MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

REPORT OF THE
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

OCTOBER 2014

DECISION XXV/5 TASK FORCE REPORT
ADDITIONAL INFORMATION TO ALTERNATIVES ON ODS
(FINAL REPORT)

UNEP

October 2014 Report of the Technology and Economic Assessment Panel

Decision XXV/5 Task Force Report Additional Information on Alternatives to ODS (Final Report)

Montreal Protocol
On Substances that Deplete the Ozone Layer

Report of the UNEP Technology and Economic Assessment Panel

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DECISION XXV/5 TASK FORCE REPORT:

ADDITIONAL INFORMATION ON ALTERNATIVES TO ODS (FINAL REPORT)

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

Co-ordination:	**TEAP and its XXV/5 Task Force**
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UNEP
OCTOBER 2014 REPORT OF THE
TECHNOLOGY AND ECONOMIC
ASSESSMENT PANEL

VOLUME 4

DECISION XXV/5 TASK FORCE REPORT
ADDITIONAL INFORMATION ON ALTERNATIVES TO ODS

DISCLAIMER

ACKNOWLEDGEMENT

The UNEP Technology and Economic Assessment Panel and the XXV/5 Task Force co-chairs and members wish to express thanks to all who contributed from governments, both Article 5 and non-Article 5, furthermore in particular to the Ozone and the Multilateral Fund Secretariat, as well as to a large number of individuals involved in Protocol issues, without whose involvement this assessment would not have been possible.

The opinions expressed are those of the Panel and its Task Force and do not necessarily reflect the reviews of any sponsoring or supporting organisation.

The TEAP and its XXV/5 Task Force thank the Multilateral Fund Secretariat in Montreal, Canada, for hosting the meeting, 5-9 May 2014 where final inputs from Parties were reviewed, the outline for this report was discussed and proposals were made for the last drafting in May 2014, after which last reviews took place by email circulation during the end of May 2014. Following the publication of the Draft Report in May, the opportunity was taken to consult informally with Parties at the Open-ended Working Group meeting in Paris held during July 2014. These inputs were further considered and, to the extent possible, addressed in the period through to the finalisation of the Report in October 2014.

Foreword

The May 2014 TEAP Report

The May 2014 TEAP Report consisted of six volumes:

Volume 1: May 2014 TEAP Progress Report

Volume 2: May 2014 TEAP Essential Use Nominations Report

Volume 3: May 2014 TEAP Critical Use Nominations Report

Volume 4: TEAP Decision XXV/5 Task Force Report on information on alternatives to ODS

Volume 5: TEAP Decision XXV/6 Report on TOC appointment processes, future configurations and the streamlining of annual (progress) reports

Volume 6: TEAP Decision XXV/8 Task Force on the funding requirement for the 2015-2017 replenishment of the Multilateral Fund for the Implementation of the Montreal Protocol.

- **Volume 1** contains the TOC progress reports, and a chapter "Other TEAP Matters", discussing the status of (re-) nominations and challenges to the participation of experts, as well as an annex with the list of TEAP and TOC members, status May 2014
- **Volume 2** contains the assessment of the 2014 essential use nominations by the CTOC and the MTOC
- **Volume 3** contains the assessment of the 2014 critical use nominations by the MBTOC
- **Volume 4** was the draft report of the TEAP Task Force responding to Decision XXV/5 on information on alternatives to ODS in the refrigeration and air conditioning, foams, medical uses, fire protection and solvent sectors. This has subsequently been superseded by this Final Report, as published in October 2014.
- **Volume 5** contains a description by the TEAP on the TOC appointment processes and their future configurations and the streamlining of the annual (progress) reports in response to Decision XXV/6
- **Volume 6** is the report of the TEAP Task Force responding to Decision XXV/8 on the funding requirement for the 2015-2017 replenishment of the Multilateral Fund for the Implementation of the Montreal Protocol.

This is the revised Volume 4, the final report of the Decision XXV/5 Task Force on information on alternatives to ODS.

The UNEP Technology and Economic Assessment Panel (TEAP):

Lambert Kuijpers, co-chair	NL	Jose Pons-Pons	VEN
Bella Maranion, co-chair	USA	Ian Porter	AUS
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DECISION XXV/5 TASK FORCE REPORT

ADDITIONAL INFORMATION ON ALTERNATIVES TO ODS

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1 Executive Summary

Overview

Decision XXV/5 is the first in a series of Decisions on alternatives to ozone depleting substances to request TEAP to develop and assess the impact of specific mitigation scenarios as part of its reporting back to the Parties. In responding to this mandate, TEAP has sought to draw from its earlier evaluations of alternatives (Decisions XXIII/9 and XXIV/7) in order to provide a grounded basis for such mitigation scenarios. The information has been updated where appropriate, although the changes have generally been minor because of the short time period between the finalisation of the TEAP Report on XXIV/7 (September 2013) and the publication of this Report (May-October 2014).

