, manufacturers either apply an IHX or larger degree of sub-cooling, while for R-744 appropriate system design (e.g. IHX) and controls are required (Zilio, 2009, Strupp, 2011, Koehler, 2018; Westerloh, 2019).

10.6 Concluding remarks

- Currently, more than one refrigerant is used in the car and light truck mobile air conditioning: HFC-134a remains largely adopted worldwide, while HFO-1234yf is currently the main refrigerant option in Europe and North America.
- The deployment of highly electrified vehicles (PHEV and BEV) in Europe, China and North America will lead to the implementation of a heat pump function. Manufacturers are working on the improvement of this feature by using cycle variations such as by using an economizer coupled with vapour injected compressors.
- Two German OEMs have started to apply R-744 in some of their premium models. If the cost of the R-744 system will become competitive, it may be possible that R-744 will be taken into consideration especially for highly electrified vehicles, due to its good performance when operated as a heat pump.
- For the Indian market, one car manufacturer has expressed interest in the adoption of HFC-152a.
- Other low GWP synthetic refrigerants and refrigerant blends (e.g. R-444A, R-445A) have been investigated but it is not likely that they will be used in the near future.
- In existing systems, primarily designed for CFC-12 or HFC-134a, hydrocarbons (e.g. R-290) are used in some regions (e.g., Australia).
- At the moment, it cannot be foreseen whether or not all these refrigerants will be used in parallel in the market for a long period of time. It is also unclear whether the bus sector (where currently HCFC-22, HFC-134a, R-407C or R-410A are used) and the heavy-duty truck sector will follow these trends.

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Annex to Chapter 10

Annex B: Regulatory actions affecting vehicle air conditioning and refrigerants
This annex summarizes for several, but not all, different regions the legal situation for vehicle air conditioning systems.

-Light Duty Cars and Trucks

Brazil and Latin America: No specific regulations are in place in Brazil regarding mobile air conditioning. The current most important regulation (Resolução 267_00 CONAMA) states that the current gas refrigerant has to comply with the Montreal Protocol and to have low ozone depletion potential (ODP).
The refrigerant currently used not only in Brazil but in whole Latin America is HFC-134a.

China: In China, the refrigerant in Mobile Air Conditioning (MAC) systems had been completely changed to HFC-134a since June 30, 2007. The consumption of HFC-134a in MAC in 2012 can be estimated to be about 20,000 tons. The Chinese government also realizes the importance of reducing the emission of greenhouse gas (GHG) since HFC-134a has a high GWP value. For the refrigerant in the vehicle, the work of Chinese government is mainly focused on refrigerant recovery and reducing the refrigerant charge amount since the substitute of HFC-134a is still not very clear.

Europe: European Union (EU) regulations, which control MAC system direct emissions, fall into two groups:

- controlling leaks
- phasing out high-GWP fluorinated GHGs.

Directive 2006/40/EC (EU Directive, 2006) applies to passenger cars and light commercial (categories M1 and N1) and covers both the emissions from air-conditioning systems in motor vehicles and the ban on use of refrigerants with a GWP greater than 150 in new type vehicles from January 1, 2011 and all new vehicles from January 1, 2017. Due to the shortage of the low-GWP refrigerant HFO-1234yf, which had apparently been chosen by most if not all OEMs, the European Commission decided not to enforce the Directive until the end of 2012. Although the MAC systems of new types of vehicles to be type approved had to be compatible with MAC directive 2006/40/ EC requirements, manufacturers were allowed to fill new type approved production vehicles with HFC-134a until 31 December 2012. The European Commission (EC) has confirmed several times that this situation of refrigerant shortage has been resolved to its satisfaction and therefore the MAC Directive has been in full effect since 1 January 2013. The type-approval authorities of the Member States are responsible for the monitoring of the implementation of the measures above and for verifying the conformity of production after 31 December 2012.

EU Commission Regulation (EC) No 706/2007 (EU Regulation, 2007) includes a harmonised test for measuring leakages from mobile air conditioning systems. EU Commission Directive 2007/37/EC (EU Directive 2007) limits refrigerant emissions from mobile air conditioning, using refrigerants with GWP>150, to 40 g/y for single evaporator systems and 60 g/y for dual evaporator systems beginning with new type vehicles in June 2008 and all vehicles in June 2009. The European Regulation (EC) No 443/2009 (EU Regulation 2009) sets emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicle. The Regulation limits CO_2 emissions per kilometer to 130 g CO_2/km from 2012 to 2019 and 95 g CO_2/km from 2020 onwards. The regulation includes off-cycle credit for innovative technologies reducing the fuel consumption, so-called eco-innovations (chapter 12 of the Regulation), but for mobile air conditioning systems that will be regulated by a specific procedure. The EU is currently cooperating with the stakeholders to develop this procedure.

It is possible that the Regulation will be extended to all the other motor vehicle categories once the application transient on passenger cars and light commercial vehicles is completed.

India: India has comprehensive Ozone Depleting Substances (Regulation and Control) Rules, 2000 which were put in place from July 19, 2000 under the Environment (Protection) Act 1986. These rules set the deadlines for phasing-out the ozone depleting substances. There is a mandatory requirement of registration for ozone depleting substances producers, consumers, importers, reclamation centers, destruction facilities, etc. with a designated authority. The unique feature of these rules is banning of use of Rs in manufacturing of new products and equipment including refrigeration and air-conditioning equipment for cars, busses and trains as early as January 1, 2003. This not only achieved the phase-out of chlorofluorocarbons earlier than the Montreal Protocol schedule but also reduced the inventory of R based equipment which resulted in the lowering of servicing requirements of Rs. As a consequence of ozone depleting substances rules in India all light-duty vehicle Mobile Air Conditioning manufacturing was converted to HFC-134a from January 1, 2003 and all new manufacturing capacities were put up with HFC-134a and same is continuing. The busses and trains use either HFC-134a or HCFC-22. Most of the old MAC and train air-conditioning chlorofluorocarbon-based systems were retrofitted to HFC-134a. The Ozone Depleting Substances (Regulation and Control) Rules, 2000 have been amended from time to time to align with the Montreal Protocol phase-out schedule and internal policies of the country. These rules have been amended in 2014 to align with accelerated phase-out of RRs and amendment has been notified as Ozone Depleting Substances (Regulation and Control) Amendment Rules, 2014.

Japan: In August 2009, Japanese government allowed the import of HFO-1234yf into Japan without the limitation of usage amount, aspects and any special monitoring. This decision was made after HFO-1234yf was examined by Japan’s Ministry of Health, Labor, and Welfare, Japan's Ministry of Economics Trade and Japanese Ministry of the Environment based on “Toxic Chemicals Control Law”.

USA: Motor Vehicle Air Conditioning refrigerants replacing CFC-12 must be submitted to the U.S. Environmental Protection Agency (USEPA) and found acceptable under its Significant New Alternatives Policy (SNAP) Program. So far (2014), approximately 17 different refrigerants, and 3 alternative technologies, have been found acceptable under the SNAP Program (USEPA 2013). The majority of these refrigerants were aimed primarily at the retrofit of R-12 cars and found very little, if any, use. HFC-134a was until recently the only refrigerant accepted by the OEMs and quickly became the only refrigerant used in new equipment, with a few model year 1992 vehicle types using HFC-134a and all types by model year 1995 (MACS, 2003). Three of the refrigerants found acceptable have GWPs less than 150: HFC-152a, HFO-1234yf and R-744 (CO_2). All are subject to certain use conditions (for details see the particular sections covering these refrigerants). The use conditions that apply to all substitute mobile AC refrigerants are required by the USEPA to reduce the flammability and/or toxicity risks from these refrigerants as well as to avoid mixing of different refrigerants.

Joint regulations from the USEPA and the National Highway Traffic Safety Administration set requirements for corporate average fuel economy (i.e., average miles per gallon or liters per 100 kilometers) and tailpipe emissions (i.e., grams CO_2-equivalent per mile or kilometer). Although these regulations do not require specific choice of refrigerants, utilising low-leak designs and/or low-GWP refrigerants offer additional pathways to comply partially with the requirements. In addition, credits were offered for (1) improvements in air conditioning systems that reduce tailpipe CO_2 through efficiency improvements, and (2) for reduced refrigerant leakage through better components and/or use of alternative refrigerants with lower global warming potential. These regulations were enacted first for model years 2012 through 2016. That rule allowed OEMs to achieve credits in advance of the regulations for design changes in model years 2009 through

2011, a stipulation that helped spur more leak-tight and fuel-efficient systems. The second set of regulations applies to model years 2017 through 2025. USEPA expects that the credits offered in this program will incentivize the uptake of low-GWP refrigerants; USEPA estimated that uptake of HFO-1234yf would reach 20% in model year 2017 vehicles, which appears to be approximately correct, rising linearly to 100% by model year 2021 vehicles (USEPA and NHTSA, 2012b). One U.S. OEM committed to convert some models to HFO-1234yf refrigerant by MY2013 (General Motors, 2010); one of these models has been sold in the U.S. and elsewhere since 2012. A Japanese OEM also offered one MY2013 model with HFO-1234yf, and other models were introduced in MY2014 designs (Automotive News, 2013). Atkinson, 2014 provides a list of 9 car types which use HFO-1234yf in the US market. Since then, several other models using HFO-1234yf have been introduced, and some of these are being sold in foreign markets as well (Automotive News, 2013; Mobile Air Conditioning Society (MACS) Worldwide, 2017).

In June, 2013, U.S. President Obama announced a Climate Change Action Plan. Amongst other initiatives, the President committed the USEPA to “use its authority through the Significant New Alternatives Policy Program to encourage private sector investment in low-emissions technology by identifying and approving climate-friendly chemicals while prohibiting certain uses of the most harmful chemical alternatives” (US President, 2013). One prohibition by USEPA prohibits the use of HFC-134a in light-duty motor vehicles beginning with MY 2021 for domestic vehicles with an extension to and including MY 2025 for vehicles exported to countries that meet certain narrowed-use limits (USEPA, 2015). This action however was challenged in the U.S. Courts and a final mandate vacated the rule to the extent it requires manufacturers to replace HFCs and remanded the rule back to EPA. EPA indicated it intends to issue a proposed rule for comment to address the remand, but this has not been issued as of July 2018. Also, three plaintiffs in the original case have asked the U.S. Supreme Court to rehear the case; no decision with respect to that has yet been issued.

USEPA has a new drive schedule that is required to be run from 2016. Initially the credits are determined strictly by a menu driven formula, but from 2017, the new AC17 test schedule must be run and the resulting CO_2 emissions must support the credit before it can be applied. This drive schedule is a dynamic one with solar load applied in a test chamber. (Nelson, 2012 and Brakora, 2013).

Buses and Heavy-Duty Trucks

For Medium- and Heavy-Duty trucks, the USEPA has applied or proposed requirements for the leak-tightness of MAC systems, but has not proposed or offered credits for changes to a low-GWP refrigerant. These standards currently apply for combination tractors, pickup trucks and vans in a Phase 1 rule and for vocational vehicles, which include all other heavy-duty vehicles such as buses, refuse trucks, and concrete mixers, in a Phase 2 rule. (USEPA, 2016b).

There are no other particular legal restrictions on bus refrigerant, apart from those discussed above. However, the bus industry follows closely the developments in passenger cars, which led to the predominant use of HFC-134a, although R-407C and others are also used. Given possible safety implications of the flammable low-GWP alternatives, however, it may be that bus and heavy-duty truck MAC systems will eventually use a different set of refrigerants than those used in light-duty vehicles.

Chapter 11

Energy efficiency and sustainability applied to refrigeration systems

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11 Energy efficiency and sustainability applied to refrigeration systems

This chapter includes and highlights selection criteria for refrigerants considering sustainability aspects. This chapter will also address energy consumption for refrigeration systems as a design factor, and as a significant and rising part of the total global energy demand.

While keeping focus on environmental impacts - namely the depletion of the stratospheric ozone layer and global warming - a wider range of relevant environmental, as well as social considerations, are briefly described in this section, for consideration by decision makers.

The application of the UN Sustainable Development Goals (SDGs) to products will be addressed in general in the following section, and applied to refrigeration systems in the later sections of this chapter.

Considering the complex relationships between R/AC and sustainability imperatives, this chapter offers:

- highlights recent UN initiatives and how they relate to the sustainable refrigeration concept;
- sustainable refrigerant selection criteria;
- engineering assessment tools;
- considerations about refrigerant conservation, including the current situation of the HCFC phase-out in Article 5 countries;
- an assessment of energy use by refrigeration and air conditioning equipment, from the viewpoints of energy management, efficiency, and the application of renewable energy sources as well as thermal energy storage;
- an updated review on regulations related to RACHP technology options in particular, and in the context of a circular economy at large;
- a description of systemic approaches and initiatives towards:
  - sustainable cold chains, ultimately favouring responsible production, transport, storage and consumption;
  - sustainable building concepts;
  - sustainable energy storage.

11.1 Introduction

In 1983, the United Nations created the World Commission on Environment and Development (later known as the “Brundtland Commission”), which defined sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 1987).

The definition of the UN term for “sustainable development”:

1. *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:*
   - *the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and*
   - *the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.*
2. *Thus, the goals of economic and social development must be defined in terms of sustainability in all countries - developed or developing, market-oriented or centrally planned. Interpretations will vary, but must share certain general features and must flow from a*

consensus on the basic concept of sustainable development and on a broad strategic framework for achieving it.

Development involves a progressive transformation of economy and society. A development path that is sustainable in a physical sense could theoretically be pursued even in a rigid social and political setting. But physical sustainability cannot be secured unless development policies pay attention to such considerations as changes in access to resources and in the distribution of costs and benefits. Even the narrow notion of physical sustainability implies a concern for social and economic equity between generations, a concern that must logically be extended to equity within each generation.

Refrigeration and air conditioning (R/AC) present positive and negative impacts to sustainability. R/AC respond to fundamental human needs: refrigeration is essential to food quality, to ensure the supply of medicines and vaccines, air conditioning provides thermal comfort and makes living in hot or humid climates possible; therefore, it is of utmost importance to food security, human health and well-being. Although the world is producing more than enough food, its loss and waste throughout the supply chain prevent eradication of hunger: one-third of food produced for human consumption is lost or wasted globally, representing a waste of resources increasing greenhouse gas (GHG) emissions in vain (FAO, 2016). Therefore, as a positive contribution to sustainability, refrigeration avoids GHG emissions by reducing food loss.

However, environmental impacts do occur along the life cycle of refrigeration equipment, and are mainly related to:

- Direct: refrigerant and insulation foam blowing agent choice and management; end-of-life procedures
- Indirect: Materials inventory and energy consumption through the equipment life cycle
- Global and/or local: Consumption and pollution of natural resources and their costs not included in the product costs for water, groundwater, air, soil and contribution by the extraction of raw materials, deposition of waste products and entry of polluting substances and their decomposition products.

Responsible management of these R/AC environmental aspects contribute to climate change mitigation and to the protection of the stratospheric ozone layer, avoiding adverse impacts on human health and ecosystems. In addition, there are opportunities for developing innovative new technologies, which are usually cost-efficient.

For additional information about sustainability principles and tools considering both environmental and social aspects, see Section 11.2 of the 2014 RTOC Assessment Report (UNEP, 2015). Energy efficiency was addressed by a TEAP task force report: “Issues related to energy efficiency while phasing down HFCs” in 2018 (TEAP, 2018)

Only recently, end of 2018, published literature and initiatives cannot be analyzed and included in detail in this assessment report, but which is planned for the next or possible special reports.

Information on specific matters can also be found in the IEA report “The future of cooling” (IEA, 2018), the “Global status report on renewables 2018” (REN, 2018), and in the annual report of the Kigali Cooling Efficiency Program initiative (K-CEP) related to the Kigali Amendment (K-CEP, 2018), a philanthropic collaboration launched in 2017.

11.2 Outcomes from UN climate and sustainability frameworks

The twenty-first session of the Conference of the Parties (COP-21) to the United Nations Framework Convention on Climate Change (UNFCCC) took place from 30 November to 11 December 2015 in Paris. The negotiations culminated in the Paris Agreement, by which the parties express the *"aim to reach global peaking of greenhouse gas emissions as soon as possible, (…) and to undertake rapid reductions thereafter (…), so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"* (UNFCCC, 2015). Therefore, global net GHG emissions should fall to zero by 2100, to avoid the worst outcomes from climate change. No immediate change in refrigeration technology options can be foreseen as a result from or stimulated by this agreement. However, future regulatory measures needed to move societies towards zero GHG emissions will certainly affect equipment design in a thorough manner.

The UN Sustainable Development Goals[13] (SDGs), part of the 2030 Agenda for Sustainable Development made public in September 2015 as an outcome from the Rio+20 Conference (2012), bring no immediate impact to refrigeration. However, similarly to the climate negotiations, influences from related goals are likely in long term. Six out of the 17 SDGs are directly applicable, or connected, to refrigeration:

1. *Zero Hunger (SDG 2);*
2. *Good Health and Well-being (SDG 3);*
3. *Affordable and Clean Energy (SDG 7);*
4. *Decent Work and Economic Growth (SDG 8);*
5. *Industry, Innovation and Infrastructure (SDG 9);*
6. *Responsible Consumption and Production (SDG 12);*
7. *Climate Action (SDG 13).*

Measures to protect the environment at the national level could be locally driven or a response to a global environmental treaty such as the Montreal Protocol and they vary from one nation to another based on social, economic and environmental considerations. The balance between environmental, economic, and social interest is important.

In principle, laws preserve the protection of people from harmful acts done by others whether done intentionally or unintentionally. On that basis, people can harm the public if they cause damage to the environment; thus, there is a social responsibility for that act equivalent on cost and benefit basis to the damage caused. Similarly, institutions doing products, services or operations causing harm to the environment will affect the societies living in the same environment. The social harm caused by environmental deterioration can be quantified to identify products or services causing this harm. Doing so will make non-environmentally friendly products and services known; societies then can choose which technologies or products to use. On the other hand, stringent environmental policy can cause deterioration of the economy which will harm the society by increasing poverty and unemployment. Another important aspect is the liability of companies for environmental damage, which is increasingly being claimed, sometimes across countries and continents.

With technological capabilities, environmental regulations will not always reduce the economic growth but will transform it into a sustainable growth. However, the decision of investing in technology development is not always targeting environmental considerations; profit maximization is an integral part of the investment appraisal in the economic world.

Quantifying the environmental aspect in technological investment and the cost impact on the society has numerous considerations:

- Direct environmental impact of using a product or a service.
- Indirect environmental impact of using a product or a service.
- Lifecycle cost of a product considering its initiation, operation, service and disposal.

[13] https://sustainabledevelopment.un.org/topics/sustainabledevelopmentgoals

- Internalization of social costs (cost and benefit approach). Cost associated with taxation on inferior products.
- Precautionary approach (cost of avoiding technologies and products impacting the environment).

The cost of products, solutions or services, and their environmental and economic impact, based on the above considerations can vary from one society to another and hence the judgment on the sustainability of the product or service also varies.

11.3 Sustainability applied to refrigeration

Sustainable refrigeration systems are driven and evaluated by the following considerations:
- tools for evaluation (section 11.4)
- direct impact of refrigerants (section 11.5)
- indirect impact: energy consumption for operation of refrigeration systems (section 11.6)
- life cycle considerations (section 11.7)
- including the improvement of the efficiency of the cold chain (section 11.7.3)

Refrigeration affects the ability of global sustainability in many ways. Economic, environmental and social impacts - some positive, other negative – are produced throughout the life cycle of the refrigeration equipment, from the extraction of its raw materials until the end of life and disposal. Here, the sustainable operation of a refrigeration system is understood to mean that a complete system integration is sought, ultimately to minimize the total energy consumption which comprises the largest emission content.

Demand in the cooling sector is expected to rise rapidly over the next century, curbing this increase on demand for cooling and electricity through greater energy efficiency, NIK technologies, passive buildings etc. will greatly increase the sustainability of the sector, see chapter 12 as well.

Sustainable manufacture of systems is gradually becoming part of the decision-making process for manufacturers who used to base their design on cost grounds rather than for environmental compliance leading to the acceptance of lower efficiency systems in some cases. For example, designers today are faced with the dilemma of designing smaller units with less refrigerant charge for sustainability reasons vs. larger ones with higher refrigerant charge for energy efficiency purposes. As an additional example, a 15 to 20 K design temperature difference used for air-cooled condensers results in smaller heat exchangers which use less material; however, it is possible to get improved energy efficiency by using larger heat exchangers which use more raw material and are more expensive.

There is no clear guidance on optimising these design decisions, even though there are today some best practices like refrigerant charge optimization, the use of recycled aluminium in heat exchangers, greater use of plastics and other synthetic materials from renewable sources.

Energy efficiency and sustainability in refrigeration must focus not only on well-designed equipment and facilities, but also on their proper use, that is, well-operated and up-to-date maintenance. The savings generated by a good use of the facilities, avoiding wastefulness, is of utmost importance in the final account of energy efficiency, sustainability and protection of the environment.

11.4 Assessment tools

11.4.1 Refrigerant selection criteria

Refrigerant selection criteria and properties provide a basis for the selection of a refrigerant in an application in support of the intermediate factors. Properties and selection criteria of significance are shown in Table 11-1.

Table 11-1: Refrigerant selection criteria

Selection criteria	Factors / Properties and Impact	Expected or needed development
Climate impact	Refrigeration systems contribute to global warming by energy consumption and emissions of refrigerants	Higher acceptance for products and technologies with lower TEWI and LCCP
	ODP and GWP	ODP substances are being phased out by the Montreal protocol Stronger national regulations to implement the Kigali Amendment might lead to the phase-out of high GWP fluids
Other environ-mental impact	Short and long-term effects on air, water, soil (VOC, degradation products e.g. TFA)	Increased application of the precautionary principle to long-term effects Stricter regulations of refrigerants emission entry into the ecosystem Further research into the environmental impact of the degradation products of TFA and long term accumulation effects from existing and alternative HFC/HFO refrigerants is needed.
	Atmospheric dispersion effects, degradation mechanisms, degradation products and their toxicity	Possible stricter control of degradation products, more detailed investigations
	Production, destruction, recycling	Adequate recycling and destruction
Energy efficiency[14]	Emissions related to operation	Governmental labelling requirements Rules for minimum performance requirements Compliance to energy efficiency regulations will drive performance improvements in the product design
Thermal energy storage[15]	Possibility of thermal energy storage	Use is expected to grow

[14] see section 11.6
[15] see section 11.7.5

Selection criteria	Factors / Properties and Impact	Expected or needed development
Refrigerant cost	Cost and design factor	Generally higher cost for fluorinated low-GWP refrigerants and lower cost for non-fluorinated refrigerants Due to the scale effect and technology development, the market price is affected Regulated substances tend to be costlier Risk of increasing market presence of counterfeit refrigerants
Commercial availability	Market penetration driven by local demand	Availability globally is limited by local phase-out regulations Global manufacturers will develop local solutions with different refrigerants
Technological level	Increase of energy optimised operation Leak reduction Safe handling and use Education and training	Development of "smart" products which require less know-how by operators Move from refrigeration system design to optimised control technologies Flammable refrigerants become more viable options as safety related issues are addressed technically and process and infrastructure for servicing refrigerants becomes available
High ambient temperature fitness	Design factor and operation requirement, reduction in energy efficiency related to refrigerant critical temperature	System adjustment to ambient conditions (larger HX, refrigerants with low compressor discharge temperatures) Optimization for annual operation or local conditions by "intelligent" design
Safety Risk [1)]	Risk related to adjustments of the technical design of products and to operator and user know-how. Cost driver and design factor. Lack of local regulation. Lack of safety standards. Lack of adjustment of existing technicians competence Lack of evaluation tools for risk assessment for refrigeration Currently no common understanding of tolerable risk level	Improved understanding of risk, which is defined as a combination of the probability of occurrence of harm[1)] and the severity[1)] of that harm, by adoption and interpretation of risk-based or risk assessment standards and concepts, e.g. ISO guide 51 (general), ISO 13043 (MAC), ISO-DIS 20854 (reefer container) Improved understanding of the actual risks of refrigeration systems based on common principles (e.g. IEC 60079-series) and not based on the chemical nature of a refrigerant (e.g. ASHRAE refrigerant classification, ISO 817). Increasing "intelligence" of the technical system including handling of risks and operation, result in reduced risk. Better education, higher competence and higher work skills. Updated building code including flammable refrigerants

Selection criteria	Factors / Properties and Impact	Expected or needed development
Flammability and decomposition after refrigerant releases	Risks associated with improper use of flammable refrigerants Underestimation or low awareness of decomposition of fluorinated refrigerants during service Lack of local regulation, approval processes, building codes adapted to the refrigeration technology	Better understanding of the importance of risks in terms of the frequency of a hazardous event and the severity of an event triggered by flammable refrigerants. Improved awareness of risks related to release fluorinated refrigerants Improved understanding of tolerable risk and general risk related to the life cycle of refrigeration equipment. Due to flammable nature of new (unsaturated HFC) and known refrigerants (such as HFC-32, HFC-152a, HC-290, HC-600a, NH_3) it is expected that the application, design know-how, service practices and procedures, education, training, as well as adoption of technical standards for safe use of these flammable refrigerants will be developed within the next 3-5 years[16]. Development and adoption of local regulatory processes. Increase of flammable refrigerants' market share and know how to use them.
Liability, responsibility	Accidents due to improper handling of refrigerants Environmental damage	Increase of claims for local damages Inclusion of economic product risks Increase of claims for environmental damages Shareholder disinvestment Inclusion of risk for environmental damages
[1)] Definitions according to IEC 61882: - Risk: Combination of the probability of occurrence of harm and the severity of that harm - Harm: injury or damage to the health of people, or damage to property or the environment - Severity: significance or grading of the failure mode's effect on item operation, on the item surrounding, or on the item operator; failure mode effect severity as related to the defined boundaries of the analysed system		

11.4.2 Life Cycle Climate Performance (LCCP)

Assessment tools taking into account impacts of refrigeration equipment on climate have been developed by different parties for different purposes.