It should be noted that quantitative information is only available for the refrigeration, air conditioning foam, and to a lesser extent, medical use sectors. Therefore, discussion on fire protection and solvents has remained qualitative, with the latter being added to the scope of such reports for the first time (Chapter 9). Nevertheless, for each of these sectors, efforts have still been made to address the three major inputs requested of TEAP in Decision XXV/5 – namely:

- An update on alternatives available, highlighting significant differences between non-Article 5 and Article 5 regions (Element 1(a))
- A (qualitative/quantitative) discussion of future demand for alternatives to ozone depleting substances (Element 1(b))
- A (qualitative/quantitative) discussion on the costs and environmental benefits of various mitigation scenarios (Element 1(c))

Where quantitative information has been available, it has become self-evident that the Refrigeration and Air Conditioning (RAC) sector is the dominant factor in the climate impact assessment even when existing regulatory measures are considered as part of the BAU scenario (see Figure ES-1)

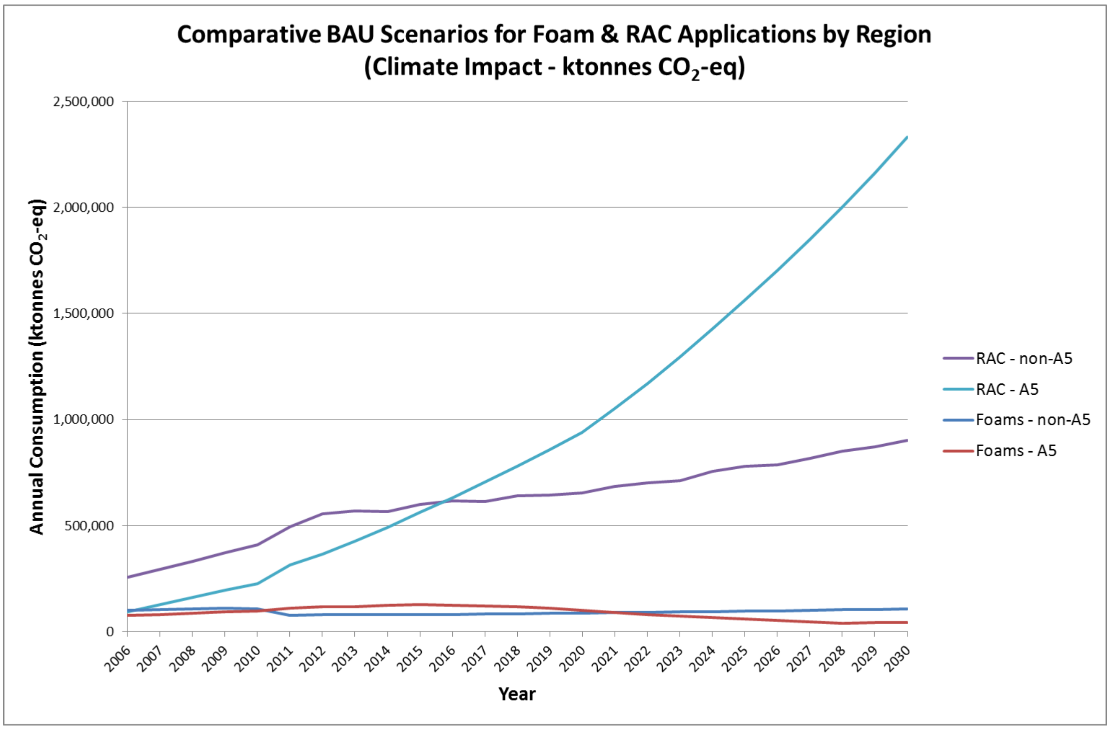


Figure ES-1 Projection of Business-as-Usual Climate Impact to 2030 for RAC and foams

Business-as-Usual Scenario

The make-up of the Business-as-Usual scenario for RAC is shown in Figures ES-2 and ES-3 below:

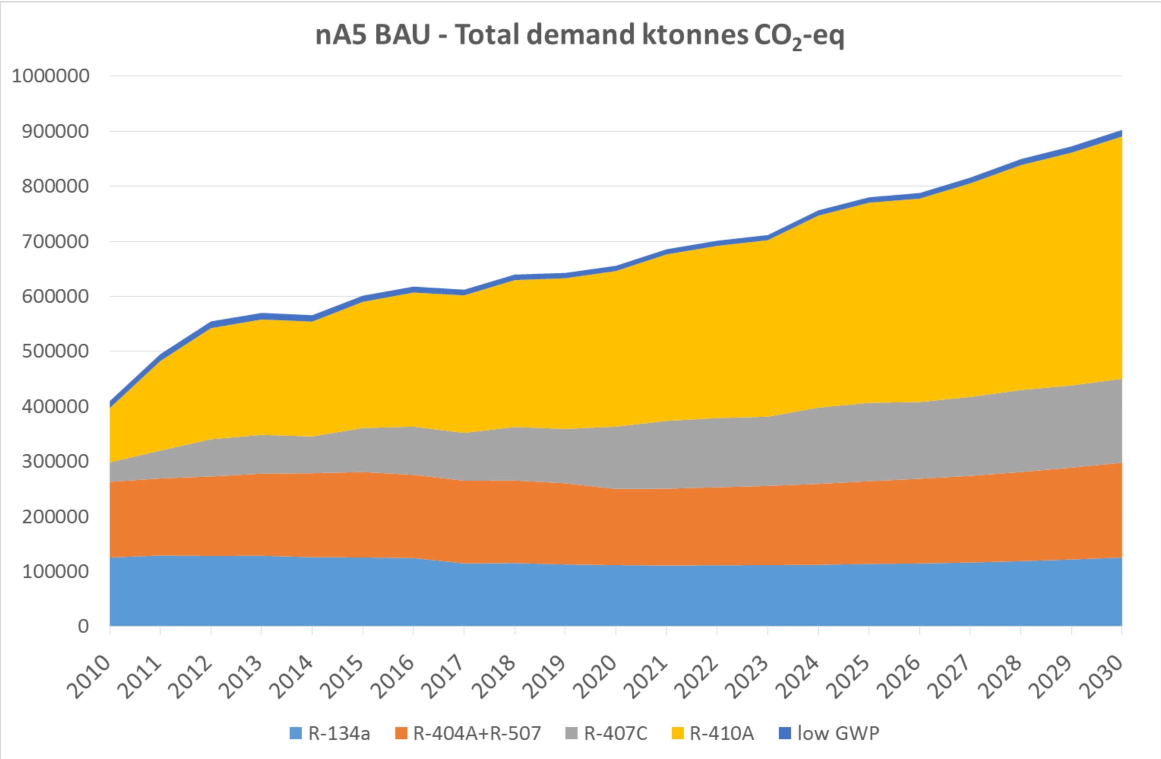


Figure ES-2 Actual and projected BAU demand of refrigerants in non-Article 5 regions