LCCP is a measure of the direct and indirect global warming impact of equipment. It is based on the total related emissions of greenhouse gases associated with the manufacturing, operation and disposal of the refrigerant, and the indirect emissions. Indirect emissions are the CO_2 that is generated at the fossil fuel power plant when energy is consumed by the refrigeration equipment and for LCCP also includes other factors such as the energy consumed to obtain raw materials

[16] Safety requirements for low-toxicity, flammable refrigerants classified as A2L, A2, and A3 are described in chapter 2 of this report

and manufacture the equipment. In that sense it is a more comprehensive measure than Total Equivalent Warming Impact (TEWI), discussed below.

The International Institute of Refrigeration (IIR) has released a spreadsheet and a manual for the calculation of the Life Cycle Climate Performance and comparison of a system in different climate zones. With the tool CO_2 emissions from production of the unit to the end of working life can be calculated. However, it does not cover the waste handling e.g. incineration of contaminated refrigerant. The LCCP tool includes some of the energy use (and related CO_2 emissions) associated with the production of the unit, however, some other items are not included, such as the one related to the energy used for mining the ore and energy for melting the original metals. Recycling of the compressor and motors, not covered by the IIR model, is a topic of its own that can help save energy and hence GHG emissions on the one side.

Using the LCCP analysis will necessarily lead to different rankings for refrigerant selection based on the application. Hwang (2007) provided an example in 2007 where, for walk-in refrigeration systems, R-410A provided higher LCCP CO_2 impact vs. indirect/secondary loop R-290 systems when the leakage rate was maintained below 10%. This may seem to some as counterintuitive since the GWP of the refrigerants are vastly different. On the other hand, there are various examples in the market that indirect systems can very well be operated in an energy-efficient and competitive manner.

Possibilities for optimization exist e.g. by using NH3, R290 as efficient refrigerants and secondary fluids, or CO_2 as a liquid to avoid suction line losses in branched systems and to eliminate overheating in the evaporators. In the MAC, chiller and supermarket sector, systems have been introduced that allow indirect cooling by thermal management for system integration and optimization, which can ultimately result in significantly lower LCCP values. In other words, the selection of a refrigerant is not only dependent on the LCCP of the refrigeration system, but on the total energy balance of the entire energy-consuming system.

LCCP analysis may be used, for example, to support requests to government agencies for the use of costly features based on improved environmental impact. This provides an effective tool for driving improvements in application level GWP in areas where energy efficiency and recycling are not otherwise regulated. In the absence of energy regulations or initiatives, the market does not reflect the need for reduced GWP at the power provider. Several computer programs have been developed to perform LCCP calculations.

- *IIR LCCP Working Group Calculation Tool*

The LCCP Evaluation Working Group at The International Institute of Refrigeration (IIR) has developed and maintains an software tool and LCCP Guidelines (Troch, 2015). Some of the values in the LCCP calculation from IIR are difficult to find, especially if one uses different refrigerants than those included in the manual.

- *GreenMAC LCCP Tool*

General Motors, the Japanese Automobile Manufacturers Association, the SAE International and the US EPA developed together the GreenMAC LCCP© model (Papasavva et al., 2010). . Using GreenMAC LCCP, Papasavva showed that HFO-1234yf provides a clear advantage over either the baseline HFC-134a or CO_2 (R744) (Papasavva and Moomaw, 2014).

- *AHRTI LCCP Tool for Residential AC*

This is a Microsoft Excel based program for residential heat pump systems. The annual energy consumption for heat pump operation is calculated using input performance data at several operating points as defined in AHRI Standard 210/240. With appropriate input, the program can handle different heat pump systems, refrigerants, locations, and CO_2 emission profiles of power plants. In their paper "Life Cycle Climate Performance Model for Residential Heat Pump Systems", Zhang and co-workers developed an software plugin that calculates LCCP values for residential heat pumps. The work is documented in an AHRTI report (Zhang et al., 2011).

- *Life Cycle Climate Performance Tool - V1.0*

In continuation to the AHRTI work described above, a web-based calculator was developed by the University of Maryland College Park (UMCP, 2017), under a subcontract from Oak Ridge National Laboratory (ORNL), for supermarket refrigeration and air source heat pump systems. The "LCCP Desktop Application v1.0" tool is available online (UMCP, 2017).

The results of these tools will vary based on the assumptions used, particularly the assumptions for the efficiency of the system, power generation, refrigerant leakage and refrigerant management methods. Therefore, these tools are best used for comparative analysis of competing systems. It may be possible to improve the portability of the results through the establishment of documented standards and methods. To this end, there is a need to standardize the tools by an international agency like ISO or IEC to allow comparison across manufacturers.

11.4.3 Total Equivalent Warming Impact (TEWI)

TEWI is a measure of the direct and indirect global warming impact of equipment. It is based on the total related emissions of greenhouse gases during the operation and disposal, and the indirect emissions. Indirect emissions are the CO_2 that is generated at the fossil fuel power plant when energy is consumed by the refrigeration equipment. TEWI is measured in units of mass in kg of carbon dioxide equivalent (kg CO_2-eq.). The TEWI equation can be found in (EN, 2008) and (Fischer, 1991). It can be evaluated in conjunction with seasonal profiles of temperatures and capacity. TEWI is a widely accepted tool because of its ease of use and transparent way of showing the calculation. TEWI was introduced in the 1990's and is well known in the industry. TEWI is much simpler to implement than a complete LCCP calculation. When emissions related to energy are dominant, which is often the case for RACHP applications, TEWI may be preferable to LCCP.

However, the impact of refrigerants on the environment goes beyond the direct and indirect values produced in a TEWI analysis. TEWI does not account for the process of production, transportation and other significant factors. Studies of LCCP have included the fugitive emissions of a refrigerant from production until installation in equipment, the embodied energy or GHG emissions associated with producing the refrigerant, and the GHG emissions associated with extracting materials and producing components of an air-conditioning or refrigeration system.

Other factors not included in TEWI are the following:

Energy effect of refrigerant charge leakage: as refrigerant charge leaks from a refrigeration system, the system capacity and efficiency are affected. The effect of this leakage over time on net GWP impact has been studied using LCCP by several authors (Beshr, 2014).

Refrigerant mismatch: for example, when a refrigerant that is poorly matched for the cooling task, such as CO_2 in a continuous high ambient condition, the energy consumption is elevated and can result in the release of additional CO_2 at a fossil fuel power plant when compared to a correctly matched refrigerant.

Both LCCP and TEWI are affected by the product efficiency and thus give a better indication than a simple GWP reference of what the greenhouse gas emissions associated with the use of air-conditioning and refrigeration equipment will be. LCCP and TEWI calculations provide more information on the sustainability of air-conditioning and refrigeration equipment than GWP or energy efficiency alone; therefore, these methodologies are recommended when comparing products and systems. Because of the analysis method, one will find that, even for refrigerants that have low GWP and/or low leakage rates, there will be a significant impact on the environment when calculated as LCCP.

The following table 11-2 summarises various impacts on the environment.

Table 11-2: Environmental impacts considered by LCCP and TEWI

Environmental impact	*Direct/ Indirect*	*Included in LCCP*	*Included in TEWI*
Refrigerant, reactant and byproduct emissions from the production, collection, transport of refrigerant	*Direct*	*Yes*	*No*
Equipment manufacturing process driven emissions	*Direct*	*Yes*	*No*
Refrigerant leakage during use	*Direct*	*Yes*	*Yes*
Service emissions	*Direct*	*Yes*	*Yes**
End of life emissions	*Direct*	*Yes*	*Yes**
Irregular emissions (unexpected/accidental e.g. stone hits, collisions, component reliability failures)	*Direct*	*Yes*	*Yes*
Energy to manufacture refrigerant	*Indirect*	*Yes*	*No*
Energy to transport refrigerant	*Indirect*	*Yes*	*No*
Transportation of equipment to installation	*Indirect*	*Yes*	*No*
Energy to recover, reclaim and recycle Refrigerant, heat exchangers, compressor and system	*Indirect*	*Yes*	*No*
Final disposal of materials and/or recycling at the product's end-of-life (EOL)	*Indirect*	*Yes*	*No*
Energy during use	*Indirect*	*Yes*	*Yes*

* Often accounted for by adding to refrigerant emissions during use to determine an overall annual emission rate.

11.5 Direct impact of refrigerants

In general, a refrigeration system has the fundamental market requirement of continuous cooling performance for human comfort, air conditioning, and for ensuring chemical processes and their production safety, and for ensuring the food cold chain, as examples. This fundamental requirement of customers and users results in a very high tightness requirement over the lifetime of the plants. Therefore, a refrigerating system with a refrigerant can be classified as a "durably technically tight" system, accomplished by design such as leak tight design and manufacturing procedures for components, joints and connections. Service procedures for maintenance and operation, including inspection and monitoring of leak tightness, need to be implemented to achieve maximum results.

For this reason, as operational requirements by tightness are addressed in several standards and may be enhanced through mandatory regulations, for example in the EU: requirements for leak testing according to the F-Gas regulation. Refrigeration systems are designed to achieve the level of tightness as specified in ISO 5149-2 for sealed systems.

In practice this high level of tightness cannot always be ensured, for example by design, during the operation lifetime or due to improper local installation. High tightness is always a cost driving factor, often not addressed as technically possible due economical pressure and higher costs. Another aspect is the business model of continuous sales through the refilling of equipment.

Therefore, leaks in refrigeration systems are state of the art, typically of type fugitive emissions, and with lower frequencies by accidental type of releases.

Halocarbon refrigerants such as CFCs and HCFCs deplete the ozone layer and they, as well as HFCs, harm the climate system. Additionally, there are potential environmental and health impacts from the decomposition of halocarbon refrigerants in nature (see also Chapter 2 of this report). With the near-complete phase-out of CFCs globally and HCFCs in non-Article 5 countries, the continuing HCFC phase-out in Article 5 countries, and with the Kigali Amendment starting to enter into force in 2019, attention has turned to managing banks of these refrigerants and reducing consumption and emissions of HFCs.

Refrigerants are not only used in new equipment and appliances but for most products there is a recurring consumption in servicing during the useful working life of the equipment. While the amount needed for service varies based on the product type and individual applications, in total the consumption of refrigerants for servicing is more than that used in the manufacturing of new equipment; this is particularly true for HCFCs.

While efforts are being made to reduce the impact of emissions on the environment by refrigerant management and conservation techniques as well as choice of refrigerant, in the worst cases, the entire refrigerant charged and that used for servicing over the useful working life of refrigeration and air-conditioning equipment is gradually emitted to the environment.

11.5.1 Decomposition of refrigerants and enrichment in the aquatic ecosystem/ hydrosphere

Atmospheric decomposition products of a number of HFOs include trifluoroacetic acid (TFA) (NEA, 2017), which is also a decomposition product of some HFCs. Accumulation of TFA becomes significant at a certain concentration level and will affect the local and global environment as well as the aquatic ecosystem/hydrosphere[17].

Ultimately, 92-100% of all HFO-1234yf emitted will, once decomposed, result in TFA, whereas, in the case of HFC-134a, 7-20% of its emission will yield TFA as a decomposition product (Wallington et al., 1996). Furthermore, the degradation of HFC-134a to TFA takes much longer than the degradation of HFOs; this is due to the longer lifetime of HFC-134a, as also indicated by its much higher GWP.

This high TFA rate resulting from the decomposition of a number of HFOs, especially in the case of HFO-1234yf, may be of considerable environmental relevance in view of the expected future HFO production expansion. This expansion will result in an HFO proliferation to various usages, not just to mobile air conditioning. The short atmospheric lifetime of HFO-1234yf may especially become a problem in areas with quiescent conditions and high emission rates (Qiaoyun, 2014).

An additional problem is that TFA is also produced as a degradation product from other entries (such as: solvent for proteins and as a reagent in the chemical industry, inhalation anesthetics, organic pesticide with CF_3 parts of the molecule) in the ecosystem (locally and regionally varying), which accumulates in the aquatic system. Consequently, this is a critical issue, i.e., it has to be clarified whether the accumulation of all chemicals that result in TFA will produce so much TFA that limits in basic and drinking water will be exceeded. Scheurer (2017) describes investigations of water treatment options for TFA removal for full-scale waterworks as well as for laboratory batch tests: *"Commonly applied techniques like ozonation or granulated activated carbon filtration are inappropriate for TFA removal, whereas TFA was partly removed by ion exchange and completely retained by reverse osmosis. Further investigations identified*

[17] The hydrosphere covers the entirety of the water of the earth.

wastewater treatment plants (WWTPs) as additional TFA dischargers into the aquatic environment. TFA was neither removed by biological wastewater treatment, nor by a retention soil filter used for the treatment of combined sewer overflows. WWTP influents can even bear a TFA formation potential, when appropriate CF_3-containing precursors are present. Biological degradation and ozonation batch experiments with chemicals of different classes (flurtamone, fluopyram, tembotrione, flufenacet, fluoxetine, sitagliptine and 4:2 fluorotelomer sulfonate) proved that there are yet overlooked sources and pathways of TFA, which need to be addressed in the future" (Scheurer, 2017).

From leaking refrigeration applications, amounts of refrigerants are released in such a manner that degradation happens over a longer period, related to equipment lifetime. As mentioned, the lifetimes of the HFC and HFO molecules in the atmosphere are very different. Both effects will therefore result in different time horizons for the degradation of the various HFC and HFO refrigerants. Furthermore, refrigerants have been released in the past and will be in future, thus leading to increased, later aquatic ecosystem impacts (Solomon, 2016).

A significant increase of TFA concentrations in rainfall on glaciers (Vollmer, 2015; Vollmer, 2018), in groundwater and in drinking water has already been measured to date, with higher than permitted TFA values measured in some groundwater samples (DVGW, 2017; NRW, 2018; GDCh, 2018).

It is obvious that, lacking knowledge of the TFA formers as well as which future pollution of aquatic water systems can be expected, more research is needed concerning the impact of TFA. This particularly in light of the observed rapid and widespread uptake of HFO-1234yf in MAC applications and future use of HFOs in other applications. From the TEAP XXVII/4 Task Force report (TEAP, 2016), which gives tables for the emissions of low GWP refrigerants from servicing in the future, a value of about 60 ktonnes of HFO emissions relevant for TFA formation (from both mobile and stationary air conditioning) has been derived here for non-Article 5 countries in the year 2030. It might well concern HFO emissions relevant for TFA formation derived here at a level of about 90 ktonnes from all R/AC subsectors in Article 5 countries in the year 2030 [18].

11.5.2 Reducing direct emissions

The following are recommendations to reduce direct emissions from equipment and systems at the various phases of the systems' life. These measures start with minimising emissions through design by reducing the refrigerant charge; ensuring the leak tightness of the equipment during construction, installation, use, servicing and end-of-life decommissioning; and reducing emissions throughout the five phases through proper practices and techniques.

11.5.2.1 Charge minimisation

Refrigerant charge minimisation reduces the global consumption of refrigerants as well as the quantity of possible emissions during leak events and at end of life. Refrigerant charges may be reduced through the use of e.g. microchannel heat exchangers, which reduce the internal volume of the heat exchanger, and non-refrigerant secondary cooling systems. Secondary cooling systems have the added benefit of separating toxic or flammable refrigerants from occupied spaces. However, secondary systems have an effect on energy efficiency as described in chapters 4 and 9. Examples include supermarket refrigeration equipment that is designed with secondary loops and

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[18] Estimates are based on the emissions of HFOs from MAC applications and on the expected emissions of HFOs from stationary air conditioning (estimated here at 15% of the total) that could give rise to TFA decomposition product.

cascade systems, using much smaller refrigerant charges than traditional designs. Work is also underway to develop a secondary loop system in mobile air conditioning (see Chapter 10).

11.5.2.2 Leak tightness

Leak detection equipment sensitivity continues to improve with the ability to detect levels as low as 1 ppm by volume in air, as cost of refrigerant and other risks due to flammable refrigerants continue to apply pressure on the markets to conserve refrigerant.

Product design changes have been made regarding leak tightness in response to growing environmental, regulatory, and economic concerns associated with refrigerant emissions.

Regulations that prevent the release of refrigerants without recapture, backed by severe penalties, prevent intentional release. High taxes on refrigerants have a similar effect, as the price for refrigerants can increase noticeably as e.g., shown in Norway, Denmark, Spain, and, effective 2019, in France.

11.5.2.3 Installation, servicing and maintenance good practices

Training needs to be improved when going forward to address safety and release of refrigerants as the use of flammable refrigerants gains momentum and the quantities of HFC refrigerants have increased in both Article 5 and non-Article 5 countries. In Article 5 countries, certification and training materials are very expensive for technicians, inhibiting adequate training. Installation, servicing and preventative maintenance should be addressed. Unsustainable servicing practices, such as cleaning of coils using refrigerants or topping-up refrigerant without repairing leaks with subsequent leak testing, are avoidable. Regular and thorough maintenance, carried out by certified technicians, reduces leakages and improves the energy efficiency of a system.

11.5.3 Refrigerant recovery, recycling, reclamation and destruction

This section provides an overview of refrigerant conservation. Additional details can be found in the previous 2014 RTOC Assessment Report (UNEP, 2014).

In the last few decades, there has been an increasing emphasis on conservation of refrigerants and the reduction of emissions that has led the industry to develop a specific terminology which is used in this report (ISO, 1999).

- **Recover**: to remove refrigerant in any condition from a system and store it in an external container.
- **Recycle**: to clean the extracted refrigerant using oil separation and single or multiple passes through filter-driers, which reduce moisture, acidity, and particulate matter. Recycling normally takes place at the field job site.
- **Reclaim**: to reprocess used refrigerant to virgin product specifications. Reclamation typically occurs at a reprocessing or manufacturing facility.
- **Destroy**: to transform used refrigerant into other chemicals in an environmentally responsible manner.

11.5.3.1 Refrigerant conservation process and destruction

Conservation of refrigerants is becoming an integral part of servicing practices in most countries, especially for systems having relatively large charge quantities. In order for the process of refrigerant conservation, i.e. Recovery, Recycling and Reclamation (RRR), to be successful, certain criteria have to be taken into consideration and put in place:

The incentives for RRR are related to the cost of refrigerants as well as to environmental protection in a broad sense. The regulatory framework is also a driving force for recovery of refrigerant, especially when enforced by noticeable penalties;

A study by the United States Environmental Protection Agency (EPA) estimated that most of the refrigerant recovered during servicing is either used for the same equipment or replaced with approximately equal amounts .The study assumed that refrigerant is normally recovered when servicing large equipment, and that refrigerant is rarely recovered when servicing small equipment. The net amount of refrigerant available for reclamation is hence mostly derived from decommissioned equipment (EPA, 2009). EPA data show that the amount of reclaimed HCFC-22 in 2016 was half or less of what was projected in the scenarios presented in the 2009 report as needed to cover the local servicing needs from non-virgin sources (EPA, 2017).

> *The availability of refrigerant for reclamation is a problem in other non-Article-5 countries. A study by the Air Conditioning, Heating, and Refrigeration Institute (AHRI) found that in 2014, Japan destroyed more refrigerant than what was recovered in that year by eliminating some of the existing stock. Refrigerant Reclaim Australia (RRA, 2017) reported that the total collections in 2016/2017 were 496 tonnes comprised of 324 tonnes collected and destroyed and 172 tonnes reclaimed to new specifications; it also reported that refrigerant is only available for recovery during service and decommissioning (RRA, 2017). The report equates the recovery effectiveness between 49% and 70% of the refrigerant available for recovery which is equal to an amount between 1,690 and 2,550 tonnes.*

The availability of recovered refrigerants in Article-5 countries is a problem as well, however, not because certain quantities are destroyed. A mix of economic factors, due to the low price of virgin HCFC and the high cost of reclamation, combined with a lack of mandatory regulation and the difficulty of getting proper purity levels as mandated by standard AHRI 700, makes the process difficult to implement and rarely followed unless forced by noticeable penalties.

In order for the process of refrigerant conservation, i.e. recovery, recycling and reclamation to be successful, certain criteria have to be taken into consideration and put in place.

- Successful recovery schemes in non-Article 5 countries are the result of a collaboration between the government and the local industry. Countries need a strong regulatory framework that is supported by industry associations and by trade groups, coupled with innovative collection and recycling techniques, and a strong culture of environmental protection (AHRI, 2016);
- Reclamation is essentially a market-driven industry. If there is no demand for a particular refrigerant, the costs to send recovered refrigerant to reclamation facilities will be a disincentive to reclaim;
- Efforts must be initiated early with refrigerant supply companies prepared to take back refrigerant for recycling / reclamation. Many service establishments will not be able to afford storage for recovered refrigerants, however, the proportional cost of sending small quantities of recovered refrigerant to reclamation facilities is also a disincentive to reclamation efforts. Such disincentives promote venting or reuse of previously recovered, and possibly contaminated, refrigerant, which could lead to premature failure of equipment;
- Refrigerant recovery and recycling equipment should be made available to service technicians in every sector;
- The logistic process should be easy to understand and cover all players from the sales points to the customer, and back to the point of return;
- The whole process should be performed by certified technicians (see section 11.7.2 under sustainable servicing);

- Care should be taken by policy makers to eliminate parallel routes to market of illegally imported refrigerant with potentially dangerous quality;
- RRR equipment has been developed and is available with a wide range of features and prices. However, some equipment is intended for use with one refrigerant and/or type of air-conditioning system and may not be adequate to service other refrigerants or sectors;
- Equipment with protected potential sources of ignition also exists, this for the recovery of flammable refrigerant;
- There is worldwide recognition of the need for destruction of unwanted ODS refrigerants because of ozone and climate benefits from the emissions avoided. The destruction of ODS banks has the potential to earn carbon credits through global or regional carbon markets, broadly divided into the compliance market and the voluntary market. Individual organizations are committed to actions and projects to offset their GHG emissions, on a voluntary basis. However, currently there is little financial incentive for ODS destruction and destruction is therefore only successful when it is regulatory driven.