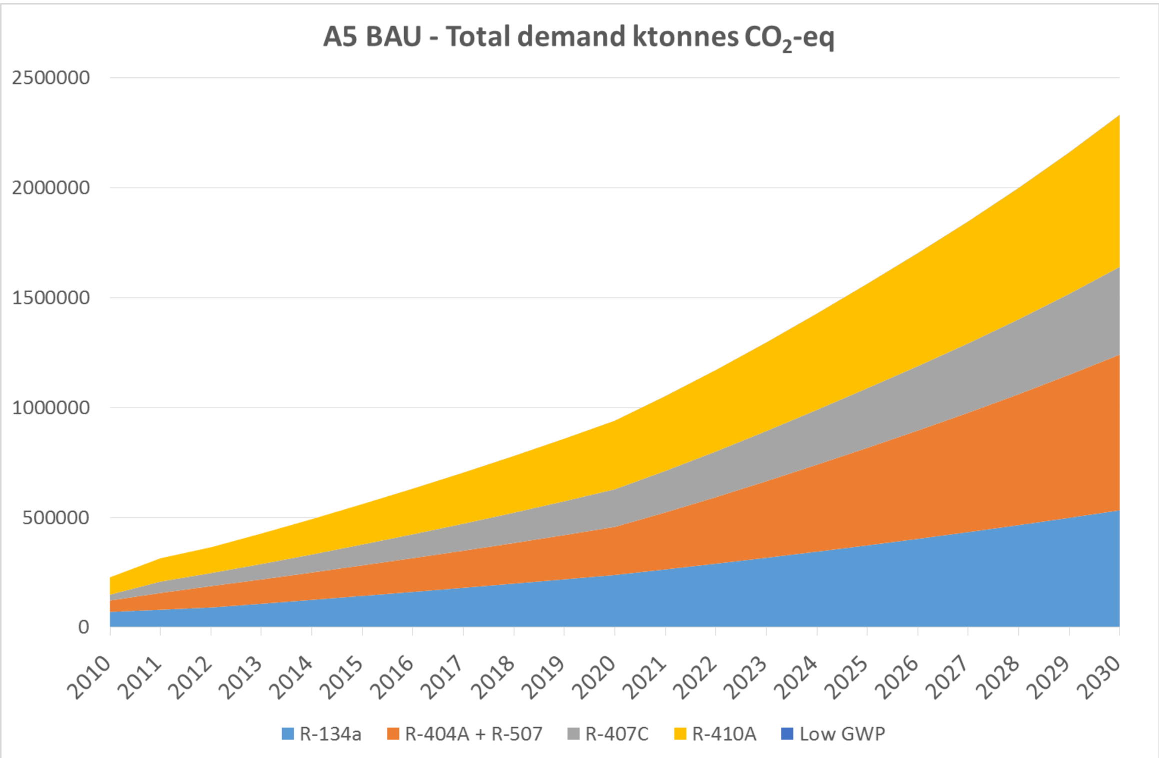


Figure ES-3 Actual and projected BAU demand of refrigerants in Article 5 regions

Mitigation Scenarios

Understandably, the grounding of the mitigation scenarios for such large consuming sectors becomes critical to the outcome of the response to Element 1(c) of Decision XXV/5 and a large part of this report addresses the technical capability and economic capacity of the RAC sector to respond. Two mitigation scenarios have been identified. One (MIT-1) is believed to be a relatively achievable scenario based on current technology options and potential trends. The other (MIT-2) is a more progressive "what if" assessment and is believed to be at the limit of what could be achievable in the period to 2030. The following two graphs illustrate the impact for non-Article 5 regions:

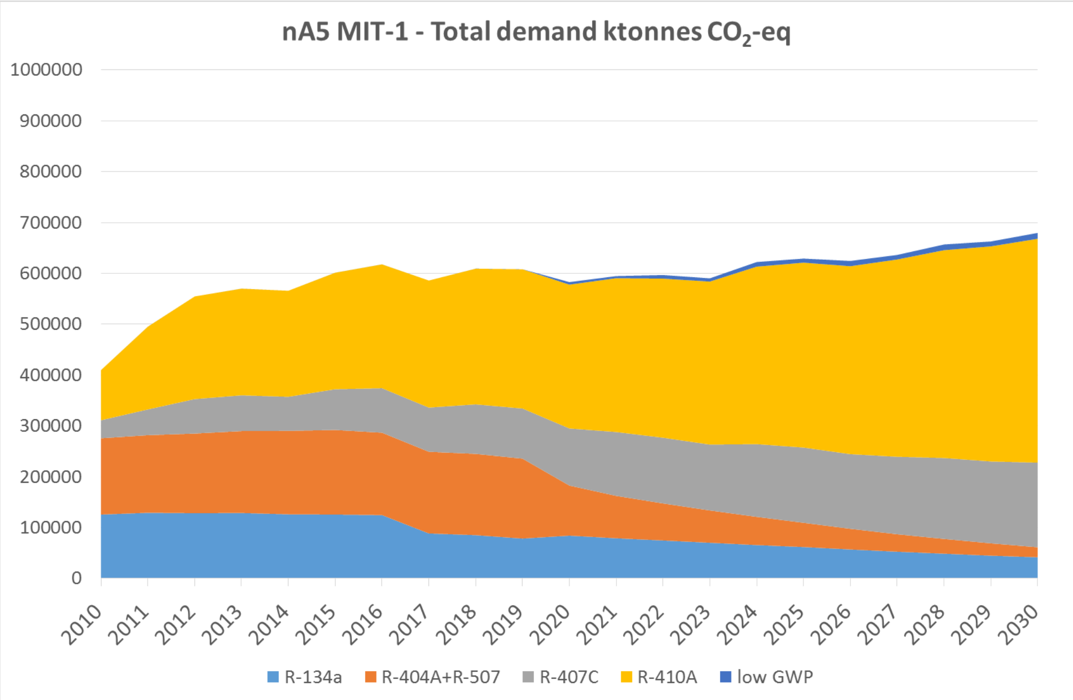


Figure ES-4 The climate impact of Mitigation Scenario 1 for RAC in non-Article 5 regions

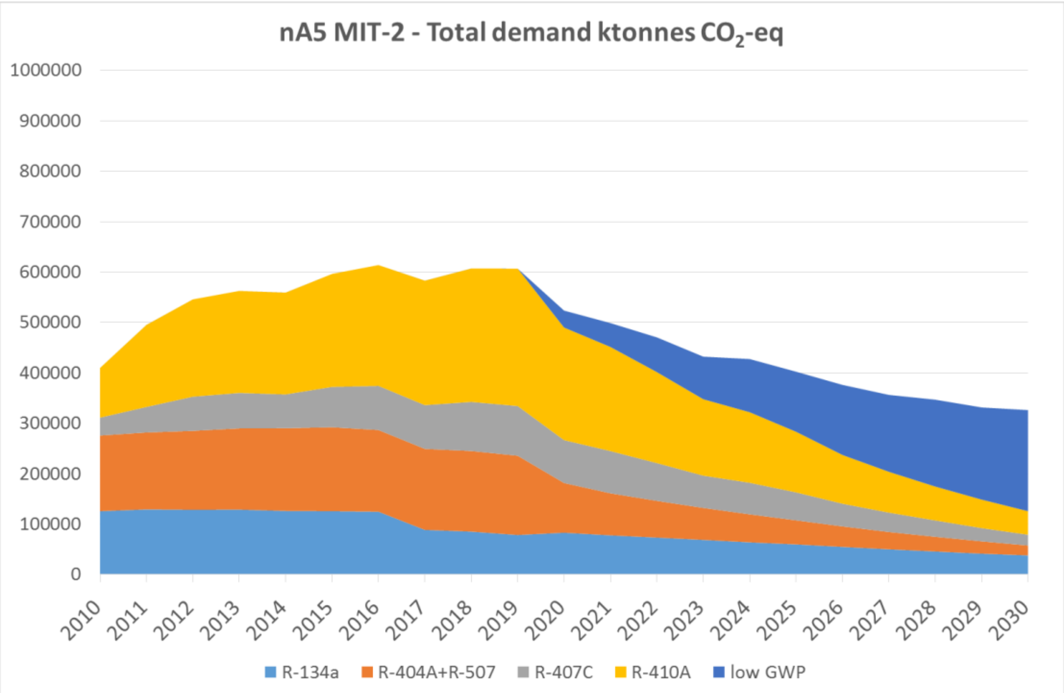


Figure ES-5 The climate impact of Mitigation Scenario 2 for RAC in non-Article 5 regions

It is clear from both graphs that the impact of measures on low-GWP alternatives is unlikely to be felt in non-Article 5 regions until after 2020. This acknowledges the fact that additional regulatory measures, such as the revised F-Gas Regulation will be necessary to trigger transitions.

For the Article 5 "case", the incursion of low-GWP alternatives is evident from the year 2000 onwards. However, the importance of guiding investment into low-GWP solutions wherever possible is clear in view of the anticipated rate of growth of the RAC sector in the period through to 2030. Figure ES-7 is particularly revealing in that the opportunity to major inroads exists beyond 2020.

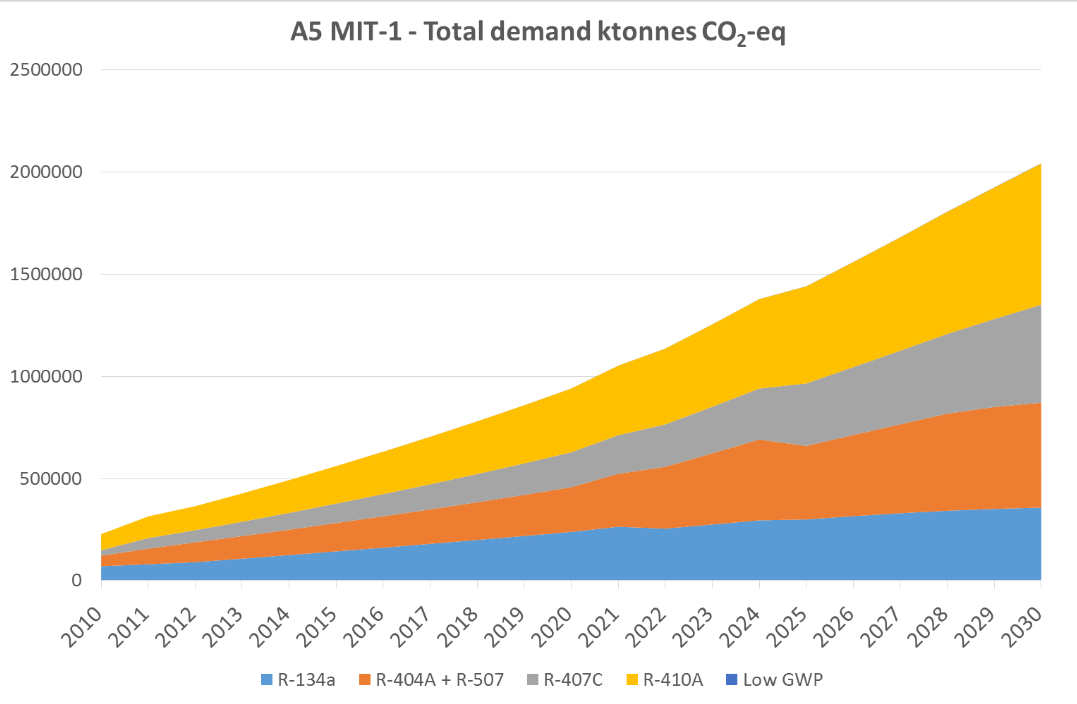


Figure ES-6 The climate impact of Mitigation Scenario 1 for RAC in Article 5 regions