11.6 Energy efficiency, indirect impacts

As mentioned in section 11.3, the indirect warming impact from energy consumption is an important sustainability aspect in a global context, and this for the following reasons:

- CO_2 emissions caused by energy use are a significant factor for the global warming impact of a certain R/AC system;
- In areas that experience the highest growth rates in refrigeration related energy usage (including Asia, non-OECD and Article 5 countries) (EIA, 2016), the energy consumption of refrigerant containing products is marginally regulated, and is primarily driven by market forces. These market forces tend to bias purchases to short term benefits rather than to invest in long-term environmental benefits;
- The fuel for energy production is a scarce resource as well as a pollutant;
- The cooling sector, especially air conditioners, contributes to peak power demand which is often the most polluting power source, thus exacerbating the indirect impacts of a refrigeration system.
- In some regions of the world indirect impacts are debated, leading to policy decisions that tend to be based on the more easily regulated direct impact of a refrigerant (e.g. solely considering the global warming potential (GWP);
- Due to intrinsic safety issues, sustainably safe product designs and especially product operation may become costlier and harder to achieve when using flammable refrigerant options. These refrigerants tend to have lower direct GWP values and may provide improved, lower energy consumption. Development of safe handling methods, training and certification requirements should be especially addressed here;
- Sustainable approaches to reduce CO_2 emissions and energy consumption are highly influenced by the building efficiency. Enhanced use of analysis that includes indirect emissions will allow the consideration of hybrid systems designs that greatly improve energy consumption. Examples include:
    - Thermal storage systems integrated into the heating or cooling system to reduce inefficient transient operation;

- Integration of the cooling system to manage the latent heat (relative humidity), leveraging perceived comfort rather than temperature;
- Integration of heat exchangers into the building envelope to recapture energy (heat or cold) before it leaves the building. About 50% of the heat load in residential buildings and 60% in commercial buildings results from heat flows through walls, foundations, and the roof (DOE, 2015);
- Integrating heat reclaim and recovery into cooling systems can cover the heat load of the building or can be fed into district heating systems.

In almost all cases, the design and use of refrigerant systems involve a comparison against alternatives. It is in this optimisation process that indirect impacts should be given particular attention to, in order to understand the best design for sustainability. This is especially important in markets where energy consumption regulations are not used to set minimum standards on adverse effects on the sustainability of the environment.

Example areas that would benefit from the use of LCCP and TEWI analysis and measurements to gage alternatives to improved selections include, among others:

- Locations with high variations on ambient conditions for heat rejection;
- Applications with high variations of cooling demand or temperatures;
- High ambient environments in general;
- Mobile air conditioning and transport refrigeration systems.

There is also an effect of leaking refrigerant over time on the indirect climate impact, as energy efficiency is significantly degraded by the use of undercharged systems (Beshr 2014).

Whatever the assessment tool is that is being used, the appropriate energy mix must be considered, referring either to global, regional or local grids. The general practice is to use the local mix of energy sources, because this is often at hand or at least easy to get. However, the mix may change in countries where the use of renewable energy is growing.

Figure 11-1 shows the share of renewable energy (including hydro) in electricity production in various continents for the years 2005, 2010 and 2015. On the one hand, it can be observed that the share of renewable energy increased only significantly in Asia, the EU, Pacific, on the other, it only slightly changed in other regions (Africa, North America). In contrast, a reduced share of renewable energy can even be recorded for certain regions (CIS, Latin America, Middle East).

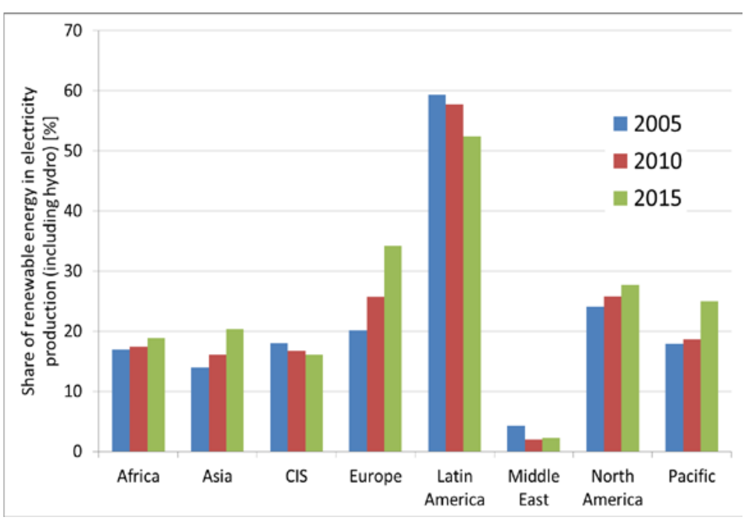

Figure 11-1: Share of renewable energy (including hydro) in electricity production 2005-15

More details can be found in the “global status report on renewables 2018” (REN, 2018).

11.6.1 Energy efficiency factors

Energy efficiency is the measure of the energy input to a machine to deliver a required output. A correct selection of refrigerant depends on a number of factors that should be considered in the TEWI/LCCP analysis, as follows:

Fluid properties affecting / decreasing energy efficiency:

- High viscosity drives increased compressor power,
- Low latent heat of vapourisation drives increased mass flow rates
- Temperature glide in blends reduces heat exchanger effectiveness unless the heat exchanger design utilizes the temperature glide; Mulroy (1988) showed a 30% increase in energy efficiency when matching the refrigerant temperature glide to the air side temperature glide.
- Reduced thermal conductivity may reduce heat exchanger effectiveness
- Specific heat capacity
- Poor adjustment for the annual operation envelope; this includes system requirements for refrigerants with a low critical point such as R-744 in high ambient conditions.

Application scope:

- *Energy efficiency is measured at individual components, refrigeration and air conditioning systems, and the surroundings (e.g. buildings). The energy efficiency at component level contributes to the upper levels, therefore efficiency is defined by proper design and application of each individual component as well as by the whole system design.*

11.7 Life cycle considerations

Concepts and selection criteria for refrigerants for various applications, i.e., for each sector of the refrigeration and air conditioning industry, are presented in other chapters of this report. Selection criteria for refrigerants with regards to sustainability are described in section 11.4.1 in this chapter.

The common understanding of sustainability applied to refrigeration among the different sectors is the need to design, operate, maintain, and take back refrigeration and air conditioning systems with minimised resource usage and emissions, both direct and indirect. Technical design criteria consider standards, regulations, as well as voluntary agreements.

Energy use worldwide is increasing with the majority of growth expected in the non-OECD countries as can be seen in Fig. 11-2 (adapted from IEA, 2017).

Energy demand between 2015 and 2040 is expected to grow by approximately 28%, or 3,770 million tons oil equivalent (mtoe) worldwide. The increase in global demand is forecast to come from non-OECD countries (i.e., developing countries). IEA expects that the OECD (developed) countries energy demand will decline by about 4% while non-OECD demand increase by 49% (GEI, 2017).

Refrigeration consumes a large portion of the total energy consumption with a forecast increase of energy use, see Fig 11-3. According to the IIR, 17 % of all electricity used worldwide is being used for refrigeration and air conditioning (IIR, 2017).

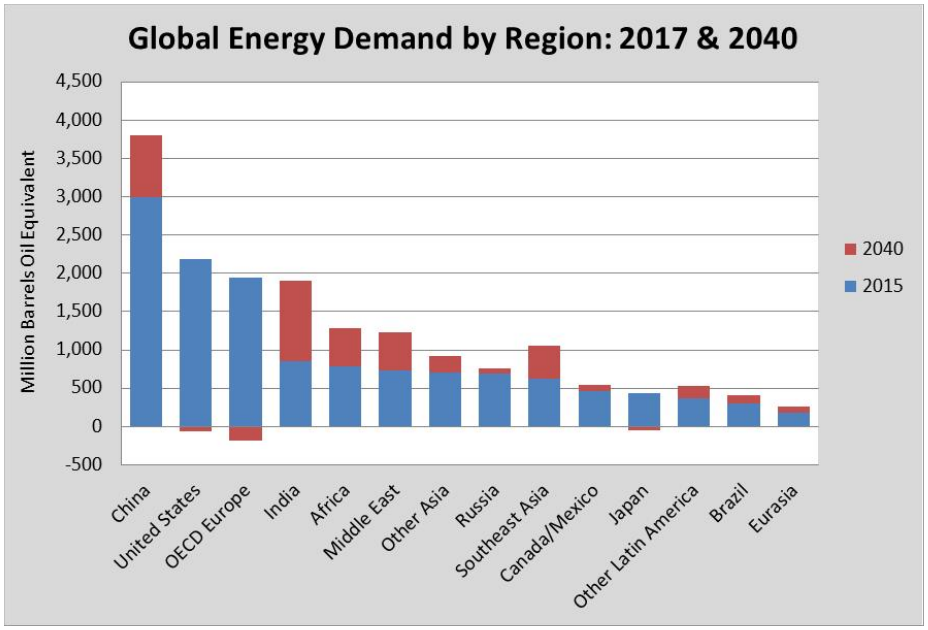

Figure 11-2: Global energy demand by region for 2017 and forecast for 2040 (GEI, 2017, IEA 2018-2)

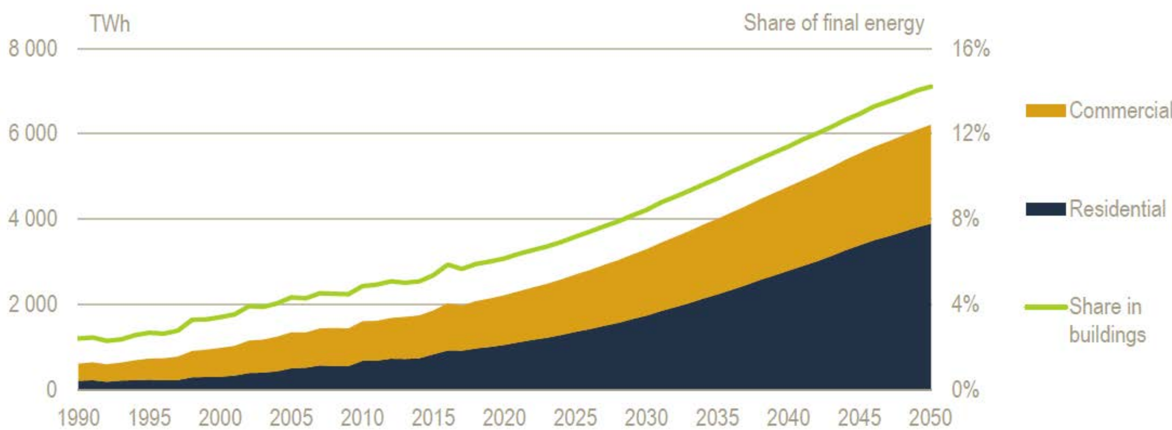

Figure 11-3: World energy use for space cooling by subsector (IEA, 2018)

The idea of the "circular economy", supported by the UN, is *"that we reuse more of what we already have"*. It will mostly impact the systems already in operation because one will replace some equipment with previously used equipment. Expansion over the current installed base will eventually start from the top of the chain. The rule of thumb for refrigerant consumption as a general approach has been: 1/3 is for new installations and 2/3 is for service. An estimate for the average lifetime of the equipment in operation is equal to more than 15 to 20 years.

11.7.1 Sustainable equipment design

From an engineering point of view, the design of components such as compressors or electrical drives has a possibility for limited improvement of a few percentage points in terms of efficiency compared to the ideal, theoretical efficiency. Compared to that, main improvements can be made through controls and smart electronic integration, minimization of heat exchanger temperature differences, and other measures. To address the direct effect, equipment can be designed to use alternative low GWP refrigerants and/or to reduce emissions. These types of improvements are driven either by cost, product innovation or by enforced standards, requirements or legislation.

Environmental sustainability, including efficiency and refrigerant management considerations, can be achieved at different levels in the design phase, by taking the following technical and regulatory criteria into consideration:

Technical considerations
Technical factors that affect the selection of the right refrigerant for a sustainable circular economy include refrigerant properties, climate impact, energy efficiency, refrigerant cost, commercial availability, high ambient temperature fitness, safety and flammability, while:

- Meeting customer design requirements, including the proper specification of annual cooling/heating demands;
- Minimising refrigerant usage and selecting alternative refrigerants that meet energy efficiency requirements;
- Integrating the technical equipment design into larger systems or a whole building design by e.g. utilising the heat rejected by a refrigeration system for e.g. heating or hot water purposes or by incorporating thermal energy storage;
- Evaluating targets of competing nature in the decision-making process: low first cost versus high efficiency.

Regulatory considerations
The EU commission has proposed a targeted improvement of legislation on hazardous substances in electrical and electronic equipment (EC, 2015a) as part of an action plan for the Circular Economy in the EU (EC, 2015b). This initiative ties with regional priorities by supporting long-term competitiveness with innovative production and consumption models, saving energy and avoiding the overuse of natural resources. A recent report also points at the wider benefits of the circular economy, including lowering current carbon dioxide emission levels. The revised legislative proposals on waste set clear targets for the reduction of waste and establish an ambitious and credible long-term path for waste management and recycling.
Key elements of the revised waste proposal include:

- A common EU target for recycling 65% of municipal waste and 75 % of packaging waste by 2030;
- A ban on landfilling of separately collected waste;
- Economic incentives for producers to put greener products on the market and support recovery and recycling schemes, including the ones related to refrigeration and air conditioning equipment.

Decisions in the design phase are often influenced by competing goals: low investments vs. installation of an energy efficiency system, which typically result in higher first costs.

Therefore, first costs are conflicting with the goal to invest in a high energy efficient system, although the operating costs of an efficient system quickly amortize any additional costs associated with the purchase; they therefore also reduce the greenhouse gas emissions during the lifetime of the system. To resolve this conflict between low first cost, operating cost and refrigerant emissions, new financing methods and evaluation criteria for the technical operation of systems are being developed -- in terms of their contribution to the environment.. These financial mechanisms can contribute significantly to the reduction of energy consumption and refrigerant emissions and in this way to improving the system design. In order to be really relevant, these mechanisms must be able to account for an adequate balance between life cycle cost and LCCP/TEWI.

Figure 11-3 depicts how the circular economy affects an industrial ecosystem. The capital and product flows are the only two parameters that are allowed to increase while all other flows or parameters should decrease with time. Waste from production must be recovered and reused whenever possible; greenhouse gas and other harmful emissions as well as chemical waste must be minimised. Supply of clean water is a major problem in many parts of the world; the use of potable water in refrigeration systems therefore has to be minimised. The amount of raw products used should be reduced or minimised. The circular economy approach aims to decrease the use of natural resources with increased efficiency, so the usage of primary energy will be reduced at the same time.

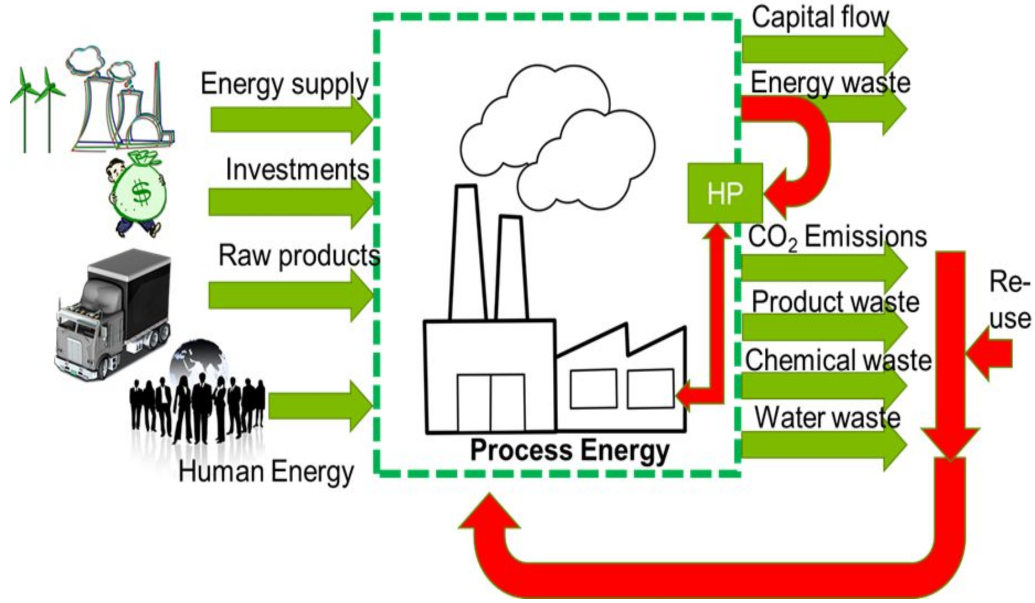

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Figure 11-3: The circular economy and the flows to and from an industrial plant

11.7.2 Sustainability within refrigeration and air-conditioning servicing

In addition to conserving resources and reducing environmental impacts, the proper servicing of equipment affects sustainability in other ways. With the wider use of flammable and potentially toxic refrigerants, proper servicing procedures — including recovery, recycling and reclamation — need to be established and adhered to in order to protect service technicians as well as the local population.

With the growing use of hydrocarbon and other flammable refrigerants, handling must be done with care throughout the lifecycle of the equipment, from design through disposal, especially by servicing personnel. Due to the flammability and possible decomposition of refrigerants, new recovery devices have been designed with spark-proof components and these should be selected over other devices not designed in that way. For hydrocarbon refrigerants venting during service might be the local norm for small charge systems, which may be legal due to minimal environmental impacts, if applied, it must be done with care. Training and recommended practices have been developed for servicing equipment with flammable refrigerants (e.g., RSES 2011, AIRAH 2013, AHAM 2016). Care is also required when servicing equipment containing HFOs. Many of these compounds, and some blends containing them, are flammable and care is needed. Venting flammable refrigerants is hazardous. Hydrogen fluoride and other chemicals that are all highly toxic, will be produced when HFC, HCFC, CFC and HFO refrigerants burn or decompose, even at temperatures below ignition temperature (JRAIA, 2017). This means that extra care must be given to avoid such situations and to provide safety measures (e.g., ventilation) if the above occurs.

Training on proper procedures is often based on cultural norms, e.g., through an apprenticeship program, otherwise it can be required by regulations.

- ***EU F-gas Regulation:***
  - *Undertakings and natural persons carrying out the installation, servicing, maintenance, and repair or decommissioning of refrigeration and air conditioning equipment shall be certified and shall take precautionary measures to prevent leakage of fluorinated greenhouse gases.*
  - *Operators of equipment that contains fluorinated greenhouse gases in quantities of 5 tonnes of CO_2 equivalent or more shall ensure that the equipment is checked for leaks; appropriate records have to be kept for each piece of equipment.*
  - *Recovery of F-Gas refrigerant is mandatory and one has to be make sure the refrigerant is recycled, reclaimed or destroyed.*
  - *Member states have to ensure that training programmes exist as well as their adequate implementation.*
  - As of 1 January 2020, there will be a ban on the use of F-Gas with GWP $\geq$ 2500 for servicing and maintenance of refrigeration equipment with charge size $\geq$ 40 tons CO_2 equivalent. Recycled F-Gas can be used until 1 January 2030, but only by the service company or the owner of the system itself.
- ***U.S. Clean Air Act Regulations:***
  - *The U.S. Clean Air Act (CAA) prohibits knowingly venting or releasing CFC, HCFC and HFC refrigerants in the course of maintaining, servicing, repairing, or disposing of air conditioning and refrigeration equipment. In 2016, U.S. EPA finalised a rule that updated the existing refrigerant management requirements to HFCs extending requirements that previously applied only to CFCs / HCFCs. Recently the U.S. EPA proposed to revise the maintenance and leak repair provisions so they would only apply to equipment using CFCs and HCFCs. U.S. EPA is also taking comment on whether the HFC management requirements should be rescinded in full.*
  - *Removing the required service practices for HFCs is inconsistent with the recommendations of sustainable refrigeration as described in this chapter.*
- ***UNEP is partnering** with industry associations to introduce a parallel and fast track qualification program that can support governments' efforts to regulate the servicing sectors. The Refrigerants Driving License (RDL) is an initiative aiming at introducing a globally recognised qualification program for the sound management of refrigerants through setting the minimum qualification requirements for technicians in the R/AC service industry, and to create the international recognition of such a program by industry and governments (Ozone, 2017).*

11.7.3 Sustainable cold chains

Today's food system is built upon refrigeration. For many foods, refrigeration is a feature of almost every stage in the supply chain (Garnett, 2011). Cold chain for perishable foods is *"the uninterrupted handling of the product within a low temperature environment during the postharvest steps of the value chain including harvest, collection, packing, processing, storage, transport and marketing, until it reaches the final consumer"* (Kitinoja, 2013). Its ultimate objective is the supply of good quality perishable food by slowing down bacteria growth. Poor practices in the cold chain do not prevent that bacteria growth and reduce food availability, causing the overuse of natural resources, boosting GHG emissions, as well as producing severe health problems (Kefalidou, 2016).

A sustainable cold chain can be defined as the set of processes in refrigerated environments which present the lowest use of natural resources and lowest emissions of GHGs and other pollutants, delivering good quality, healthy food to the consumer, with minimum waste across the value chain.

To reduce food losses, the cold chain refrigeration is considered as a key technology. On the other hand, expansion of current cold chain technology worldwide will result in an increase of energy demand for the operation and in refrigerant losses from refrigeration systems.

The cold chain includes following sectors where refrigeration is applied:

- Agriculture,
- Harvesting,
- Fishing: land based refrigeration and on board of vessels,
- Intermodal transport: transport refrigeration by truck, trailer, rail, vessel,
- Processing: industrial refrigeration,
- Storage: warehouse, cold storage, industrial refrigeration,
- Retail: commercial and supermarket refrigeration,
- Food service: restaurants, local consumer services.

A study carried out for the UK government (Garnett, 2011) indicates that the reduction potential of emissions from refrigeration (indirect and direct) in the cold chain is 20-50% due to improving its energy efficiency. Factors are proper design and specification, use and maintenance of equipment, especially: (1) reduction of the load in transport refrigeration, (2) reduction of heat gains, (3) ensuring the rapid transfer of temperature-controlled food, (4) proper insulation, (5) reduction / control of fan power, (6) optimization of temperature difference in processes and equipment designs, (8) adjustments and optimization of control algorithms.

ASHRAE has developed, while partnering with US DOE and other institutions, an energy design guide for grocery stores, bringing design concepts and practices able to deliver 50 % energy savings, toward net zero energy buildings (ASHRAE, 2015). The report includes two case studies from major supermarkets. In Northern Ireland (UK), Carbon Trust and the local retail trade association NIIRTA have published a guide to implementing energy savings for retailers, considering four situations: day-to-day, refrigeration servicing, retrofitting and full replacement of refrigeration equipment (Carbon Trust, 2012).

The political measures to realise these huge savings potential are (Garnett, 2011):

- Implementation of “Energy Using Products Directives”
- Enhanced Capital Allowance Scheme
- Domestic energy labelling schemes
- Energy efficiency classification system for components and products.

11.7.4 Sustainable building concepts

The technological development in building materials, energy sources, controls and communication has taken 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 utilised with the use of mixed technologies and solution which offers an opportunity to achieve higher environmental benefits.

This approach is trending now in buildings, or in sustainable building concepts. Sustainable building design can lead to great reductions in annualised energy use, and in some cases, eliminates the annualised cost of energy (Net Zero Buildings). The sustainable building concept is looking at the building with its location, design, materials, systems, equipment, occupants and controls as an integrated system designed for better environmental benefits. Measures considered to evaluate the sustainability of a building are as follows:

- Lower CO_2 emissions;
- Lower water consumption;
- Lower waste, more recycling and reusing;
- Higher environmental quality (indoor air quality, natural lighting, background noise, etc.).

Demand based, or application based concepts in building design and development require a proper framework of building energy models, regulations and codes to implement. A number of national, regional and international codes have been developed and are used globally for new buildings and for retrofitting existing buildings as well; yet, more work needs to get going to support the growing interest in this concept globally.

11.7.5 Sustainable energy storage, thermal energy storage

Increasing use of renewable energy sources for electricity generation will require energy storage. Thermal energy storage is one of the most energy and cost efficient ways of storing energy. Storing thermal energy on the cold side of a refrigeration or air conditioning system can decrease operating costs by operating when electricity is cheaper, i.e., at times of overcapacity. If the operation of the refrigeration system can be moved to night hours and if the condensing temperature is reduced according to the lower night outdoor temperature, thermal energy storage in a refrigeration system can also be energy efficient (Kauffeld, 2012). A shift of operating hours towards low outdoor temperature periods can also address the challenge of hot climates. Typically, outdoor (night) temperatures are 5 degrees lower at locations with an ocean climate, whereas temperature differences between night and day can be up to 15 degrees for continental climates.

Thermal energy storage can also be used for peak load shaving, i.e., evening out the cooling load which results in smaller size equipment (e.g., compressor size).