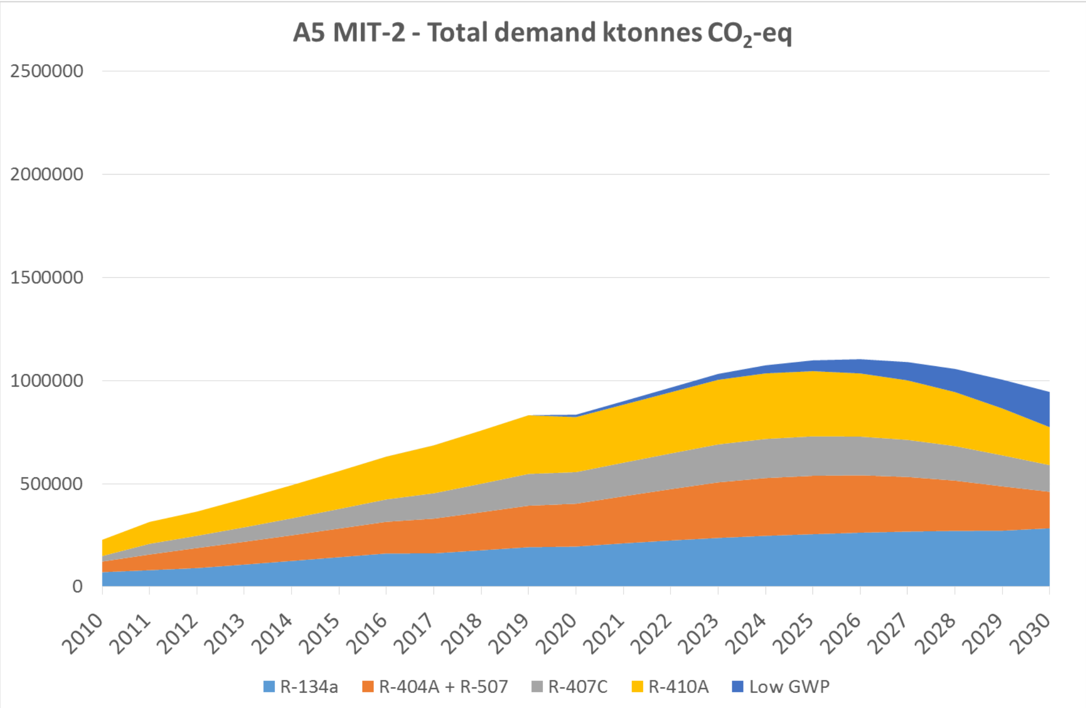


Figure ES-7 The climate impact of Mitigation Scenario 2 for RAC in Article 5 regions

The Task Force has also made efforts to quantify the potential cumulative climate impact arising from mitigation activities in both the foam and RAC sectors. Although the foam contribution is modest, it is still believed to be desirable, especially since any measures to reduce reliance on high-GWP blowing agents will have an enduring effect beyond 2030. The most notable benefits are likely to come from the XPS sector in the period beyond 2025.

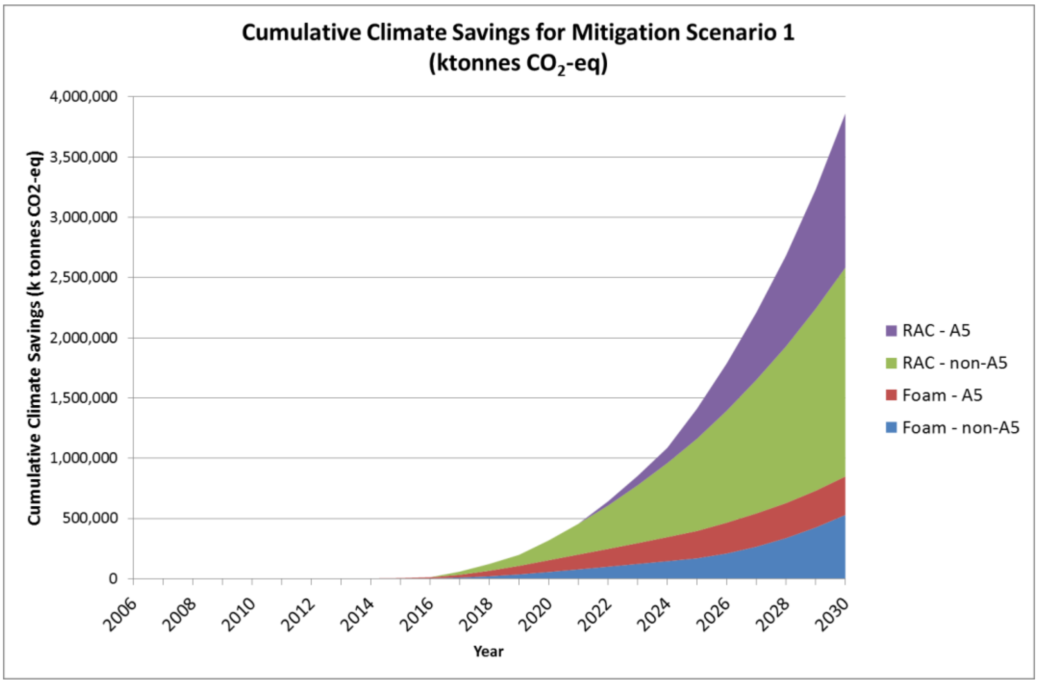


Figure ES-8 Cumulative Climate Savings compared with BAU from Mitigation Scenario 1