11.8 Concluding remarks and opportunities for improvements

With the Kigali Agreement, the Montreal Protocol has taken another major step in supporting the sustainability principles by targeting HFC refrigerants for phase-down that have a high global warming potential. Throughout their work on the Montreal Protocol, the parties have always focused on aspects of sustainability by advancing technologies with low GWP and high energy efficiency. Further, the Multilateral Fund has supported projects for recovery, recycling, and reclamation, however, with mixed results.

This chapter has gone beyond the traditional look at sustainability related to refrigerants as followed in earlier RTOC assessment reports, to a more holistic look at the lifecycle of an air conditioning or refrigeration system.

Consideration has been given to the available assessment tools and the aspects of efficient equipment and efficient building design. Other opportunities have been identified to achieve sustainability improvements during the entire lifecycle of a refrigeration system through the reduction of use of raw materials and the establishment of codes of ethical conduct for suppliers along the value chain.

Such improvements may be facilitated with:

- Development of standards that allow measuring and reporting of the sustainability of products and processes;
- Awareness raising through the value chain;
- Education on sustainability and its implications;
- Regulations and political actions defining technical conditions;
- Integration of social and environmental externalities into corporate governance and reporting
- Financial incentives to take account of environmental damage.

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Chapter 12

Not in Kind Technologies

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12. Not in Kind Technologies

12.1 Introduction

Mechanical vapour compression (MVC) has been the dominant refrigeration and air conditioning system since the mid-20th century. Vapour compression systems use natural refrigerants such as carbon dioxide, ammonia and hydrocarbon as well as synthetic refrigerants such as CFCs, HCFCs and HFCs. With the discovery of the detrimental environmental effects of CFCs and HCFCs refrigerants to the protective ozone layer, efforts were made to develop refrigerants that do not deplete the ozone layer. Those efforts resulted in wider use of HFC refrigerants, which were partly responsible for raising ambient temperatures and aggravating climate change, because of their high of Global Warming Potential (GWP).

In 2016, parties consented to reaching a binding agreement on phasing down HFCs; the 28th meeting of the Parties (MOP) held in Kigali adopted the Kigali Amendment on HFCs (see further Chapter 1).

The phase-down of HFCs presents challenges to vapour compression technology. Some lower GWP refrigerants suffer from some thermodynamic and safety attributes chief among those possible lower efficiency, possible lower volumetric capacity compared to HCFC-22, the dominant HCFC refrigerant. Natural refrigerants, which may have taken precedence because of their benign environmental characteristics, also suffer from toxicity; R-717 (ammonia) is an example. Low operating pressure at both ends of the vapour compression cycle, R-718 (water) is an example, high operating pressures and low critical point requiring extensive design modifications as with R-744 (carbon dioxide), or high flammability in the case of R-290 and hydrocarbons, generally.

Testing programs for new low-GWP refrigerants have been designed, such as AHRI AREP, US DoE at ORNL, UNIDO/UN Environmental PRAHA and EGYPRA programs, to test new refrigerants and find out about their behaviour especially under High Ambient Temperatures (HAT) conditions.

Some of those new low GWP refrigerants are now commercially available, constraints are emerging that show that there must be trade-off for those refrigerants to compensate for their higher cost, sometime a loss of efficiency and safety in particular flammability. The US Department of Energy published a study (Goetzler, 2014) that looked into alternative Not-In-Kind (NIK) technologies to vapour compression for space heating and space cooling.

This chapter will look into technologies that do not employ vapour compression technology and will explore those Not in Kind Technologies (NIK) that offer at least 15% energy savings compared to vapour compression as well as compare their attributes and properties in a tabulated form. The limitations of the comparison is explained in more details in section 12.2

Those comparisons will include:

- Heating and cooling capabilities.
- Development status.
- Expected efficiency.

Definitions of In-Kind and Not-In-Kind technologies used in this text
In-Kind technologies in this text are those using primarily mechanical vapour compression to produce air conditioning or refrigeration.
Not-In-Kind technologies used in this text are those not using primarily mechanical vapour compression to produce air conditioning or refrigeration.

12.2 Energy savings, development status and geographical applicability of 17 NIK technologies

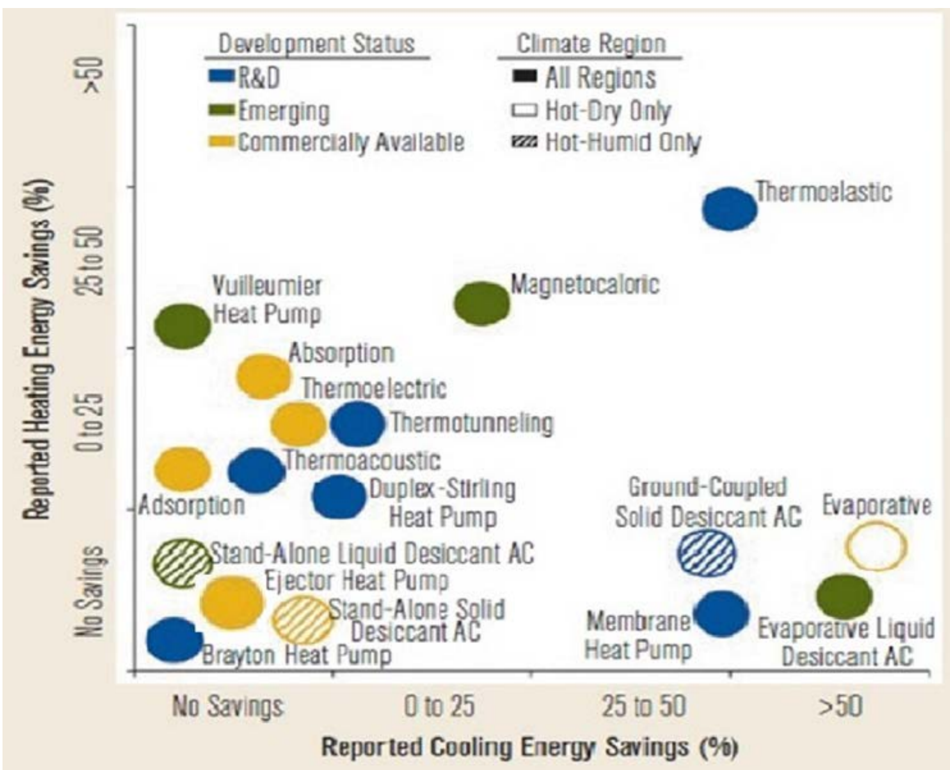
Figure 12-1 shows the reported cooling and heating energy savings of 17 technologies compared to a baseline vapour compression technology. The vapour compression technology was chosen to meet current energy saving standards or typical current practices when standards do not exist. The development status of the technology is classified here as:

- In R&D status
- Emerging technology.
- Commercially available.

The applicability to geographical regions is classified here as:

- Applicable to all regions.
- Applicable to hot-dry regions only.
- Applicable to hot-humid regions only.

Figure 12-1 shows that only a few cooling technologies report energy savings of over 50% with one commercially available for hot-dry regions, while the majority have either no appreciable cooling efficiency savings or up to 10 % savings. One technology reported over 50% cooling efficiency savings, classified as commercially emerging and for all regions. For heating applications, more technologies are available with better energy efficiencies than for cooling mode. In addition, more technologies are grouped in the energy efficiency 0 to 25% and 25 to 50% than in the cooling mode.



Source: ASHRAE journal, October 2014, Technical Feature Section: "Alternative to Vapour-Compression HVAC Technology. By: William Goetzler, member ASHRAE and Robert Zogg, Jim Young and Caitlin Johnson. Ref. 2-Modified.

Figure 12-1: Energy savings cool and heat, development status and region of applicability for 17 NIK technologies.

Some of those technologies control both sensible and latent heat independently. This is an added advantage when compared to vapour compression. It is important to note that some NIK technologies, although they seem to have little energy savings in their cooling mode such as absorption refrigeration, however, have an important role to play as an alternative technology because they operate on low grade energy such as natural gas, reject heat, etc. In addition, they are used regularly during peak hours for reducing peak electrical power consumption and in summer for increasing gas turbine performance of power stations.

It must be emphasized that the energy savings referred to are not necessarily definite and may change. Comparing technologies on an energy saving scale, only, may be misleading, as there are multiple arrangements made in each case such as intrinsic heat exchanger efficiencies, cycle management strategies and a wide range of experimental data. Therefore, a comprehensive and fair comparison among NIK technologies is not currently conclusive; this comparison should be taken as definite superlative comparison. Overall, efficiencies of the majority of NIK technologies are still evolving.

12.3 Alternative technologies to vapour compression

The US Department of Energy published a study in 2014 (Goetzler, 2014) that looked into alternative NIK technologies to vapour compression for space heating and space cooling. The study did not look into refrigeration NIK technologies. The study classified alternative NIK technologies according to their energy saving potential. ASHRAE Journal published a technical feature article in 2014 (ASHRAE, 2014) that looked into the study and provided some insight on its findings.

The classification is divided into three groups according to their particular driving energy. Those are:

- Thermally Based.
- Electro- mechanical Based.
- Solid state Based.

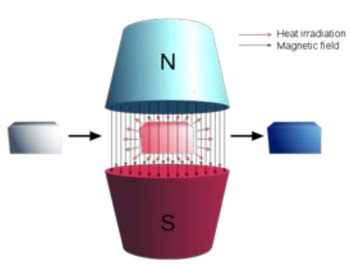
Some of the technologies looked at were discarded because they were either low in efficiency or capacity or were still in an early stage of development.

The remaining 17 technologies are considered viable alternatives for vapour compression. Those technologies are listed in Table 12-2. In the text, technologies are classified as follows:

Commercially Available: At least one company is producing it.
Widely Commercially Available: Available at more than one company.
Emerging: Has passed R&D phase and is now established prior to commercial availability.
R&D: In the research and development phase not yet totally established.

12.3.1 Solid state based technologies:

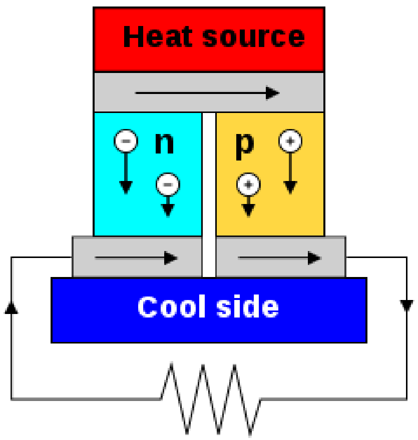
12.3.1.1 Magnetocaloric: Development Status: Commercially available



The magnetocaloric effect is the basis of this technology, where paramagnetic materials show reversible temperature change if exposed to a changing magnetic field. magnetocaloric technology can be used for heat pumps as well as air conditioning applications.

Magnetocaloric technology is reported to have the potential to reduce energy consumption of 20% when compared to mechanical vapour compression (Magnetic, 2016; SAE, 2013).

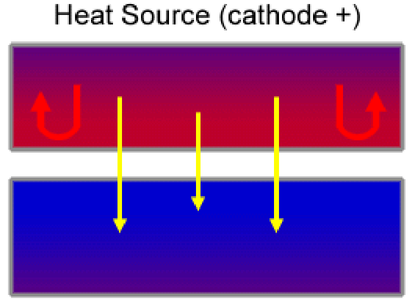
12.3.1.2 Thermoelectric: Development Status: Widely Commercially available



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. It is expected 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 and also in low efficiency systems. Those are available for cars for temperature conditioning of seats, especially for High Ambient Temperature conditions when cars are parked for extended periods while exposed to direct sunlight. Spot cooling for electronics equipment, portable refrigerators, wine cabinets -to improve the efficiency of vapour compression systems sub-coolers- are some of the applications of thermoelectric technology. Small water coolers, compact refrigerators and portable coolers are also applications that are commercially available.

12.3.1.3 Thermotunneling: Development status: R&D



By introducing a gap the return path for conducted heat (red arrows) is eliminated, making Power Chips extremely efficient.

Thermotunneling technology is a development of thermoelectric technology to improve energy efficiency. Thermotunneling technology is more efficient than thermoelectric and is claimed to be superior to mechanical vapour compression by about 30 % (Dieckmann, 2011; Dieckmann, 2011b).

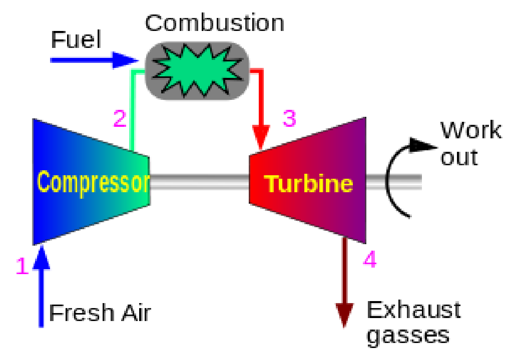
Thermotunneling technology is an emerging technology not yet mature except in small cooling applications of 50 W and less.

12.3.2 Electro-mechanical technologies

12.3.2.1 Brayton cycle heat pump:

Development status: R&D for building space air conditioning

Development Status: Available for transportation, refrigeration and process



The Brayton cycle concept is not new and has been commercialized 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.

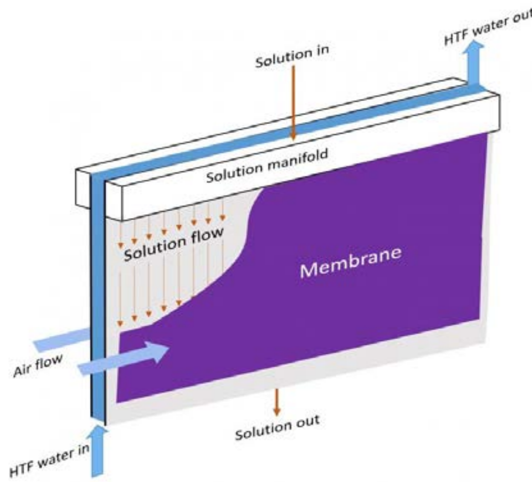
It has also been used in lower temperature refrigeration in applications such as batch blast freezing and freezing tunnels as well as low temperature cold storage and cryogenic cooling. Brayton cycle technology has a lower COP compared to base line MVC, at 1.3 to 1.6 (Butler, 2001), but is the preferred cooling and heating technology for applications where reliability is paramount and where low maintenance is required compared to baseline MVC.

It is likely to remain a viable option for transportation cooling (aircrafts, trains, ships), process and industrial low temperature cooling.

12.3.2.2 Evaporative cooling: Development status: Widely commercially available

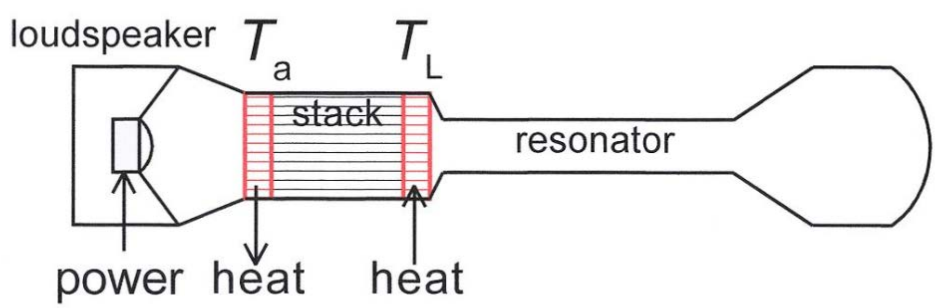
Direct evaporative cooling is an established cooling technology for low humidity ambient. Indirect evaporative cooling allows cooling the air stream without raising its humidity, even in higher humidity ambient and allow using the system in hybrid arrangements with other cooling systems, thus improving efficiency. This expands the use of evaporative cooling; improve the efficiency of hybrid systems while reducing water consumption. indirect evaporative cooling has the potential of achieving COPs of up to 27. It is a marked improvement over many systems in energy efficiency. Modular capacities available are; 13, 26, 39, 52, 78, 104 and 156 kW (3.7, 7.4, 11, 17.8, 22.2, 29.6 and 44.35 TR). Many manufacturers produce indirect evaporative cooling in various designs configurations. Water consumption is an important factor in regions where water is scarce, although modern indirect evaporative cooling units utilizes reduced water consumption rates compared to early models. Several manufacturers in the USA, Europe, India, China, the Middle East and Australia produce indirect evaporative cooling systems. Refrigeration capacities are somewhat limited because of the large geometric sizes of air handling units housing indirect evaporative cooling systems (Kozubal, 2012; SWEEP/DoE, 2004; SWEEP/WCEC, 2007).

12.3.2.3 Membrane heat pump: Development status: R&D



Membrane technology for air conditioning provide dehumidification of the space using a special polymer membrane to separated moisture from air. The dehumidified air is either cooled or heated to reduce energy consumption. Polymer membranes were developed originally for the filtration and purification of sea and brackish water or for enthalpy wheels for recovering exhaust air (ARPA, 2013; Dais, 2012).

12.3.2.4 Thermoacoustic: Development status: R&D

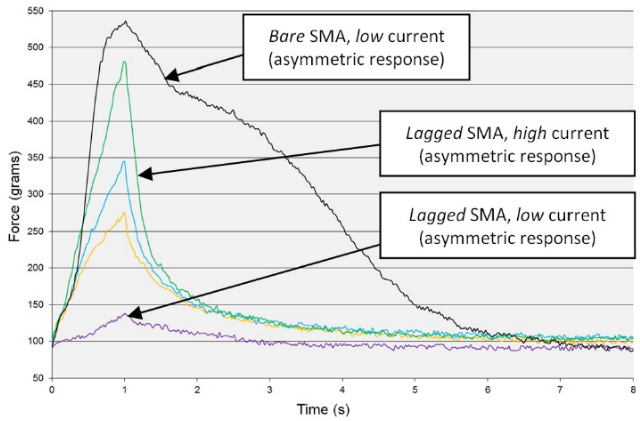


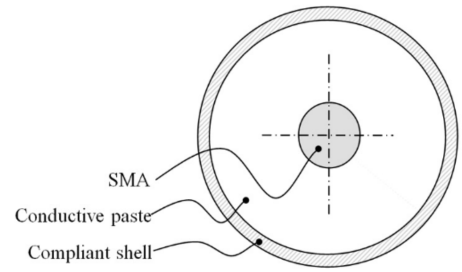
Thermoacoustic technology uses sound waves to cool or heat air. The sound waves have pressure oscillations, which cause gas to compress and expand. Compressed gas heats up while expanded gas cools down. There are two types of thermoacoustic units: standing wave and travelling wave. A noble gas is used in those units.

A cryogenic freezer is the only thermoacoustic product commercially available at present. Thermoacoustic technology is better suited for refrigeration applications rather than for air conditioning.

Efficiency figures are not yet available although it is thought that there will be saving in energy consumption in refrigeration applications, especially in supermarkets (ARPA, 2013b).

12.3.2.5 Thermoelastic: Development status: R&D

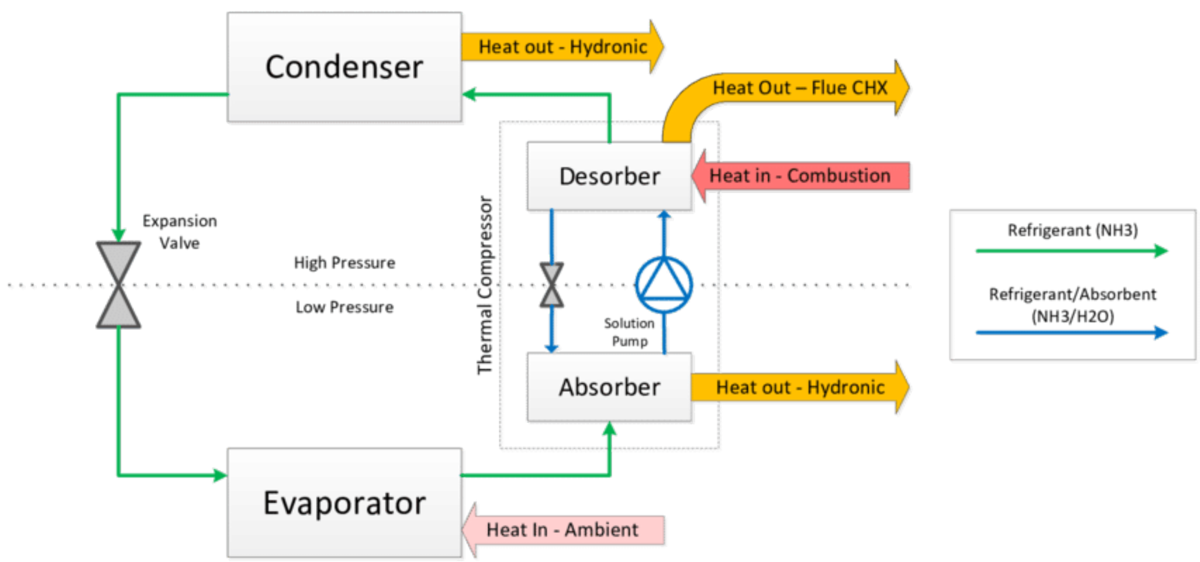




The technology uses Shape Memory Alloys (SMA), which are alloys such as nickel titanium alloys (NiTi) which when mechanically stressed will go into a solid-to-solid phase transformation and reject heat. The phenomena are reversible and SMA absorb heat as they return to their original shape. Plans are underway to develop a window air conditioner in the near future. A car air conditioning prototype based on thermoelastic technology is also planned (ARPA, 2013c; MEST, 2013). This promising technology is in its early stages of research and development. It has a projected COP of 6 compared to a COP of 3 for MVC.

12.3.3 Thermal based technologies.

12.3.3.1 Absorption heat pump: Development status: widely commercially available



Available refrigeration capacity of absorption units is shown in the figure below. The figure shows both lithium bromide- water and water- Ammonia units of various denominations.
It is important to note that the COP of an absorption chiller is a heat ratio and cannot be compared directly with that of a vapour compression chiller; because the latter is a ratio of useful refrigeration effect divided by the work of an electric motor-driven compressor, a different more refined form of energy.

In order to compare both COPs, it is important to reduce that of a vapour compression chiller by the inefficiencies of producing electric power, such as the electric power plant efficiency, transformers efficiencies, transmission efficiencies and so on. At the end, reducing the COP of vapour compression to 35% of its value is nearer to its actual value. Vapour compression systems are thus more efficient than absorption system by a small margin.

However, the uniqueness of absorption systems in utilizing a crude form of energy together with their low electric power requirement makes them an important element when choosing a chiller for an application.

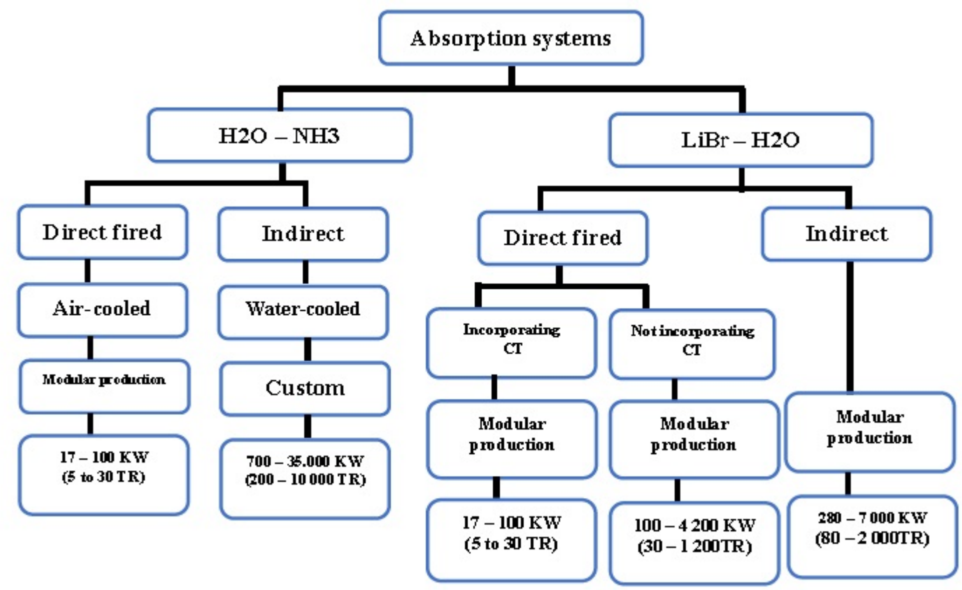
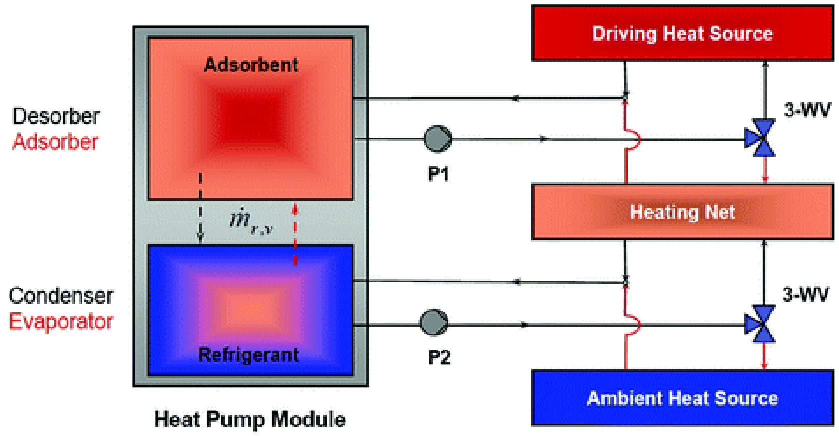


Fig. 12-2: Commercially available capacities of absorption units

Absorption systems using water-ammonia working solutions are used for low temperature refrigeration applications as well as for air conditioning, since ammonia, the refrigerant, can operate at low evaporation temperature (Olama, 1980).