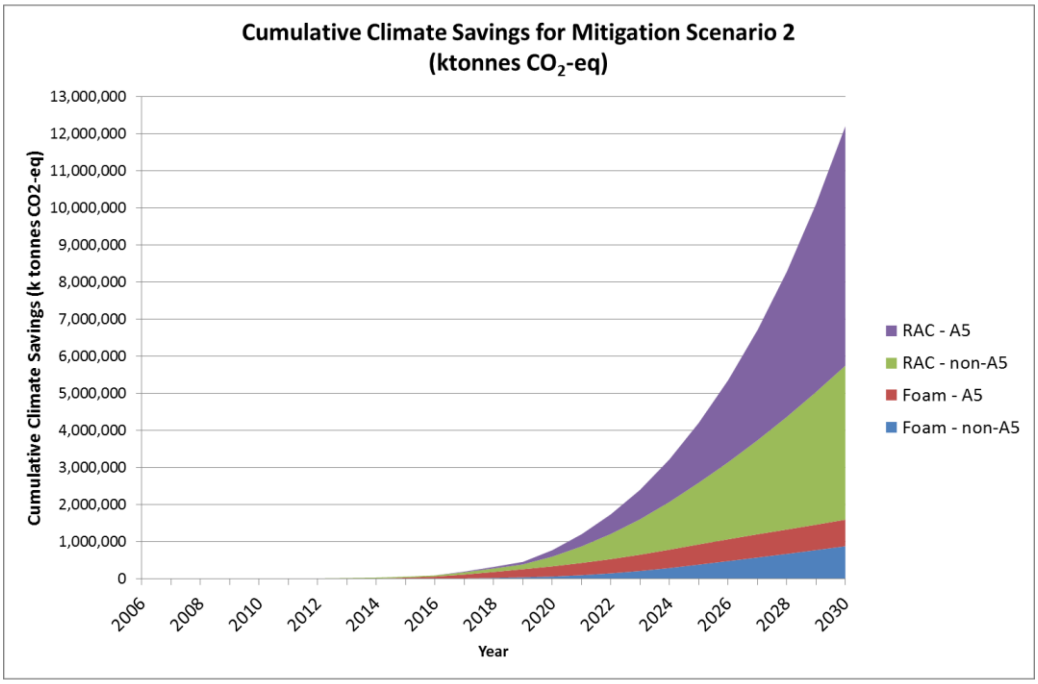


Figure ES-9 Cumulative Climate Savings compared with BAU from Mitigation Scenario 2

It can be seen that the cumulative savings by 2030 from Mitigation Scenario 1 are approximately 3.8 billion tonnes CO_2-eq, while the delivery from Mitigation Scenario 2 is in the region of 12 billion tonnes CO_2-eq.

Cost assessment

With respect to cost, the ranges are inevitably wide because the circumstances surrounding any future transitions have a major bearing. It is clear that technology transitions that can coincide with other process upgrades will be more cost-effective than those that are forced to be implemented independently because of specific regulatory measures. Most importantly, the costs will be least where new RAC and foam manufacturing capacity investment is directed away from high-GWP options at the outset. Hence, efforts should be focused on ensuring that low-GWP options are well proven at the earliest opportunity in order to inspire investment confidence.

Within the RAC sector, the costs for Mitigation Scenarios 1 and 2 in Article 5 regions have been estimated and the ranges are shown in the following two tables.

Sector	**Conversion to**	**Amount (tonnes)**	**Manufacturing conversion (tonnes)**	**Costs (US$ million)**
MAC	Low GWP	75,000	45,000	405-810
Refr.sectors	R-407A/C/F	90,000	54,000	54-162
Stationary AC		135,000		0
Total				**459-972**

Table ES-1 Costs for the MIT-1 scenario in Article 5 countries

Sector	**Conversion to**	**Amount (tonnes)**	**Manufacturing conversion (tonnes)**	**Costs (US$ million)**
MAC	Low GWP	75,000	45,000	270-810
Refr.sectors	Low GWP	90,000	54,000	324-972
Stationary AC	Low GWP	135,000	81,000	486-1458
Total				**1080-3240**

Table ES-2 Costs for the MIT-2 scenario in Article 5 countries

Although there is considerable further information available on climate abatement costs, the whole life costing approach used is not particularly helpful in that it typically offsets investment costs against future energy efficiency gains. Often these cost and benefits are attributed to different parties.

Qualitative Summaries

Whilst the quantification of costs and savings has not been as possible, or as detailed, for other sectors, it is important to note the following conclusions for fire protection, solvents and medical uses:

- The process for assessing and qualifying new fire protection agents for use is long and is also application specific. Whilst the phase-out of ODS in this sector is well underway, there will be some reliance of high-GWP solutions for the foreseeable future. Control of avoidable emissions continues to improve, thereby minimising impacts.
- In the solvents sector, there is still limited use of HCFC-141b and HCFC-225ca/cb. However, there is increased interest in a number of the emerging unsaturated halogenated substances, since the range of halogens (chlorine, fluorine and/or bromine) provide a range of solvating capabilities which should address any short-comings of currently available alternatives.
- Metered dose inhalers use HFC-134a and HFC-227ea, with cumulative emissions between 2014-2025 estimated to have a climate impact of 173,000 ktonnes CO_2 equivalent under a business-as-usual scenario. Completely avoiding high-GWP (HFC) alternatives in this sector is not yet technically or economically feasible. In the sterilants sector, where there is almost non-existent use of HFCs and a wide variety of alternatives available, the impact of avoiding HFCs would be minimal.