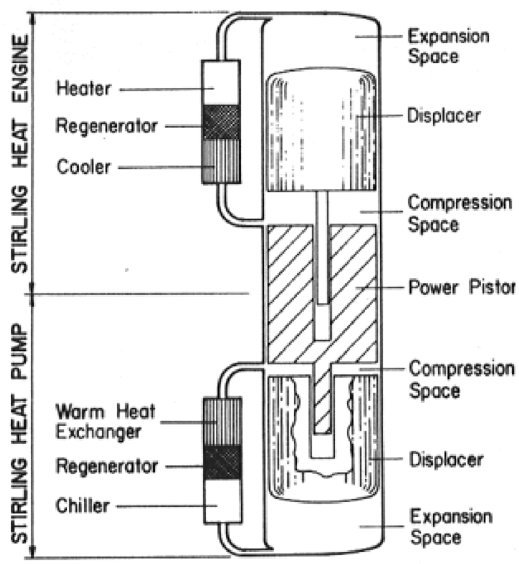
Lithium bromide – water-working solutions operate at above freezing temperatures, water is the refrigerant. They are used in air conditioning applications only. Absorption refrigeration has little energy savings in their cooling mode; however it has an important role to play as an alternative technology because it can operate using reject heat. In addition, it is used regularly during peak hours for reducing peak electrical power consumption and in summer for increasing gas turbine performance of power stations. Absorption chillers/heaters are also connected to solar collectors for operation with solar energy.

12.3.3.2 Adsorption heat pump: Development status: commercially available



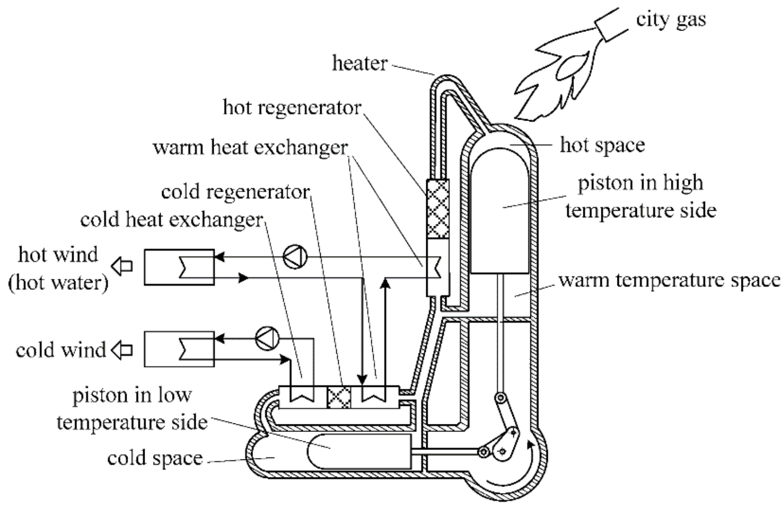
Adsorption technology (Vodianitskaia et al., 2017) uses a hygroscopic salt with high affinity to water as an adsorption media and water as the refrigerant. Adsorption units can operate in cooling or heating mode and have heat ratio efficiencies for cooling of 0.5 to 0.7 and for heating 1.15 to 1.4. Those values are lower than comparable MVCs although their ability to utilise low temperature hot water is unique and makes them important in waste heat or solar thermal applications. Although this technology is not very recent, it is nevertheless moving steadily to new areas of use, especially in the heat recovery applications. Current range is 35 to 1,170 kW (10 to 330 TR), a smaller range than that of absorption units.

12.3.3.3 Duplex-Stirling heat pump: Development status: R&D: commercially available for cryocooling and some commercial refrigeration applications



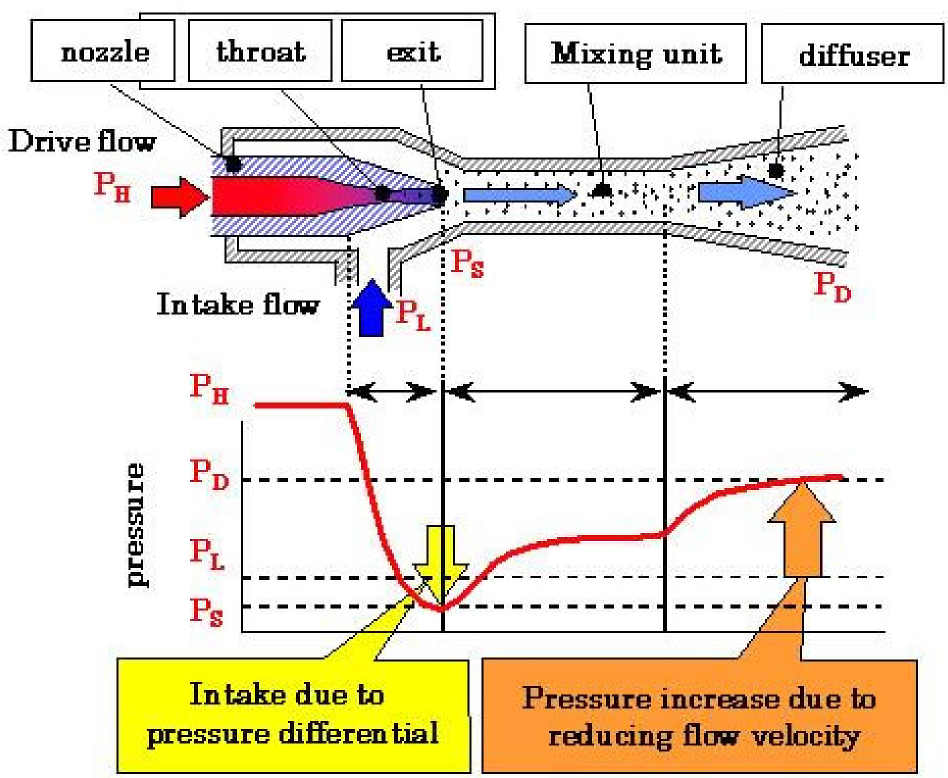
The low COP of the technology is the reason why there are no Duplex Stirling space air conditioning units at the present time (ACL, 1986). Process cooling type Stirling coolers operating with an electric motor are available in cryocooling, ultra-low temperature freezers and a small fraction in portable freezer/refrigerator boxes. These systems provide a comparable performance to mechanical vapour compression at -20 °C temperatures.

12.3.3.4 Vuilleumier heat pump: Development status: emerging



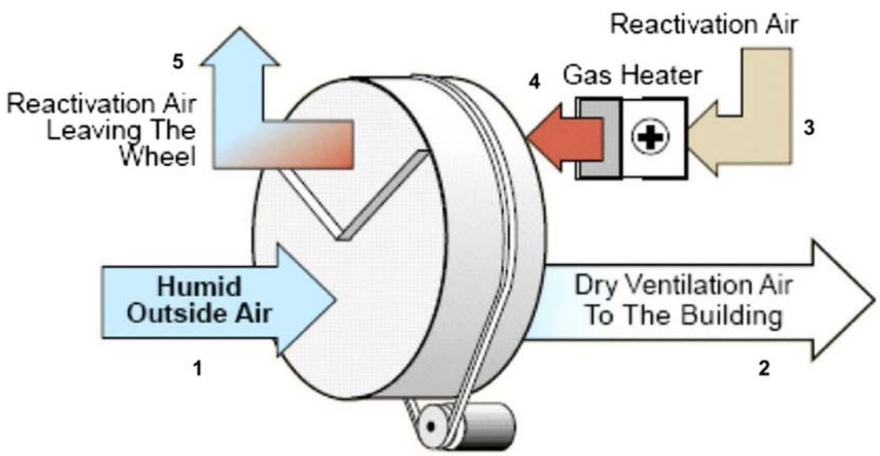
Vuilleumier heat pumps are similar to Duplex Stirling engine heat pumps, but utilise two pistons instead of one piston. This emerging technology is reported to have a COP for heating of 1.6 to 2.2 and a COP for cooling of 0.8 to 1.2. The technology that is claimed can provide an energy saving of 26 % for heating over baseline MVC (Munters, 2009; Xie et al., 2008).

12.3.3.5 Ejector heat pump: Development Status: commercially available



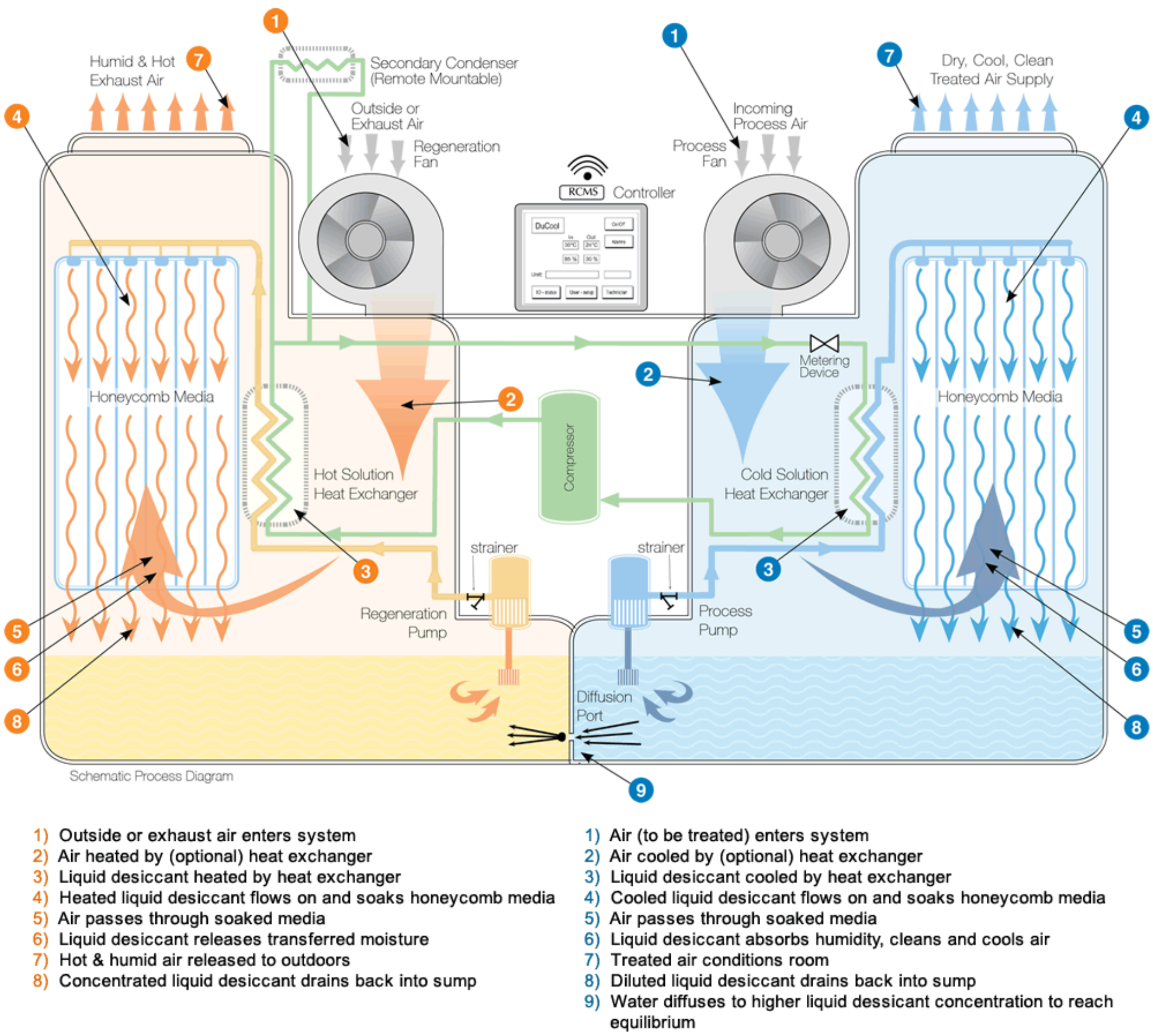
The COP of ejector heat pumps is generally lower than MVC or thermally activated systems, which makes it difficult for the technology to have market penetration. Nevertheless, the technology has undergone a transformation lately because of its ability to use rejected recovered heat to drive the system. Efforts are made to use ejector technology with CFD analysis and refrigerant optimization in prototype construction (Aidoun and Martel, 2009). Although ejector cycles use the same refrigerant for both primary and secondary flow, binary refrigerants are being tested to improve the cycle performance.

12.3.3.6 Stand-alone solid desiccant AC: Development status: commercially available and Ground-coupled solid desiccant AC: Development status: R&D



Stand-alone liquid desiccant technology is an available technology. Ground coupled solid desiccant cooling technology is in the R&D stage.

12.3.3.7 Stand-alone liquid desiccant AC: Development status: emerging and Evaporative liquid desiccant AC: Development status: emerging



The systems are in emerging phase. They have the potential to achieve a reduction in energy consumption of 39 to 84 % compared to MVC.

12.4 NIK Technologies providing minimum 15 % energy saving compared to vapour compression technologies

In Table 12-1 those NIK technologies are compared to MVC, mechanical vapour compression, that provide a minimum of 15 % energy savings. Two technologies were ranked highest in a DoE study (Goetzler, 2014).

Those are:

- the thermoelastic and
- the membrane heat pump.

Table 12-1: Eight NIK Technologies with a minimum of 15% energy savings compared to vapour compression

NON-VAPOR-COMPRESSION TECHNOLOGY	HEATING OPERATION	COOLING OPERATION	DEVELOPMENT STATUS	EXPECTED COST/ COMPLEXITY[b]	NON-ENERGY BENEFITS	MARKET BARRIERS
Thermoelastic[c]	✓	✓	R&D	Comparable		Reliability Risks
Membrane Heat Pump[c]		✓	R&D	Comparable	Air Quality, Demand Reduction	Water Use
Absorption Heat Pump	✓	✓	Commercially Available	Moderately Higher	Can Use Low-Grade Thermal Energy, Demand Reduction	Toxicity and/ Or Reliability of Working Fluids
Evaporative Cooling		✓	Commercially Available	Comparable	Demand Reduction	Water Use, Reliability Risks, Only Applicable in Hot-Dry Climate Regions
Evaporative Liquid Desiccant AC		✓	Emerging	Significantly Higher	Demand Reduction	Water Use, Reliability Risks
Magnetocaloric	✓	✓	Commercially Available	Moderately Higher	Noise Reduction	
Ground-Coupled Solid Desiccant AC		✓	R&D	Significantly Higher	Can Use Low-Grade Thermal Energy, Air Quality, Demand Reduction	Only Applicable In Hot-Humid Climate Regions
Vuilleumier Heat Pump	✓	✓	Emerging	Slightly Higher	Improved Reliability, Demand Reduction	

Source: ASHRAE journal, October 2014, Technical Feature Section: "Alternative to Vapour-Compression HVAC Technology. By: William Goetzler, member ASHRAE and Robert Zogg, Jim Young and Caitlin Johnson.
a Per installation, based on primary energy and year-round operation (heating and cooling), where applicable.
b Compared to vapour compression.
c These two technologies were ranked highest in the DoE study.

12.5 Conclusions

Plans are underway for assembling a one TR (3.52 kW) window air conditioner prototype operating on thermoelastic technology, at the University of Maryland, USA. In the US DoE's ARPA-e and the DoD Environmental Security Technology Certification Program, one manufacturer developed a one TR (3.52 kW) prototype space-conditioning system that operates on Membrane Heat Pump technology using this two-stage, latent and sensible stages technology. The manufacturer predicts an EER of 26 Btu/W.hr or greater (Olama, 2014).

Absorption heat pumps are commercially available and have an inherent advantage since they can operate on low grade heat thus saving precious on peak electric power. Evaporative cooling has always been an attractive alternative in hot-dry conditions, although indirect and direct evaporative cooling can be used in both dry and humid hot conditions; reason is that its water consumption rates have improved.

Evaporative liquid desiccant technology, a R&D technology, also consumes water and careful selection is needed in regions where water is scarce. Ground coupled solid desiccant AC is also a R&D technology and uses low grade thermal energy.

Magnetocaloric technology is commercially available for commercial refrigeration applications, although only one company claims production. It can therefore not be considered as widely commercially available.

Vuilleumier heat pump technologies are in the emerging phase and are definitely promising technologies.

Absorption fuel-fired technology as well as Vuilleumier heat pumps use low grade energy and serve both cooling and heating modes. For colder climates, where cooling efficiency is offset by a much greater heating efficiency, those technologies will offer important energy savings despite their lower cooling efficiency.

Table 12-2: NIK Technologies, development Status and short description

Type	**Development Status**	**Description**
A-Solid State Based Technologies:		
Magnetocaloric	Commercially available	Magnetocaloric effect is the basis of this technology, where paramagnetic materials shows reversible temperature change if exposed to a changing magnetic field. Ex : commercial refr. display units.
Thermoelectric	Widely commercially available	Based on thermoelectric Peltier effect of different material, when voltage is applied across them a thermal gradient occurs. Used for larger size applications. Plans to develop a window air conditioner. A car air conditioning prototype is planned.
Thermotunneling	R&D	Thermotunneling technology is a development of thermoelectric technology to improve energy efficiency.
B- Electro-Mechanical Based Technologies:		
Brayton Cycle heat pump	R&D for building space air conditioning Available for transportation, refr. and process cooling	Used in aircraft air conditioning systems, in the liquefaction of natural gas to transport from upstream liquefaction plants to degasify and pump downstream to consumers. Also in blast freezing and freezing tunnels and low temperature clod storage and cryogenic cooling.
Evaporative cooling	Widely commercially available	Indirect evaporative cooling allows cooling the air stream without raising its humidity and allows using the system in hybrid arrangements with other cooling systems. This expands its use, improves its efficiency while reducing water consumption
Membrane heat pump	R&D	Membrane technology for air conditioning provide dehumidification of space using a special polymer membrane to separated moisture from air. To reduce energy consumption, the dehumidified air can either be cooled or heated.
Thermoacoustic	R&D	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.
Thermoelastic	R&D	Shape Memory Alloys, when mechanically stressed will reject heat. The phenomena is reversible and SMA absorb heat as they return to their original shape. Ex: air conditioning cars seats, spot cooling for electronics equipment, portable refrigerators, wine cabinets, water coolers.

Type	Development Status	Description
C- Thermally Based Technologies:		
Absorption heat pump	Widely commercially available	Available with large range capacity for lithium bromide- water absorption units. Water- ammonia units of various capacities also available. Efficiency improving steadily.
Adsorption heat pump	Commercially available	Uses a hygroscopic salt with high affinity to water as an adsorption media and water as the refrigerant.
Duplex-Stirling heat pump	R&D Commercially available for cryocooling, comm. refrig. applications.	Uses a Stirling engine.
Vuilleumier heat pump	Emerging	Vuilleumier heat pumps are similar to Duplex Stirling engine heat pumps, but utilize two pistons instead of one piston.
Ejector heat pump	Commercially available	Uses an ejector technology to produce heat. Recovered ejector heat improves efficiency.
Stand-alone solid desiccant AC	Commercially available	Uses liquid desiccant technology for cooling.
Ground-coupled solid desiccant AC	R&D	Ground coupled solid desiccant cooling technology combine two technologies.
Stand-alone liquid desiccant AC	Emerging	Liquid desiccant technology is used instead of solid desiccant.
Evaporative liquid desiccant AC	Emerging	Combines liquid desiccant technology and evaporative cooling technology.

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Chapter 13

High ambient

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13 High Ambient

13.1 Recognition and perception of the issue

Until recently, there has been almost no recognition of the issue of High Ambient Temperature (HAT), beyond by those that reside in affected regions, where it comes to the implications associated with HAT on RACHP systems and equipment. This is largely due to the majority of the world's population living within temperate and tropical climate zones, where there are standard conditions for RACHP equipment. As such, few people have an appreciation for the circumstances and implications associated with operating RACHP systems in HAT regions.

HAT regions can be observed from the map in Fig. 13-1, which can be viewed with respect to global population density, as shown in Fig. 13-2. Generally, population density is inversely proportional to regions where the highest annual temperature exceeds 50°C. However, there are some regions, which do have a relatively high population density, despite being subject to HAT. These are Eritrea, India (central), Iran (southern), Iraq, Oman, Pakistan, Saudi Arabia (parts of) and USA (South Western, e.g., Arizona). There are other countries which also experience HAT, but those HAT regions are extremely sparsely populated. Incidentally, for reference, the hottest place on Earth is the Lot desert in Iran, where temperatures exceed 70°C.

Considering these populated HAT regions, their demand for RACHP products is 4-6% (derived from JRAIA, 2018) of global demand. Accordingly, global manufacturers of systems and components have hitherto tended to pay less attention to the special conditions and considerations that apply.

Whilst the general perception of those not residing in HAT regions is that addressing HAT issues is simply resolved by installing larger ACs or condensing units, the actual situation is much more complicated. For instance, systems need to be designed to handle the substantially broader range of temperatures and the various deleterious effects they can have on system operation, special considerations apply to installation such as avoidance of heat islands and in addition it normally involves substantial additional cost, partly because of larger equipment but also because of non-standard construction.[19] However units designed for HAT conditions have higher cooling capacity and higher condensing pressure leading to potentially higher leakage rate.

Accordingly, more comprehensive considerations may be given to HAT regions by policy makers and manufacturers.

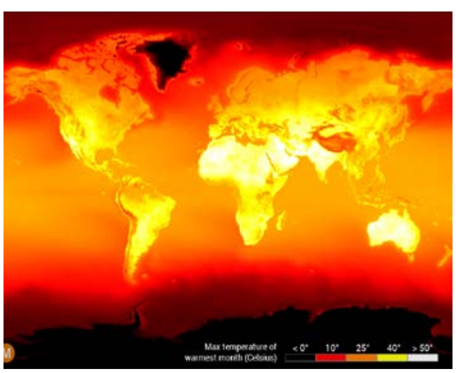

Figure 13-1: World map showing maximum temperature of the warmest month (http://metrocosm.com/peak-temperature-map/)

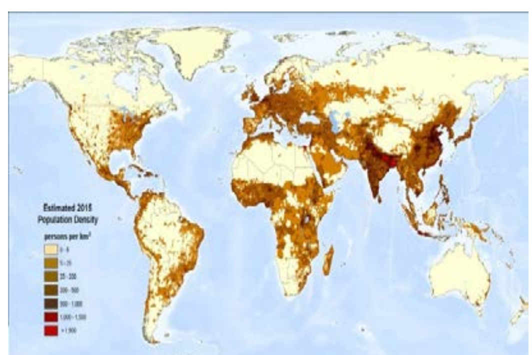

Figure 13-2: World map showing human population density (http://www.fao.org/nr/nr-home/en/)

[19] Sections elsewhere in this chaptere provide more detailed explanation of these issues.

13.2 Definition of high ambient temperature according to Kigali and countries covered

Previous TEAP Task Force reports summarised the methods to assess the temperature conditions using the incidence of the number of hours, weather profiles, cooling degree days, or bin weather data. These methods are used for designing air conditioning and refrigeration systems utilising existing tables for most cities around the world, or for specifying components for safe operation at certain conditions (TF-XXVII/4, 2016).

Montreal Protocol Parties (at OEWG-37, 2016) agreed to a definition of a “High Ambient Temperature Country” for a country that would have an incidence of at least two months per year over 10 consecutive years of a peak monthly average ambient temperature above 35°C. Countrywide values in the dataset applied (and decided by Parties at OEWG-37) are calculated by taking a spatially weighted average of all weather stations within that country.

For the "Peak Monthly Average" temperature, according to the Kigali HAT definition (Decision XVIII/2), the weighted average temperature is derived from the daily highest temperatures, according to the Natural Environmental Council (NEC) of the United Kingdom are used (CED, 2011).

These peak monthly average temperatures are checked over 10 years (2005–2014 for the latest available figures). For example, for each country, the peak average temperatures for the month of January during 2005-2014 are averaged to get the peak monthly average temperature for the January month.

Exemption for Parties (countries) has been agreed upon where suitable alternatives do not exist for the specific subsector of use. This exemption allows for a delay in the HFC freeze date and initial control obligations by an initial duration of four years. The exemption so far applies to 35 countries (i.e., the following Parties):
Algeria, Bahrain, Benin, Burkina Faso, Central African Republic, Chad, Cote d'Ivoire, Djibouti, Egypt, Eritrea, Gambia, Ghana, Guinea, Guinea Bissau, Iran, Iraq, Jordan, Kuwait, Libya, Mali, Mauritania, Niger, Nigeria, Oman, Pakistan, Qatar, Saudi Arabia, Senegal, Sudan, Syria, Togo, Tunisia, Turkmenistan and United Arab Emirates.

13.3 The high ambient issue-impact on capacity, efficiency and refrigerant selection

As ambient temperatures increase, the application system heat load increases while the refrigeration system capacity decreases due to higher condensing temperatures. This is a normal thermodynamic issue, but will be much more accentuated with higher ambient temperatures. Similarly, condensing pressure and thus compressor discharge temperatures also increase, leading to higher risk of reliability problems (Li, 2014). This will impact the capacity of the system and reduce the efficiency of the system installed, which will lead to a higher energy consumption for the cooling capacity to be provided.

The two key thermodynamic parameters that affect performance, particularly at high ambient temperatures, are the critical temperature and molar heat capacity (Domanski et al, 2000). At higher ambient temperatures and if no mitigation measures are taken some refrigerants will be operating too close to their critical pressure and the prescribed high pressure for good operation. Consequently, mitigation measures are taken to assure good operation if these refrigerants are used.

Example: at 67°C corresponding to the maximum allowable pressure prescribed by EN378:

- HCFC-22 corresponding pressure is 2,760 kPa equivalent to 55% of its critical pressure;
- R-410A corresponding pressure is 4,347 kPa equivalent to 91% of its critical pressure.

In non-HAT countries systems are normally rated for 35°C (T1 in ISO 5151:2014) with appropriate performance (under standards requirements) and up to 43°C for some countries. The high ambient temperature (HAT) condition requires a design at 46°C (T3 in ISO 5151:2014) with appropriate operation up to 52°C ambient temperature or more. At HAT conditions, the heat load of a conditioned space can be up to six times more than that for moderate climates with larger capacity refrigeration systems needed, also implying larger refrigerant charges. Specifically, heat loads are normally comprised of a constant contribution (such as from electrical appliances, occupants, etc. that do not vary with external ambient temperatures) and a variable contribution (such as heat conduction through walls, etc. and infiltration of ambient air) which are more or less proportional to the internal-external temperature difference. For example, in cool climatic regions specific heat loads may be in the order of 50 W/m^2 whereas in HAT climates specific heat loads may be up to 250 or 300 W/m^2.

Measures can be taken to mitigate the impact of operation in high ambient regions. In order to keep the condensing temperature as well as discharge temperature in the allowable operation range of the compressor used, larger condensers as well as capacity control and injection are applied that will also result in a larger refrigerant charge per kW cooling capacity.

13.3.1 Exemptions: defining the equipment

The TEAP XXVII/4 Task Force in its 2016 report, investigated criteria for defining high ambient temperature (HAT) countries. These definitions were evaluated and Parties decided on criteria as given above. The report also described results from the testing of alternatives to HCFC-22 where it concerns refrigeration capacity and efficiency (COP). Parties, in Decision XXVIII/2, decided to allow an exemption for Parties with high ambient temperature (HAT) conditions where suitable (HFC) alternatives do not exist for the specific sub-sector of use specifically:

- Multi-split air conditioners (commercial and residential)
- Split ducted air conditioners (commercial and residential)
- Ducted commercial packaged (self-contained) air-conditioners.

The exemption should become effective and available as of the HFC freeze date, with an initial duration of four years. The high ambient temperature (HAT) parties to which the above applies should formally notify the Ozone Secretariat of their intent to use this exemption no later than one year before its HFC freeze date, and then every four years thereafter (if they wish to extend the exemption). It was also mentioned that parties operating under this high-ambient-temperature exemption should separately report their production and consumption data for the sub-sectors (as specified above) to which the exemption applies. It was also decided that amounts of HFCs (Annex F substances) that are subject to the high-ambient-temperature exemption are not eligible for funding under the Multilateral Fund, while there would be the exemption for the high ambient temperature (HAT) parties.

Parties also decided that the Technology and Economic Assessment Panel (TEAP) will assess the suitability of HFC alternatives for use where suitable alternatives do not exist; this is based on criteria agreed by the parties that will include (but not limited to) the criteria listed in Decision XXVI/9. TEAP should also recommend sub-sectors to be added to or removed from the three sub-sectors given above. Furthermore, it was requested that the assessment referred to above will take place periodically, starting four years from the relevant HFC freeze date and every four years thereafter.

Parties also mentioned that, in a year no later than the year 2026, one should consider for the parties operating under the high ambient temperature exemption whether to extend the "compliance deferral" (exemption) for an additional period of two years and whether further deferrals should be considered thereafter.

Furthermore, for high ambient temperature countries, as for others, the linkage between the HFC and HCFC reduction schedules relevant to sectors and the preference to avoid transitions from HCFCs to high-GWP HFCs would have to be considered. One should therefore provide flexibility if no other technically proven and economically viable alternatives would be available. This would relate to certain sectors, in particular the industrial (process) refrigeration sector, in cases where no other alternatives are available, and where HCFC supply may be unavailable from existing allowable consumption, stocks as well as recovered/recycled material.

13.4 Challenges

HAT countries are facing many challenges that are related to finding the right alternatives for the HCFCs given the thermodynamic performance of refrigerants at higher ambient temperatures and the need for larger equipment with larger refrigerant charge.
The general impression is that products operating at HAT conditions are not different from those designed for lower temperature regions. The fact is that a HAT product should be specifically designed for HAT conditions using a specific refrigerant suitable for that application. The product should also have all the safety measures for the appropriate operation.

Since the number of units installed in HAT countries is lower than those installed in more temperate climates, manufacturers tend to concentrate their efforts on developing products for the temperate climates and use the same products in the HAT regions. Consequently, there is less differentiation in the products than the minimum needed for hot climates. The need for specific designs for HAT creates an additional economic burden for the introduction of new products more frequently. It also results in a reduced choice of products for each application.

13.4.1 Regulation: MEPS

Cooling and air conditioning is a necessity in most of the HAT counties and can consume up to 70% of the energy used in buildings. Regulations are developed to assure better utilization of energy and protection of consumer by supporting efficient products. Minimum Energy Performance Standards (MEPS) are varying from one country to another. Some countries, like Saudi Arabia, is following one of the most stringent MEPS standards in the residential applications.

Energy efficiency of equipment is expected to improve as the technology develops; therefore, MEPS standards are revised every three years to set the requirements based on technological capabilities, which will contribute to the energy conservation policies for the country. Testing and rating requirements for the MEPS standards are mainly based on the international standards like ISO and AHRI; and a reference MEPS standard followed by the industry is the ASHRAE 90.1 building efficiency standard.

13.4.2 Power availability and sources

Due to the high demand for cooling, HAT countries are always facing challenges in generating the required power to cater for the development plans. Cost of power is relatively high if the power source is from fossil fuel. The feasibility of producing energy from renewable sources has been higher but improved lately which can provide an opportunity in this area, however, HAT regions’ demand for power is very high and continues to be a challenge.

13.4.3 Water availability and sources

HAT countries are also facing challenges in availability of natural water, for example, most of the drinking water in countries of the Arabian Peninsula is desalinated sea water and too expensive to be used in cooling. This is causing a challenge to use water cooled equipment.

13.4.4 Refrigerant management and servicing

In high ambient regions, the average condensing temperatures are higher than in other regions and vapour-liquid heat transferring takes less proportion of the total condensing heat load due to the higher condensing temperatures. Average higher compression ratios due to larger temperature lift results in higher compressor power and potential shorter compressor life. The viscosity of the oil decreases and the insulation of the motor is affected. This coupled with the long working hours leads to higher risk of compressor breakdown and other failures (Li, 2014).

At HAT conditions, there is an increased possibility for systems to be contaminated with moisture, which requires special service skills and the need to improve service practices. This enforces the importance of education and training for the operators and technicians handling systems. The risks associated with flammability, while not limited to HAT countries, are accentuated due to the higher refrigerant charge associated with systems operating at higher temperatures.

HAT countries need special requirements for maintenance and repair including but not limited to some extra components and controls like leak sensors and liquid injection to reduce the discharge temperature.

For the same surface area to be conditioned, the average capacity of units installed in HAT regions is larger than those in more temperate climates with larger refrigerant charge. The larger charge and the low maintenance associated with some of the countries in those regions might result in higher direct emissions.

13.4.5 Technological capabilities of the local industry

The PRAHA project (see section 5 in this chapter) concluded that the research and development (R&D) personnel at OEMs in some of the HAT countries have diverse skills and design capabilities but need to acquire the knowledge of designing for low-GWP, flammable alternative refrigerants with the assistance of the technology providers. A full product redesign is needed for most of the products with a comprehensive process of design analysis, optimization and validation of results. (PRAHA, 2016).

Some manufacturers have started experimenting with low-GWP alternatives and designing for high ambient temperatures and designers are acquiring the maturity in designing and optimising products using those alternatives. On the other hand, research programmes at local institutes and centers in HAT countries related to assessing future refrigerants and technologies have not been implemented yet.

A second phase of the PRAHA project is working with global associations and research centres to support the process of decision-making related to the acceptance and promotion of low-GWP alternatives. Building the local design capabilities empowers local institutes to play key roles in assessing the local technological needs related to the promotion of low-GWP alternatives through the development of a comprehensive risk assessment model (PRAHA, 2017).

13.5 Limitations and design considerations

The objective of this section is to summarise the performance of the various HCFC-22 options for high ambient air conditioning applications.

The governing thermodynamic properties and principles result in a declining capacity and efficiency as the heat-rejection (refrigerant condensing) temperature increases. This is valid for all refrigerants including HCFC-22; however, some of the HCFC-22 replacements exhibit greater degradation in capacity and efficiency than HCFC-22 under high ambient temperature conditions.

Another consideration is related to the possible impact on the required refrigerant charge, where higher ambient temperatures can imply greater heat loads, larger system capacity and thus larger refrigerant charge. Therefore, where limits on refrigerant charge apply, those limits may be approached at smaller capacities; in these cases, additional (safety) measures may need to be applied to the equipment as well as a more thorough focus on system charge optimisation; this is being perceived as a consideration seldom applied by many system designers today.

Currently, the most widely applied replacements for HCFC-22 in most air conditioning applications are HFC blends, primarily R-410A and R-407C. HCs are also being used in some low refrigerant-charge applications. High-efficiency HFC-32 invertor-driven split wall units are already commercialised since 2015. More than 14,000 units have already been placed on the market. R-410A and R-407C both have lower critical temperatures than HCFC-22 (refer to Chapter 2 for values) because HFC-125 (a component of both R-407C and R-410A) has a comparatively low critical temperature; this is an important parameter since such refrigerants will exhibit a steeper decline in capacity with increased ambient (outdoor) temperatures than refrigerants having higher critical temperatures. This steeper decline in capacity is of particular importance in geographic regions, which have condensing design temperatures approaching the critical temperature of the refrigerant**.**

As well as the use of high efficiency components, the optimum selection of compressor, airflow, condenser design (i.e., tube diameter, fin design, coil circuitry, etc.) and expansion device can reduce the performance losses at high ambient temperatures (Bitzer, 2012). Thus, for most refrigerants, by taking measures to appropriately optimise the system, similar efficiencies to HCFC-22 can be achieved even at higher ambient temperatures.

Systems using low-GWP refrigerants are not currently available for large capacity systems in most regions with high ambient temperatures.

In HAT countries, special consideration must be taken when designing or selecting components for the air to air systems, including heat pumps. The following considerations may be taken during the design stage:

a. The condensing temperature must be reduced in order for the refrigeration cycle not to reach or be close to the refrigerant critical temperature. The low critical temperature for R-410A, requires the system condensing temperature to be lower than 70°C; consequently, special larger or more effective condensers are needed;
b. The discharge temperature is also an important factor to be considered when designing for HAT conditions. For air-to-air systems this can be controlled by using electronic type expansion valves and liquid injection systems;
c. Two-stage compressors can be used; however, there are obstacles for using them including cost and availability as two-stage compressors are currently available from a limited number of manufacturers. Most of the compressor manufacturers have chosen the invertor technology instead.

13.5.1 Refrigerant charge amount

With the use of larger condensers (fin-and-tube type) for HAT conditions to reduce the condensing temperatures, the refrigerant charge amount becomes an issue as it will be increased in this type of heat exchangers. There are technologies that are commercially available, including smaller tube diameters and microchannel condenser coils, which reduce the size of the internal condenser volume while also providing higher efficiency. The need for changing the design and the technology of the air-cooled condensers to meet HAT condition efficiencies requires a major change to the production lines for manufacturing the condenser coils adding a major component to the cost of line conversion.

The limitation of the refrigerant charge amount in existing and new systems is governed by two factors, the refrigerant acute toxicity exposure limit (ATEL) for the non-flammable gases and refrigerant lower flammability limit (LFL) or ATEL (whichever is the lower) for flammable refrigerants. This will be discussed in section 13.5.3 below.

13.5.2 Designing for MEPS: size and cost of units

Designing to meet the Minimum Energy Performance Standards (MEPS) in HAT countries is another important factor as most of these countries have new and upgraded MEPS. This requires special design of bigger, more efficient units with an obvious impact on the unit size and cost to meet these new MEPS.

13.5.3 Meeting safety considerations

With the transition from HCFCs and high GWP HFCs to medium and low GWP alternatives, refrigerant-related safety issues – specifically, flammability, toxicity and higher pressures – have come more into focus. RACHP systems and equipment should present a low risk to end users, operators and technicians and this is normally achieved through satisfying the design and construction requirements of the applicable national legislation. Such legislation also invokes to some extent risk analysis and risk assessment, which are used to demonstrate that all factors, variables, usage circumstances, etc., have been considered with respect to the various foreseeable hazards. Equipment and installation safety standards, where they exist, are either secondary means of complying with legislation or are voluntary best practice (at time of issuance) guides which in either case assist with minimising risk. The recent Decision XXVIII/4 Task Force report "Safety Standards for Flammable Low global warming potential (GWP) Refrigerants" provides a detailed overview of available safety standards including scope and content as well as relationship with legislation. In addition to the Decision XXVIII/4 Task Force report, Chapter 2 of this report also identifies the relevant international and regional safety standards, which can be applicable to all countries, including HAT countries.

13.5.3.1 Safety standards

Table 13-1 lists the main categories of requirements from the safety standards (as identified in Chapter 2), and identifies how each of those categories may be impacted on differently if the RACHP systems were intended for use in a HAT country relative to Medium Ambient Temperature (MAT) and Low Ambient Temperature (LAT).

Table 13-1: Main categories of safety standards and impact of HAT

Requirement	**Impact of HAT relative to MAT and LAT**
Classification (occupancies, systems, location, refrigerant)	None
Quantities of refrigerant per occupied space	Yes - higher heat loads infer more refrigerant
Space volume calculations	None
Requirements for mechanical components and piping	
- General requirements	None
- Specific requirements for particular components	None
- Materials	None
- Testing (strength pressure, tightness, functional)	Yes - strength and tightness needs to account for higher anticipated pressure
- Marking and documentation	None
Requirements for assemblies	
- General	None
- Design and construction (pressure requirements, piping, fittings, pressure protection devices, sources of ignition, etc.)	Yes - strength needs to account for higher pressure
- Testing (strength pressure, tightness, functional, conformity)	Yes - strength needs to account for higher pressure
- Marking and documentation	None
Location of refrigerating equipment (open air, machinery room, occupied space, ventilated enclosure, etc.)	None
Machinery rooms (ventilation, combustion equipment, lighting, accessibility, storage, emergency switches, openings, etc.)	None
Requirements for alternative provisions (occupied space, ventilation, safety shut-off valves)	None
Electrical installations	None
Safety alarms (general, power, warnings, specific for R717)	None
Detectors (location, function, performance, installation)	None
Instruction manuals, notices, and inspections	None
Maintenance and repair including change of refrigerant type	Tools and equipment handling units designed for HAT conditions need to be rated for higher temperature and pressure.
Requirements for recovery, reuse and disposal, transfer, transport, storage, disposal and documentation	Special machines used for HAT

The only types of requirements for safety standards that are impacted by high ambient temperatures are design/test pressures and refrigerant charge limits. The charge limits have an indirect impact.

Design/test pressures

Systems, piping and components are expected to withstand the internal pressure exerted by the refrigerant. Since any saturated vapour increases pressure with higher temperatures, RACHP equipment used in HAT countries must broadly withstand higher refrigerant pressures (for a given refrigerant) that those intended for use in cooler climates. Different standards offer various means of determining maximum pressures and similarly ways of dealing with potentially high and deleterious pressures.

As an example, Figure 13-3 compares the design pressures for individual strength pressure test (which is 1.43 × PS; the maximum allowable pressure) is shown for three different ambient conditions, assuming a 10 K temperature difference according to ISO 5149-2 ("ISO"). Similarly, values are also provided according to the IEC 60335-series of product standards, that specify 3 × maximum condensing pressure. It can be seen that maximum pressure under 55°C ambient is approximately 1.5 times that at 35°C. Withstanding these pressures is usually one option for ensuring pressure safety; often maximum pressure of a system is constrained by system components in which case other approaches may be followed (e.g., functional test) that for instance rely on pressure limiting devices.

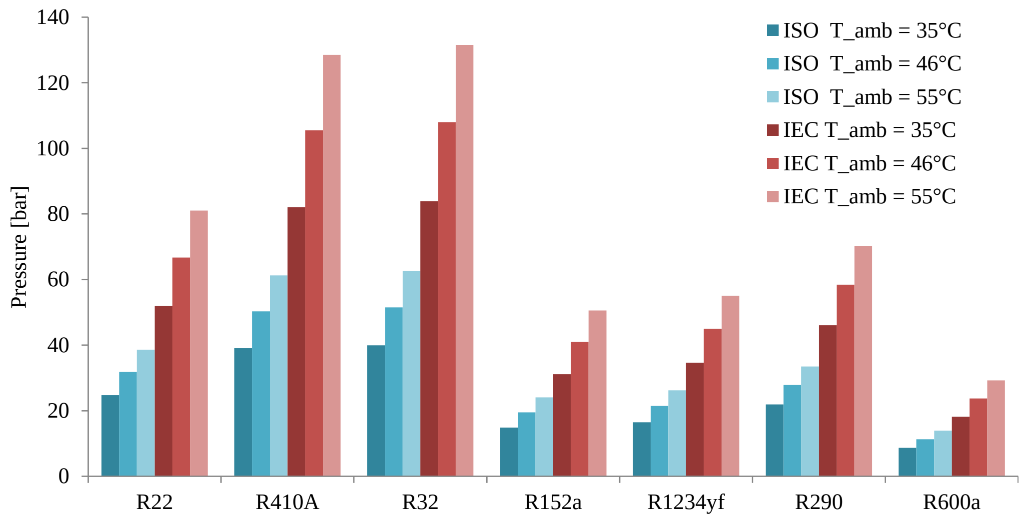

***Figure 13-3: Comparison of maximum strength test pressure for selected refrigerants according to ISO 5149 and IEC 60335-series*[20]**

Quantities of refrigerant per occupied space

Depending upon the circumstances, the maximum amount of refrigerant may be constrained according to the size of the space within which it will be installed and this is affected by the lower flammability limit (LFL) and acute toxicity exposure limit (ATEL). For flammable refrigerants, especially A2 and A3, the LFL dictates the constraint whereas for R-717 (which is class 2L) and R-744 (which is non-flammable), the ATEL has a strong influence.

For most types of RACHP systems, a higher ambient temperature has some impact on the refrigerant charge; for a system intended for 55°C ambient as opposed to 35°C and fixed nominal cooling capacity, charge may change by -10% to +10% depending upon refrigerant and temperature levels. However, higher ambient temperatures do impact on the cooling capacity for certain applications, such as cold stores (with external walls, doors, etc.), vending machines

[20] Calculation using refrigerant properties based on specifications in the standards

intended for outdoors and air conditioning of rooms (with external walls, doors, etc.) and buildings. Thus systems for applications where the cooling demand is negligibly affected by ambient temperature maximum quantities of refrigerant are not really affected. However, for those in which cooling demand is influenced by ambient temperature, systems with greater cooling capacity are needed. Assuming a fixed specific refrigerant charge (i.e., kg of refrigerant per kW of cooling capacity) it follows that more refrigerant is needed to cool a given size of space. For a given space size, refrigerant quantity may be limited within various safety standards as a function of LFL and/or ATEL as well as other parameters; detailed explanation is provided in the Decision XXVIII/4 TF report as well as Chapter 2.

Some examples are provided, comparing current charge limits and likely needs of an air conditioner's charge (according to current systems) for applications with low (L), medium (M) and high (H) specific heat loads in Figure 13-4 and 13-5 for A2L and A3 refrigerants, respectively. For A2L refrigerants, there is a wide margin between needed charge and the charge limits, for the example. For A3 refrigerants, the limit is exceeded beyond a certain room size for high specific heat loads, for the example. For some other applications, the relationship between charge limit and room size is linear, so the cross-over seen in Figure 13-5 does not occur.

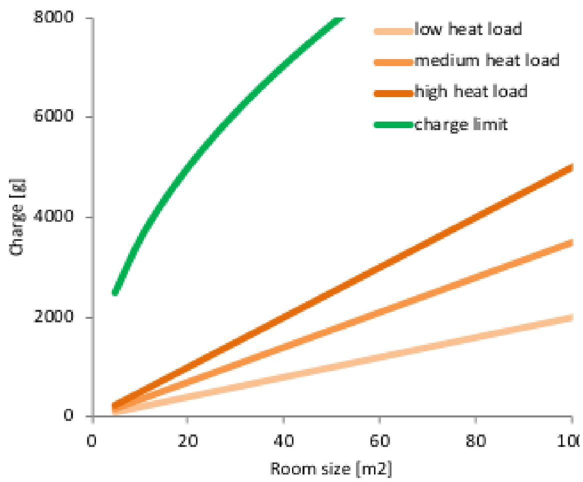

Figure 13-4: Comparison of charge limits for 2 m[21] units and likely charge needs for A2L refrigerants

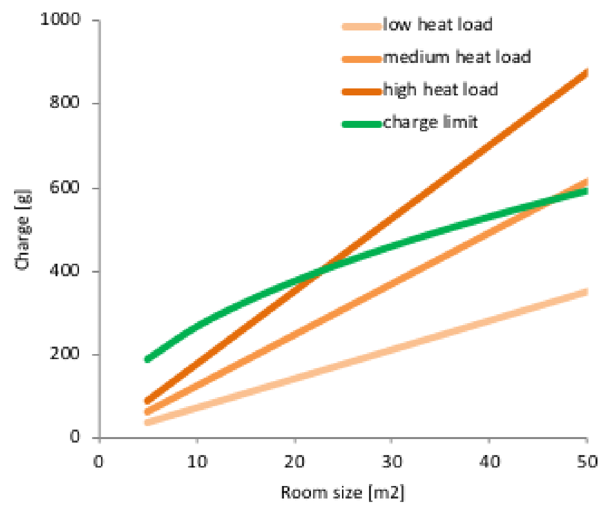

Figure 13-5: Comparison of charge limits for 2 m[22] units and likely charge needs for A3 refrigerants

Given these potential constraints, particularly for A2 and A3 refrigerants, certain measures can be introduced to minimise the likelihood of concentrations approaching the LFL occurring within the cooled space. Examples include use of unit airflow, improved tightness of systems and use of shut-off valves to limit the releasable charge. Work is underway with various safety standards to introduce such measures so that the refrigerant charge limit does not interfere with the amount of refrigeration required to satisfy high specific cooling demands.

13.5.3.2 Risk assessment

Given the potential constraints introduced by flammability of alternative refrigerants, flammability risk assessment (FRA) is a key aspect to consider with respect to the impact of HAT.

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[21] Indoor units installed at 2 meter height
[22] Indoor units installed at 2 meter height

There are various approaches to conducting FRAs, as can be identified throughout the literature. The Decision XXVIII/4 TF report offers a digest of many of the studies that have been carried out on various elements of, or entire FRAs specific to flammable refrigerants in RACHP equipment and applications. Whilst these studies seldom consider the effect of ambient temperature specifically, it is only one of a myriad of variables that are taken into account and may be examined, specifically.

Amongst the FRA methodologies there are various thermophysical and chemical processes and mechanisms that are investigated experimentally and numerically and an understanding of these enables an appreciation of the effect of ambient temperature on each. Key influencing factors are listed in Table 13-2 and items that are impacted by HAT are identified.

Table 13-2: Factors affecting flammability risk and impact of HAT

Parameter	**Impact of HAT (i.e., 35°C vs. 55°C)**
Leak and leak frequency	
Frequency of occurrence of leak and size of leak hole	Of 20+ leak mechanisms, corrosion is most affected by temperature, but depending upon type of corrosion may be increased or reduced by temperature
Mass flux of release	Leak mass flux is dictated by refrigerant pressure. With higher ambient, standstill and condensing pressure will produce higher mass flux; approximately 1.5 to 2 times higher, depending upon refrigerant
Flammability characteristics	
Lower flammability limit (LFL)	For A2 and A3 refrigerants LFL is affected negligibly but for some 2L refrigerants the absolute increase is greater, especially those of borderline flammability
Minimum ignition energy	Reduces by a few percent for A2 and A3
Adiabatic flame temperature	Increases proportionally to ambient (starting) temperature
Flame speed/burning velocity	Small increase (around 5%) for A2 and A3 refrigerants
Minimum experimental safe gap	Varies marginally for most fluids
Heat of combustion	Negligible for most refrigerants
Formation of flammable mixture	
Quantity of refrigerant/space dimensions	See Figures 13-4 and 13-5
Formation of flammable mixtures	Higher leak mass flux can lead to larger flammable volumes
Dilution and persistence of mixture	Density of refrigerant and air both vary with temperature so both buoyancy and entrainment are negligibly affected, although thermal gradients in structures are greater which can generate more mixing
Probability of ignition source	
Density of ignition sources	Not affected
Frequency of active events	Not affected
Severity of consequences	
Degree of confinement	Not affected
Presence combustible materials	Not affected
Room explosion relief	Not affected
Occupant density	Not affected

According to table 13-2, most factors have a negligible influence, although for some refrigerants with borderline flammability the relative contribution to risk may be significant (although in absolute terms still minute) on account of changes in flammability characteristics. The most significant impact is that for a given leak hole size the mass flux of a release will be greater, potentially leading to larger flammable mixtures (depending upon the circumstances).

The Phase-II of the PRAHA project has an element for developing a risk assessment module for HAT countries.

13.6 Testing and research programs

Four research projects have been launched since 2012 to test units working with various refrigerant alternatives at HAT conditions:

- "Promoting low GWP Refrigerants for Air-Conditioning Sectors in High-Ambient Temperature Countries" (PRAHA). Phase-I for testing five alternatives to HCFC-22 and R-410A in window units, mini-splits, ducted units and packaged units of various capacities. Units designed and built by six manufacturers in the Gulf countries and testing was done at an independent lab. Project finalised and report published in 2016 (PRAHA, 2016). Phase-II on risk assessment modules and design optimization is on-going;
- "Egyptian Project for Refrigerant Alternatives" (EGYPRA). Launched in 2015, the project tests units built by eight Egyptian manufacturers working with eight alternatives to HCFC-22 and R-410A. Mini-split equipment with three different capacities, and one central packaged air conditioner with 35 kW capacity were locally designed, built and tested by the manufacturers, the testing witnessed by an independent consultant. Report to be made public in 2019;
- Oak Ridge National Laboratory (ORNL) "High-Ambient-Temperature Evaluation Program for Low-Global Warming Potential (Low-GWP) Refrigerants". Test 1 in 2015 tested ten alternatives to HCFC-22 and R-410A in two ductless mini-splits of equal capacity units at the ORNL facility. Units were soft optimised for the different refrigerants. A report was published in 2015 (ORNL, 2015). Test 2 in 2016 tested eight alternative refrigerants in two packaged units in a similar manner to Test 1. A report was published in 2016 (ORNL, 2016).
- The AHRI Low GWP Alternative Refrigerants Evaluation Program (AREP) Phase-II tested seven alternative refrigerants to R-410A in various air conditioning machines either as drop-in or soft-optimised. The testing was done at the respective manufacturers' premises. Reports were published in 2015 and 2016 (AREP, 2015).

Table 13-3: Comparison of research programs

Description	Low-GWP AREP (AHRI)	ORNL – DOE Evaluation Program		EGYPRA (UNEP, UNIDO, Egypt)	PRAHA (UNEP, UNIDO, HAT countries)
		For mini split units	For packages units		
Type of test	Soft-optimization and drop-in tests of several A/C, Heat Pumps, chillers, and Ref applications	Soft optimised tests, of Two (2) base Split A/C units, each 1.5 TR nominal capacity	Soft-optimised tests, of two (2) packaged units, 7.7 and 11 TR nominal capacity	Build and test 36 prototypes in 3 A/C split categories and one Central A/C category	Build and test 23 prototypes in Window, split, ducted and A/C package categories
Status	**started 2014 and completed**	**Started and completed 2015**	**Started and completed 2016**	**Started in 2015 and planned to be completed by 2018**	**Started 2013 and completed**
Testing	Units were manufactured or obtained by each party and tested at each party's facilities	The units were optimised and tested at ORNL	The units were optimised and tested at ORNL	Prototypes built at eight OEMs, witness tested at own labs	Prototypes built at 6 OEMs, test at Independent Lab
Testing temperatures Outdoor	AHRI-B (27.8°C) AHRI-A (35°C) T3 (46°C) T Hot (52°C) T Extreme (55°C) *Note: varies by experiment	AHRI-B (27.8°C) AHRI-A (35°C) T3 (46°C) T Hot (52°C) T Extreme (55°C)	AHRI-B (27.8°C) AHRI-A (35°C) T3 (46°C) T Hot (52°C) T Extreme (55°C)	T1 (35/24°C) T3 (46/24°C) T Hot (50/24°C) T Extreme (55/24°C)	T1 (35/24°C) T3 (46/24°C) T3+ (50/24°C) Endurance (52/24°C) *Note: WB used for window unit testing
Testing temperatures Indoor	AHRI-B (26.7/19.4°C) AHRI-A (26.7/19.4°C) T3 (26.7/19°C) T Hot (29/19°C) T Extreme (29/19°C)	AHRI-B (26.7/19.4°C) AHRI-A (26.7/19.4°C) T3 (26.7/19°C) T Hot (29/19°C) T Extreme (29/19°C)	AHRI-B (26.7/19.4°C) AHRI-A (26.7/19.4°C) T3 (26.7/19°C) T Hot (29/19°C) T Extreme (29/19°C)	T1 (27/19°C) T3 (29/19°C) T Hot (32/23°C) T Extreme (32/23°C)	T1 (27/19°C) T3 (29/19°C) T3+ (29/19°C) Endurance (32/23°C)
Refrigerants tested	R-32, L-41a, ARM-71a, DR-5A, HPR-2A, L-41-1 and L-41-2, DR-55, L-40, N40b, AC5, N13a, L-20	R-290, N-20B, ARM-20b,R-444B, R-454C vs. HCFC-22 R-32, R-447A, R-452 B, HPR-2A vs. R-410A	R-444B, ARM-20b, R-454A. ARM-20a vs. HCFC-22 R-32, R-452B, R-447B, ARM-71a vs. R-410 A	R-290, R-444B, R-454C, R-457A vs. HCFC-22 R-32, R-447A, R-454A, R-459A vs. R-410A	R-290, R-444B, R-454C vs. HCFC-22 R-32, R-447A vs. R-410A
Other components	**N/A**	**N/A**	**N/A**	**Same Central unit with micro-channel**	**Several other assessment elements**

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Chapter 14

Modelling

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14 Modelling of RACHP systems

14.1 Overview

There are a number of models used to calculate data for refrigeration and air conditioning applications:

1. Thermodynamics based models that, in a straightforward manner, calculate energy efficiency and energy consumption for an RACHP application under certain well determined ambient (i.e., running) conditions;

2. Combined thermodynamic, flow and heat transfer models used in R&D studies to investigate the impact of refrigerant heat transfer, refrigerant properties, flow patterns (either steady state or dynamic simulation) and to investigate component, cycle and equipment design. In principle the focus is on the refrigerant and the consequences of its properties for the design. Important articles have been published by McLinden et al. (2017);

3. Models that focus on total (climate relevant) emission reductions from the application of RACHP equipment. They depart from assumptions or data on the number of pieces of equipment of certain types in the RAC(HP) subsector and from test data regarding energy efficiency improvements possible by changing refrigerants; they can therefore calculate climate benefits expressed in CO_2-eq. These models often combine both the climate benefit from the impacts of energy efficiency increase and the heat-cooling load reduction, which makes the whole "climate relevant reduction" not very transparent; this also because the fuel mix in power generation (the power factor) also plays an important role here;

4. Inventory ("bottom-up") models that calculate the amounts of refrigerant charged into RACHP equipment, where the equipment numbers are based on sales data of various types of equipment for a country or region, which can then also be defined as the (total, regional) bank of refrigerants. Together with assumptions regarding leakage and recovery during the equipment operation and at end of life, and most importantly, during servicing and maintenance, the refrigerant demand and the refrigerant emissions can be determined for a given year. Also the fluctuations in the size of the bank over a certain period can be calculated. Once a period is studied, it is evident that, in a first instance, economic data on growth and shrinking have to be taken into account as the dominant parameter for the time dependent demand and resulting bank and emissions behaviour. A description of the model is given in the Annex to the RTOC 2010 Assessment Report (RTOC, 2010). This type of model has been applied for scenario calculations up to the year 2050 in various TEAP Task Force reports that investigated possible future high GWP HFC as well as low GWP refrigerant demand. These reports were particularly published in the period 2012-2016, e.g., see (TEAP, 2016a).

During the last assessment period, 2014-2018, and even before, the focus for modelling has been on "bottom-up" models used to predict the regional or global refrigerant demand for RACHP equipment. This is clearly reflected in this 2018 Assessment Report. As mentioned above, it requires the determination of the number of pieces of equipment charged with refrigerants (which then forms the total inventory or "bank"), and knowledge related to the average lifetime and the emission rates of equipment, plus assumptions on recycling, disposal, and other parameters. Important parameters are the number of pieces of equipment (per sub-sector) manufactured in certain countries or certain regions per year, where the changes are very much dependent on economic growth (GDP) parameters, the types of refrigerants used, the ongoing development in equipment design, and, last but not least, the required refrigerant demand for servicing. A very sensitive issue here is the growth in the sales of pieces of equipment, which is, particularly at present and particularly for the AC subsector, completely disconnected from the overall economic national or regional growth parameters (e.g., far more growth in AC cooling equipment than can be derived from general GDP parameters).

It is therefore quite challenging to find good data on the production of various types of equipment and the related sales for domestic use and export; needless to say, that these are extremely important data (or parameters) for any “bottom-up” method. It can be stated that good progress has so far been made up to the year 2018 in determining these parameters, albeit with considerable uncertainty ranges, based on the publication of sales data and on specific refrigerant manufacturing information for the period 2014-2017. It is expected that the availability of all the data and parameters will enable to develop adequate “bottom-up” scenarios for the refrigerant demand (as well as the related banks and emissions) during the next 4 year assessment period (2019-2022), i.e., towards the freeze year for HFCs for the Group I Article 5 countries as mandated under the Kigali Amendment.

One important issue needs to be mentioned here, which is the check of the “bottom-up” refrigerant demand data for the R/AC sector with reliable chemical manufacturing data for both HCFCs and HFCs globally, as well on one or more regional bases. It is an advantage that the (RACHP) market for (high GWP) HFC chemicals can be determined reasonably well since the use of (certain) high GWP HFCs for other application sectors is quite moderate and can be estimated pretty well. However, it does need to be acknowledged that this does not apply for one refrigerant, i.e., HFC-134a. Where HCFC production data can be taken from Article 7 reporting to UNEP, only certain production data for developed (Annex I) countries can be taken from reports to the UNFCCC, furthermore, the high GWP HFC production data have to be extrapolated from manufacturers’ data, derived from market data reports from consultancy companies etc., as well as from specific country (“HFC surveys”) information.

An advantage is that production in (developed) non-Article 5 parties of some of the most used HFCs in the RACHP sector is reported to the UNFCCC, next to HFC emissions data, where the latter is a reporting requirement under the Kyoto Protocol. Further analysis then has to dive into further HFC chemical production data likely available from a very small number of chemical manufacturers in Article 5 parties, where both domestic production and production for export of equipment are parameters that need to be looked into in a detailed manner. The reliability of these data will be an important issue, of course.

There is some similarity of the HCFC RACHP market in the past compared to the current HFC market, which is helpful in deriving trends, although growth parameters of the latter market make comparisons often challenging. This “chemical check” has also been one of the most important efforts during 2014-2017.

14.2 Some specific applications

In section WG2.1 a list with the four different types of models have been given. Below one can find a number of examples that are of these various types.

1. One of the main purposes of the use of thermodynamic models is to investigate the characteristics and energy efficiency of (new) refrigerants or refrigerant blends compared to a base case. In 2017, one important contribution was published by McLinden (McLinden et al., 2017), who investigated a very large number of low GWP fluids, based on alkanes, olefines, alkynes (triple bound molecules), ethers etc. A thermodynamic model was used to investigate refrigerant capacity and COP (energy efficiency) characteristics compared to the currently used R-410A for specific temperature conditions. Although it was concluded that there may be some new fluids to be considered, these are expected to not lead to real thermodynamic efficiency improvements compared to the existing ones. Next to ammonia, propane-

like fluids are the ones that are shown to have good efficiency characteristics (i.e., propane, propene, cyclopropane, isobutane, propyne).

2. In 2016, the (RTOC) inventory model has been used in the Decision XXVII/4 Task Force report, in order to further investigate the demand for high GWP HFCs and low GWP fluids for the RAC(HP) sector until 2050. In particular, the impact of the length of the conversion period of the manufacturing in certain refrigeration and AC sub-sectors was considered.

3. In August-September 2016, results of the (RTOC) inventory model were used to create a sort of database for the demand of all refrigeration and AC (RAC(HP)) subsectors for a business as usual case for 2015-2050; this was done separately for non-Article 5 and Article 5 parties. Next to refrigeration and AC, data estimates were generated (and these were also extrapolated into the future) for other HFC consuming sectors (foams, aerosols, fire protection). Using all the data, the 2016 HFC Montreal Protocol amendment proposals were evaluated and compared (TEAP, 2016b), in particular where it concerns their climate benefits compared to a BAU case (i.e., the reduction in Mt CO_2-eq. compared to BAU). Good results were obtained which could be used in the discussions towards establishing the baselines and reduction schedules as currently laid down in the Kigali Amendment. It should be mentioned that the demand is, of course, directly linked to economic growth parameters as well as assumptions on equipment leakage during lifetime.

4. A similar inventory method has been used in the "Gapometer" modelling approach (EPEE, 2016). Rather than studying overall characteristic parameters (i.e., demand, banks, emissions) for non-Article 5 and Article 5 parties, and checking them against global HFC production data in a certain year, this method has been applied to separate Article 5 (and non-Article 5) parties. On the basis of the availability of specific HFC consumption (i.e., demand) data from HFC country surveys, applied to equipment numbers estimated, first estimates could be provided of the demand for specific HFCs for a number of years into the future. This is again related to the availability of data assumptions for economic growth and equipment parameters which are directly related to the refrigerant bank (equipment) and the demand for specific HFCs. It will be clear that, using this bottom-up method, refrigerant emissions can be calculated as well.

5. A slightly different inventory-emissions calculating method, with details published in 2016, gives the potential of savings in emissions towards the future. An overall analysis of the emission potentials of various sectors, including PFCs and HFC-23, was given in the publication by Purohit and Hoglund-Isaksson (2016). The authors also give first estimates for abatement costs. Where the study is based on an existing emissions calculating model, it is also clear that the results are dependent on multiple assumptions regarding physical parameters and geographical distribution of emissions, where underlying assumptions on the demand function etc. are needed. Results are therefore far more dependent on the quality of changing technology data as well as physical input data than on the above mentioned bottom-up types of modelling.

6. Modelling has also been done with a focus on total (climate relevant) emission reductions. They depart from assumptions or data on the number of pieces of equipment of certain types in the AC subsector in particular and from test data regarding energy efficiency improvements possible by changing or converting of refrigerants. Together with assumptions about the leakage of refrigerant during the operation and at end of life, plus the savings in CO_2-eq. by a conversion to low GWP refrigerants, a total saving in CO_2-eq. can be calculated. The emphasis here is not on the refrigerant charge amounts, but on refrigerant emissions and the CO_2 emissions related to electricity use; this is then dependent on the hours of operation, capacity, equipment energy efficiency development, as well as on the power mix in separate countries,

etc. All information is subsequently translated into total CO_2 emissions savings.

The adoption and ratification of the Kigali Amendment will drive new studies on the impact of the use of lower GWP fluids. This will likely include a further emphasis on the impact of energy efficiency and the consequences for energy demand and related CO_2 emissions (TEAP, 2018; Kuijpers et al., 2018). The quality of the rapidly evolving technical data will be fundamentally important, in order for the modelling to provide correct and timely conclusions on the mitigation offered by lower GWP refrigerant fluids, and for prioritising policy.

14.3 Results from TEAP Task Force reports

The Decision XXIII/9 Task Force report (TEAP, 2012) was one of the first reports following a request to the TEAP to report on quantities and types of alternatives already and projected to be phased in as replacements for hydrochlorofluorocarbons, disaggregated by application, in both Article 5 and non-Article 5 parties.

The data on refrigerant inventories (banks) in this report are again based on the Tier 2a methodology as defined in the Revised Guidelines for Greenhouse Gas Inventories (IPCC, 2006) and the bottom-up calculation methodology has been published in Annex 2 of the RTOC 2010 Assessment Report (RTOC, 2010). For the projections from 2010 to 2015, certain assumptions were made for near term refrigerant choices projected to be made by non-Article 5 parties. These assumptions were also thoroughly discussed with a number of experts from global manufacturing companies specialised in stationary air conditioning and commercial refrigeration. First, the data on refrigerant banks for commercial refrigeration and stationary air conditioning were derived for a number of large Non-Article 5 and Article 5 countries as well as several regions. These were then added up with totals assigned to one of two groups, the Article 5 and the non-Article 5 parties. For the year 2015, the data on HCFC replacements as in the approvals by the Multilateral Fund were also used.

The refrigerant demand includes refrigerant charges for new equipment and refrigerant quantities used for servicing the installed bases of equipment. Imported refrigerant quantities were included in the demand; they were taken into account through annual equipment sales.

The XXV/5 Task Force report (TEAP, 2014) made significant progress in defining a Business as Usual (BAU) and two mitigation scenarios, for both R/AC and foams. On the basis of bottom-up modelling, banks and demand were calculated up to the year 2030. The most important result from this study was the huge increase in the refrigerant demand over a period of 20 years following a BAU scenario, as well as the impact of certain mitigation scenarios on the refrigerant demand over the same period.

The XXVI/9 Task Force report (TEAP, 2015) gave information again on the quantities and types of alternatives. The refrigeration and air-conditioning sectors were disaggregated into six sub-sectors in this report. However, due to the diversity of equipment that can be found within the same sector, a more disaggregated level is needed in order to calculate the emission factors and the activity data, such as equipment lifetime, average charge, and refrigerant type. For example, if one considers the commercial refrigeration sector, the emission factor varies widely between the different refrigerating systems that can be found within this sector: the emission factor for standalone equipment is in the range of 1% and, for large centralised systems, it can reach a value of up to 30%. The mass-balance approach shows limitations especially if the recharge frequency is not on annual basis as *for MAC systems*: what then enters for the servicing in a given year is not equivalent to what has been emitted in that year. A delay of 5 to 8 years could be observed for certain cases. In a mature market, where the average charge of MAC systems does not change and emission characteristics are also constant over time, this model can be used since principle vehicle characteristics are identical.

In this report, the GWP for low GWP replacement refrigerants was constructed as follows. In domestic refrigeration the use of isobutane was assumed with a very low GWP. In cases where the replacement refrigerant were known (ammonia, hydrocarbons) very low GWP factors were used. In case of commercial refrigeration one assumed (1) the use of either carbon dioxide, or pure low-GWP refrigerants or refrigerant blends in supermarkets, (2) the use of low GWP hydrocarbons in mass produced units, and (3) HFC-HFO blends or carbon dioxide in case of condensing units (with an average GWP of 300 assumed). For the stationary AC subsector as a whole, an average GWP of 300 was also used, where, on the other hand, MAC replacement refrigerants were assumed to have negligible GWP.

The XXVI/9 Task Force report, in its Table 5-2, gave percentage ranges for most sub-sectors related to equipment, which was assumed to show different annual leakage percentages (e.g. in transport it would be refrigerated trucks, containers, other types of products, in stationary AC, one can separate between many types of equipment, each with specific leakage rates).

Table 14-1: Lifetime and leakage per year for equipment assumed in the various R/AC sub-sectors for non-Article 5 and Article 5 Parties. The lifetimes and percentages in the two groups of countries vary dependent on the specific country (from the XXVI/9 TF report, Table 5-2).

Country	Sub-sector	Lifetime (year)	Leakage/year
non-Article 5	Domestic refrigeration	15	1%
	Industrial refrigeration	15-30	15%
	Transport refrigeration	9-30	15-30%
	Commercial refrigeration	15	15-30%
	Stationary AC	10-25	2-10%
	Mobile AC	15-16	10g/y for cars 15% for other
Article 5	Domestic refrigeration	20	2%
	Industrial refrigeration	15-30	15-30%
	Transport refrigeration	9-30	15-30%
	Commercial refrigeration	20	15-40%
	Stationary AC	10-25	2-10%
	Mobile AC	15-20	10g/y for cars 10-20% other

Depending on the application sector, uncertainties are different either because the activity data include different uncertainties or because emission factors may vary significantly from one country to the other. (RTOC, 2010) describes a simple approach that gives a quality index expressed in percentages. For activity data the market, the refrigerant charge and the equipment lifetime are the main elements that define the data quality. For emission factors, fugitive emissions and recovery efficiency at end of life are the two key parameters. Uncertainties on input parameters are based on expert judgements of the different sectors. The XXVI/9 TF report was the first Task Force report that gave a table containing these values.

Table 14-2: Uncertainties on input parameters for the various RAC sub-sectors (from the XXVI/9 report, Table 5-3)

Uncertainties on input	MAC	Stat AC	Industrial	Transport	Comm.	Domestic
Equipment market (a)	2.50%	2.50%	10%	12.50%	7.50%	2.50%
Equipment lifetime (b)	7.50%	2.50%	7.50%	2.50%	7.50%	12.50%
Equipment aver. charge (c)	2.50%	12.50%	10%	7.50%	7.50%	2.50%
Emission rate (d)	10.00%	7.50%	10%	7.50%	10%	12.50%
Recovery efficiency (e)	10.00%	7.50%	12.50%	7.50%	12.50%	2.50%

Uncertainties in the banks were estimated at 12.5-22.5%, uncertainties in emissions 12.8-37%, specific numbers are assumed to be dependent on the sub-sector. For the total RAC sector, the uncertainty range in the demand calculated was estimated from -10 up to +30%.

Estimates should be cross-checked with reported HFC consumption and production data, specified per refrigerant (or refrigerant blend). However, for non-Article 5 Parties, the annual emissions and demand reporting via UNFCCC is not very reliable (since certain chemicals are reported as part of a group, in t CO_2-eq., and for Article 5 Parties, data are not available on an annual basis, if at all. This XXVI/9 Task Force report is the first one to give estimates for HFC production of the four main HFCs (based on the 2012 UNFCCC data and a large number of estimates for the production in Article 5 Parties, i.e., mainly China). These HFCs are the ones used in the RACHP sector. It showed a total production of about 475 ktonnes as a forecast for the year 2015 for the four main HFCs (about 910 Mt CO_2-eq., if calculated in climate terms). The global production capacity for these HFCs was estimated much higher, at a level of about 750 ktonnes. It needs to be emphasised that the global HFC production (for the four main HFCs) determined in this way was estimated to have a ± 10% uncertainty for the separate HFC chemicals. These production data were assumed to be reasonably reliable global estimates (at the time of publication of the report) and they could be used in order to check the demand (consumption) data determined via the bottom-up method used. For clarity, it applied to the following HFCs (as used in the RACHP sector): HFC-32, -125, -134a and -143a.

Table 14-3: Estimates for global HFC production (for HFC-32, -125, -134a and -143a) (from the XXVI/9 TF report, Table 5-4)

Gg (ktonnes) for HFCs (per year)	(Montzka, 2015) Emissions year 2012	UNFCCC based estimate for non-A5 prod. (2012)	Estimate for non-A5 production (for 2015)	Estimate from various sources A5 production (for 2015)	Estimate global production year 2015 (*)
HFC-32	16 (21**)	≈ 22	23	71	94
HFC-125	41	< 30	31.5	98.5	130
HFC-134a	173	< 100	97	126	223
HFC-143a	21	<10	11	17	28

Note: (*) Global production is equal to non-Article 5 plus Article 5 country (China, minor other) production
Note: (**) Estimate from Rigby (2013)

The production amount of HFC-32 was assumed to be growing rapidly, mainly due to production in Article 5 Parties. The same would apply to HFC-125. In 2015, HFC-143a production was assumed to be 28 ktonnes. The HFC-134a amount produced was thought to be in the order of 220-230 ktonnes (223 ktonnes given in the table above); this may have been slightly underestimated, amounts could have been in the order of 240-250 ktonnes in the period 2015-2017, for all applications (including outside RAC). The bottom-up method gave a global result of about 28 ktonnes for HFC-143a, which seems to be consistent. Values for HFC-134a estimated in the RACHP sector were in the order of 170-180 ktonnes, which would be consistent with total estimates for RACHP and other (non RACHP) HFC-134a uses (as in the table above). The production quantity of HFC-32 and HFC-125 together can be calculated as about 225 ktonnes in 2015 from the table above. The bottom up method calculates 250-260 ktonnes for the year 2015, which seems to be too high, maybe due to the use of particular assumptions for the use of R-410A for stationary AC in the bottom-up method, or production might also have been slightly underestimated.

In the Decision XXVII/4 Task Force report one can find the request by parties to expand the demand scenarios to (the period 1990-) 2050, twenty years after 2030, which was the last year applied in the scenarios used in the XXVI/9 Task Force report. Three, ever more detailed versions of the XXVII/4 Task Force report were published in the course of 2016 (TEAP, 2016).

Several scenarios that apply to the R/AC sector were investigated for the XXVII/4 Task Force report. For the BAU scenario various regulations and actions as well as pending regulations applied by Parties were considered, with the F-gas regulation in the European Union (EU) and regulations in the United States (US), making certain HFCs unacceptable for certain sub-sectors by specific dates were applied. This implies that, in the business-as usual (BAU) calculation, certain high GWP substances in specific subsectors were replaced by low or lower GWP substances. Three mitigation scenarios were considered (a) a MIT-3 scenario: 2020 *completion of* conversion in non-Article 5 Parties of all RAC sub-sectors and the start of the manufacturing conversion of all RAC sub-sectors in 2020 in Article 5 Parties (2020-2050) (see Figure 14-3), (b) a MIT-4 scenario: the same as the MIT-3 scenario, but with the assumption of the year 2025 for the start of the manufacturing conversion for stationary AC in Article 5 Parties (2020-2050), and (c) a MIT-5 scenario: the same as the MIT-3 scenario, but with the assumption of a 2025 *completion of* conversion in non-Article 5 Parties of all RAC sub-sectors and the start of the manufacturing conversion of all RAC sub-sectors in 2025 in Article 5 Parties (2020-2050).

It was mentioned that, for Article 5 Parties, manufacturing conversion projects would need preparation to be funded; it would also take a certain period of time before conversion projects would have been approved by a funding authority, so that they can be initiated. Finally, experience with CFCs and HCFCs had shown that, the slower the conversion of manufacturing, the longer the servicing tail will be, i.e., the longer servicing of equipment will be required.

In order to give an impression (taken from the XXVII/4 Task Force report), the growth rates apply as given in Table 14-4 below.

The bank of refrigerants is substantially larger (10-20 times) than the annual refrigerant demand. In fact, the bank as calculated determines the amount of emissions, dependent on leakage assumptions during operation. The total demand is the sum of the amount used for new manufacturing and for re-charging to balance the refrigerant that is lost via all types of emissions. Banks of refrigerants could be given for regions and/or for certain parties (countries) as used in the model, but the amounts that would then be presented would not contribute to a better understanding of the demand, which is the essential parameter in this chapter that deals with refrigerant demand scenarios.

As already mentioned in the Decision XXVI/9 TF Report and the September 2015 Update Report (TEAP, 2015; TEAP, 2015a), estimates should be cross-checked with reported HFC consumption and production data, specified per refrigerant. For the most recent cross-check, information can be found below.

The XXVII/4 Task Force report also estimated global production quantities for HFC-152a, HFC-227ea, HFC-245fa and HFC-365mfc at around 140 ktonnes, of which HFC-152a production was estimated in the order of 60 ktonnes (where the total was translated into 160-170 Mt CO_2-eq. in climate terms). However, these data are of virtually no importance for the RACHP sector. In the XXVII/4 Task Force report, the total HFC production for the year 2015 was estimated at about 1220 Mt CO_2-eq.

While the production data for the four main HFCs are reasonably reliable global estimates, they have been used to check (and calibrate) the RACHP demand data determined via the bottom-up method used; details are given in the section below. For the RACHP sector as a whole, the total bottom-up demand that has been calculated for the year 2015 for non-Article 5 Parties (200.5 ktonnes) and Article 5 Parties (272.9 ktonnes) equals 473.4 ktonnes. This relates to the four main HFCs (also given in Table 14-3). It would imply that about 50-55 ktonnes of the four main HFCs (mainly HFC-134a) are used in sectors other than RAC, globally; these other sectors would mainly be foams, medical and technical aerosols. It was stated that one needs to take into account that both the production estimates and the bottom up calculated R/AC demand have >10% uncertainties for the separate chemicals and sub-sectors.

Table 14-4: Growth rates for high-GWP HFC demands in the various RAC sub-sectors (manufacturing and total) during the periods 2010-2020, 2020-2030 and 2030-2050 (the total growth rate is likely different from the manufacturing growth rate, due to the impact of the servicing sector, considering equipment manufactured earlier)(XXVII/4 Task Force report, Table 6-1)

Non-Article 5 Parties				
Sub-sector		**2010-2020**	**2020-2030**	**2030-2050**
Domestic refrigeration	Manufact.	-6.0%	-1.5%	3%
	Total	-6.0%	-1.5%	3%
Commercial refrigeration	Manufact.	-10.5%	0.1%	3%
	Total	-2.0%	-5.5%	2.1%
Industrial refrigeration	Manufact.	-2.1%	-1.8%	3%
	Total	0%	-1.2%	1.8%
Transport refrigeration	Manufact.	-9.5%	-4%	3%
	Total	-1.3%	-0.2%	0.9%
Stationary AC	Manufact.	5.8%	3%	3%
	Total	8.5%	2.8%	2.7%
Mobile AC	Manufact.	-12.5%	3.3%	3%
	Total	-3.6%	-5.5%	1.9%
Article 5 Parties				
Sub-sector		**2010-2020**	**2020-2030**	**2030-2050**
Domestic refrigeration	Manufact.	5.8%	5.8%	4.5%
	Total	4.8%	5.8%	4.5%
Commercial refrigeration	Manufact.	12.9%	8.6%	4.5%
	Total	16.5%	9.6%	5.1%
Industrial refrigeration	Manufact.	8.8%	6.8%	3.7%
	Total	6.1%	6.1%	4.2%
Transport refrigeration	Manufact.	5.8%	4.5%	4.5%
	Total	9.5%	5.7%	4.4%
Stationary AC	Manufact.	15.8%	6.0%	1.5%
	Total	17.7%	8.3%	3.0%
Mobile AC	Manufact.	5.0%	5.0%	5.0%
	Total	6.4%	5.0%	5.0%

On the conversion period, the XXVII/4 Task Force report shows a number of interesting figures, see Figure 14-1 below. A twelve-year conversion period does not yield a decrease in total demand until after 4-5 years after the start of the conversion in the year 2020. The build-up of the servicing demand (from the manufacturing that has not yet been converted) causes this profile with an increasing demand curve (during 2020-2025). Not until ten years after the start of the conversion in 2020, a demand reduction of 20-25% can be observed in this case. In the year 2026, the demand for the 12 years conversion period is almost twice as high as for the six years conversion period, which underscores that a rapid conversion will be very important. It will be clear that there is a direct relationship of the shape of the curves to the length of the conversion period. There are also cost implications. A six-year conversion period would imply twice the costs in the first six years after 2020 (2021-2026), compared to the 12 years conversion period, where the same amount will be spread over 12 years.

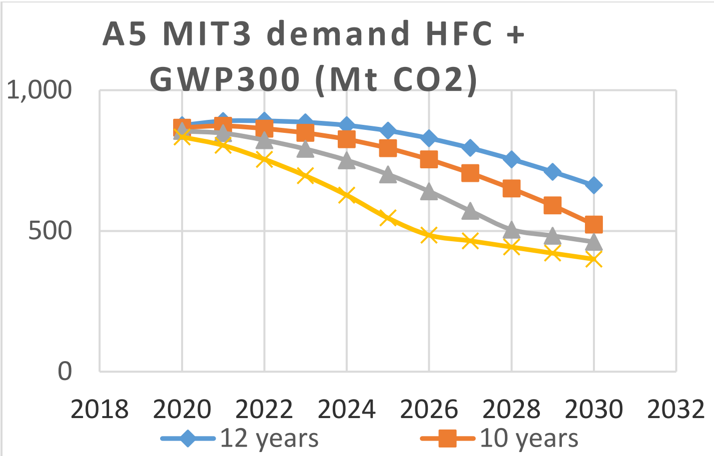

Figure 14-1: Article 5 MIT-3 demand scenario for all R/AC sectors for new manufacturing conversion periods of 6-8-10-12 years in Mt CO_2-eq. (Figure 6-17, XXVII/4 Task Force report)

Longer periods than 12 years were also considered, where this leads to very long delays in the decrease of the refrigerant demand, see Figure 14-2 below.

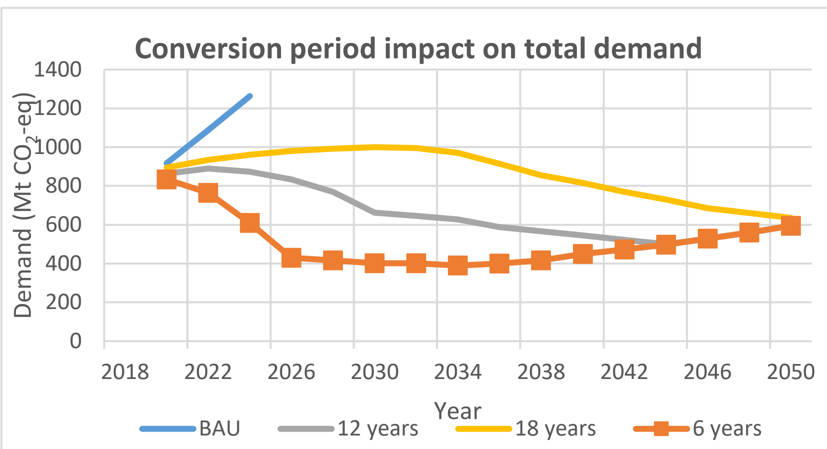

Figure 14-2: Article 5 MIT-3 total demand scenarios for 6, 12 and 18 years manufacturing conversion periods (compare also Figure 6-14 and 6-17 for MIT-3, 6 years and 6-8-10-12 years conversion periods) (Figure 6-18, XXVII/4 Task Force report)

Whereas the 6 and 12 years conversion periods result in a demand decrease after 2020, the 18 years conversion period yields an almost 10% increase in demand first, until the year 2030, then starts to decrease and reaches the 2020 demand level again in the year 2037. This is due to the build-up of servicing demand from HFC products still being manufactured, while there is economic growth for the various R/AC sub-sectors.

The 6 years conversion has no high GWP servicing demand after 2032-2034, the 12 years conversion has high GWP HFC servicing demand until 2042-2044, for the 18 years conversion period there is still some high GWP servicing demand until around 2050.

Compared to the total refrigerant demand for the period 2020-2050 for a 6 years conversion period (in climate terms), the demand increase by 70% in case of a 18 years conversion period.

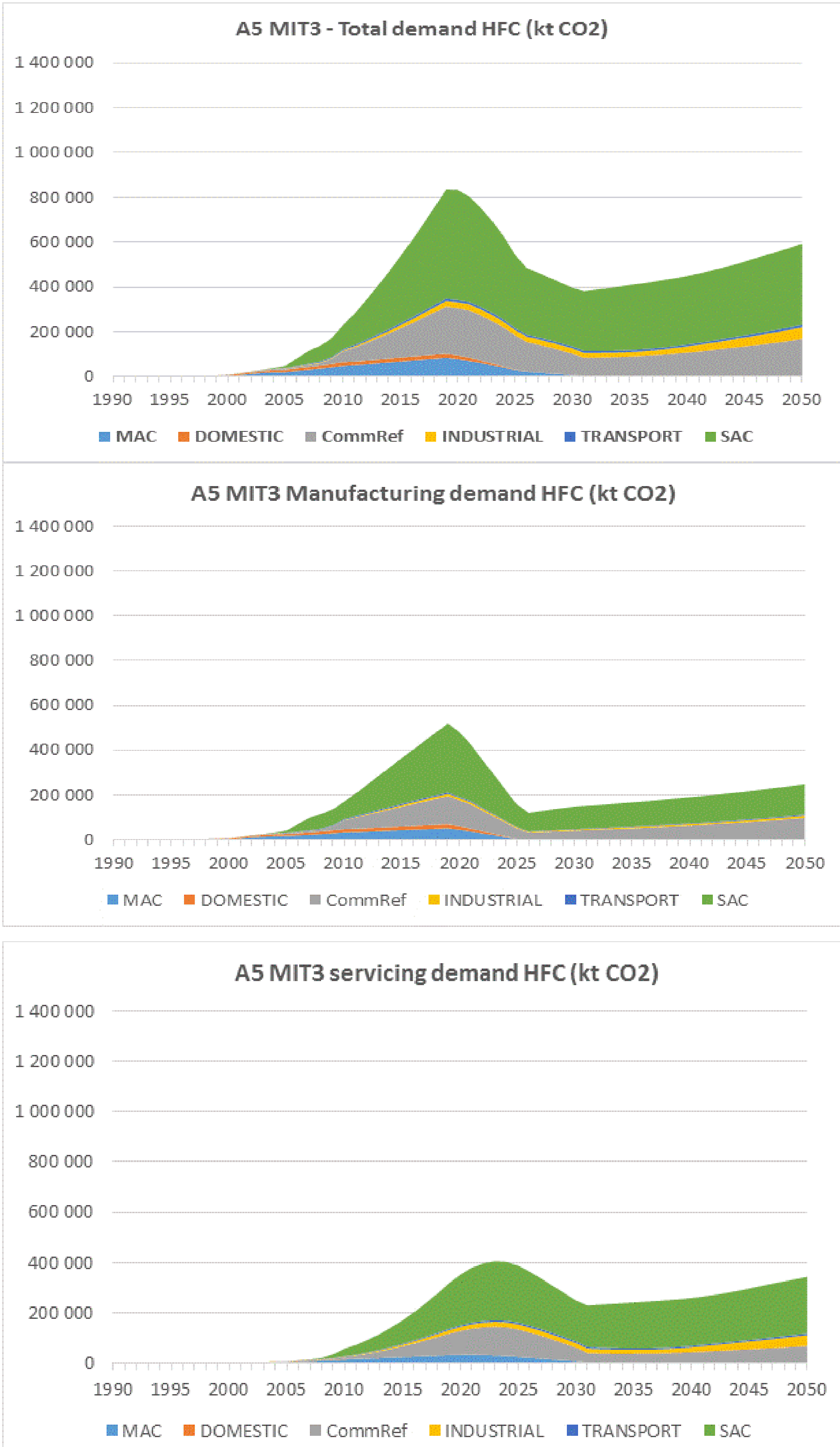

Figure 14-3: Article 5 MIT-3 scenario with the total, manufacturing and servicing demand for the various sub-sectors in ktonnes CO_2-eq. (Figure 6-14/15/16, XXVII/4 Task Force report)

14.4 Results from the TEAP Ex.III/1 report

Table 14-5 (as published in the Ex.III/1 report (TEAP, 2016a)) shows slightly adjusted estimates (compared to Table 14-3) for the global production of the main HFCs in 2015 at 665 ktonnes, equivalent to about 1220 Mt CO_2-eq.

Table 14-5: Estimates for 2015 non-Article 5, Article 5 and global HFC production (ktonnes)

HFCs	Estimate for non-A5 production (2015)	Estimate for A5 production (2015)	Estimate global 2015 production
HFC-32	23.0	71.0	94.0
HFC-125	31.5	98.5	130.0
HFC-134a	97.0	176.0	273.0
HFC-143a	11.0	17.0	28.0
Sub-total			*525*
Other HFCs (HFC-152a, -245fa, -365mfc, -227ea, -236fa)*, **			140.0
Total			665.0

* A substantial part is related to non-feedstock HFC-152a production, global estimate at slightly higher than 60 ktonnes; of this, only 5-10 ktonnes relate to use in foam production

** Estimated global production of HFC-236fa is estimated as small (300-500 tonnes); HFC-236fa is produced in one Article 5 country (Kuijpers, 2016)

The *four* main HFCs are almost only used in the RAC sector, except for HFC-134a, which is also applied in several other sectors (such as foams, aerosols, MDIs). For these four HFCs, a total (global) HFC production of about 525 ktonnes was estimated for the year 2015.

Global production quantities for other HFCs (HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa and HFC-365mfc) were estimated at around 140 ktonnes (160-170 Mt CO_2-eq.), of which a substantial part in tonnes (but not in Mt CO_2-eq.) consists of HFC-152a production (Kaixian, 2015, Kuijpers, 2016).

The consumption values calculated and estimated for all sectors and chemicals are given below, in Table 14-6.

For this report, the tonnes estimated for the RAC manufacturing and the RAC servicing sector are important (consumption of RAC manufacturing and servicing is 60% of the total in non-Article 5, 89% of the total in Article 5 parties, 73% of the total consumption globally.

Table 14-6: Estimates for non-Article 5, Article 5 and global HFC consumption in 2015 (ktonnes) (Ex.III/1 report, Table 2-2)

Sector	Estimate for non-A5 consumption (2015)	Estimate from various sources A5 consumption (2015)	Estimate global consumption 2015 (*)
R/AC manufacture	106.6	185.8	292.4
R/AC service	94.2	87.0	181.2
Foams	71.0	12.6	83.6
MDIs	10.1	3.9	14.0
Aerosols	50.0	9.0	59.0
Fire protection, others	5.5	9.5	15.0
Total	**334.4**	**305.8**	**645.2**

In the Ex.III/1 report, the HFC BAU scenario for non-Article 5 parties takes into account available, reported HFC consumption up to 2014 by non-Article 5 parties or regions to estimate total (global) HFC consumption. It needs to be noted that the annual reporting of consumption or supply may also take into account stockpiling. The value of these reports is to provide some indication of short-term trends, but analysis of BAU demand is needed for the longer term. In the Ex.III/1 report, the HFC BAU scenario for Article 5 parties is calculated without accounting for any HFC regulations as the impacts for these parties are not clear. The BAU scenario specifically takes into account economic growth factors expected for the period 2015-2050, as they were already presented (for RAC) in the XXVII/4 Task Force report (TEAP, 2016).

The construction of the HFC BAU scenario for the RAC sector includes a manufacturing and servicing component (see Table 14-7 below). The total HFC manufacturing demand is determined by the amount of equipment that is manufactured after the conversion away from HCFCs (this only applies to Article 5 parties), and by the continuing growth in the numbers of HFC equipment. For Article 5 parties, this results in a steady growth in the HFC demand for the four major HFCs used in RAC. In the case of the HFC BAU scenario for non-Article 5 parties, the demand for HFCs is reduced through the impact of existing regulations. Certain sub-sectors and certain countries are not subject to such regulations, so there will be a certain level of growth in the non-Article 5 HFC BAU demand.

The HFC servicing demand is the total HFC amount that is required to guarantee good operation of the equipment bank in the RACHP sector. The servicing component (see Table 14-7) is complex, and of equal or greater importance than the manufacturing component in the construction of an HFC BAU scenario.

Considerations include leakage, loss in case of accidents, recovery and recycling, these are all taken into account in the bottom-up model, alongside the lifetime of equipment in the various sub-sectors. With 12-20 year RACHP equipment lifetimes, the RACHP servicing amounts will be the same or larger than the amount needed for manufacturing; this is a clear outcome of the application of the bottom-up model.

Table 14-7: BAU demand for R/AC manufacturing and servicing in non-Article 5 and Article 5 parties in Mt CO_2-eq. (2015-2050) (Ex.III/1 report, Table 2-3)

HFC BAU demand in Mt CO_2-eq. (year)	**2015#**	**2020#**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Non-Article 5								
Manufacturing	209.1	185.2	207.7	238.5	280.5	319.9	370.3	429.3
Servicing	184.8	192.8	183.8	165.1	167.5	187.5	210.4	237.2
Total R/AC demand*	**393.9**	**378.0**	**391.5**	**403.6**	**448.0**	**507.4**	**580.7**	**666.5**
Total BAU (comparison)**	517	444	451	467	515	578	655	745
Article 5								
Manufacturing	388.2	592.7	847.2	1113.1	1281.5	1483.6	1728.7	2025.9
Servicing	181.9	384.0	677.6	1043.9	1441.0	1825.8	2318.8	2952.4
Total R/AC demand*	**570.1**	**976.7**	**1524.8**	**2157.0**	**2722.5**	**3309.4**	**4047.6**	**4978.3**
Total BAU (comparison)**	627	1047	1615	2264	2847	3451	4207	5157

* Note the difference and increase in order of magnitude between non-Article 5 and Article 5 parties

** See Annex III in the Ex.III/1 report for all BAU total HFC consumption values for the separate years

\# The values highlighted in yellow have been corrected to be consistent with the corresponding values in Annex III of the Ex.III/1 report

For the construction of the BAU scenarios in the Ex.III/1 report, the main HFCs have been included, not considering alternative, low GWP pure compounds or low GWP mixtures. It should be emphasised that this *neglects the possible climate impact* of the replacement by low GWP mixtures in mitigation scenarios. Where it concerns the results presented in the Ex.III/1 report, it should therefore be noted that a major use of mixtures with a certain GWP (due to the use of a certain percentage of high GWP HFCs) in the RAC sector may lead to difficulties in achieving a 75% HFC consumption reduction, or more, in future, assuming that these mixtures will remain in use.

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