2 Introduction

2.1 Terms of Reference

Decision XXV/5 of the Twenty-fifth Meeting of the Parties requested the Technology and Economic Assessment Panel (TEAP) to prepare this report for consideration by the Open-ended Working Group at its 34th meeting and an updated report for the Twenty-sixth Meeting in 2014.

2.2 Scope and coverage

The text of Decision XXV/5, as it relates to this report is as follows:

1. To request the Technology and Economic Assessment Panel, if necessary, in consultation with external experts, to prepare a report for consideration by the Open-ended Working Group at its thirty-fourth meeting and an updated report to be submitted to the Twenty-Sixth Meeting of the Parties that would:

    (a) Update information on alternatives to ozone-depleting substances in various sectors and subsectors and differentiating between Article 5 and non-Article 5 parties, considering regional differences, and assessing whether they are;

    - commercially available,
    - technically proven,
    - environmentally sound,
    - energy efficiency,
    - economically viable and cost effective,
    - suitable for regions with high ambient temperature, in particular considering the refrigeration and air-conditioning sector and their use in high urban density cities,
    - suitable for safe uses, in particular considering their potential flammability or toxicity, and their suitability for use in densely populated urban areas, and describing potential limitations of their use,
    - easily used

    (b) Estimate current and future demand for ODS alternatives, taking into account increased demand, particularly in the refrigeration and air conditioning sectors, and in Parties operating under paragraph 1 of Article 5;

    (c) Assess, differentiating between Article 5 and non- Article 5 parties, the economic costs and implications, and environmental benefits, of various scenarios of avoiding high GWP alternatives to ozone depleting substances where such avoidance is possible considering the list in paragraph (a);

    (d) Request the SAP, in liaison with the IPCC, to provide information from the contribution of WG1 to the 5th assessment report on the main climate metrics, considering the updated information under paragraph 1(a);

2.3 Composition of the Task Force

The TEAP established a XXV/5 Task Force (RTF) to prepare this report to respond to Decision XXV/5. The composition of the Task Force is as follows:

Co-chairs

- ❑ Paul Ashford (UK, co-chair FTOC)
- ❑ Lambert Kuijpers (The Netherlands, co-chair TEAP, co-chair RTOC);
- ❑ Roberto Peixoto (Brazil, co-chair RTOC)

Members:

- ❑ Rajaram Joshi (India, prospective FTOC member)
- ❑ Dave Catchpole (UK, co-chair HTOC)
- ❑ Denis Clodic (France, member RTOC)
- ❑ Daniel Colbourne (UK, member RTOC)
- ❑ Martin Dieryckx (Belgium, member RTOC)
- ❑ Rick Duncan (USA, member FTOC)
- ❑ Michael Kauffeld(Germany, member RTOC)
- ❑ Tingxun Li (China, RTOC member)
- ❑ Bella Maranion (TEAP, co-chair)
- ❑ Keiichi Ohnishi (Japan, co-chair CTOC)
- ❑ Rajan Rajendran (USA, RTOC member)
- ❑ Enshan Sheng (China, member FTOC);
- ❑ Helen Tope (Australia, co-chair MTOC)
- ❑ Helen Walter Terrinoni (USA, member FTOC)
- ❑ Samuel Yana-Motta (Peru, outside expert)
- ❑ Zhang Jianjun (China, co-chair CTOC)

Allen Zhang from the FTOC was also co-opted to consult on certain aspects of the report relating to XPS in China.

Chapter drafts were circulated to relevant sub-groups of the Task Force for development before the structure of the Report was considered in detail by TEAP at its meeting in Montreal from 5-9 May 2014. After resulting re-structuring, the subsequent full draft was circulated by email to the XXV/5 Task Force as a whole in mid-May and finally to the TEAP for endorsement at the end of May. Following presentation and review at the Open-ended Working Group meeting in Paris held during July, and the submission of written comment by Parties during August, the Task Force made relevant revisions to the Report ahead of its finalistion in October 2014.

2.4 The Structure of the XXV/5 report

The structure of the TEAP XXV/5 Task Force Report was considered in depth by the Task Force and by TEAP prior to the final formulation of the Report. Amongst the factors that were considered were:

- The relatively short period between the delivery of the final XXIV/7 Report (September 2013) and the preparation of the XXV/5 Report (May 2014).

- The similarity of the criteria set out within Decision XXIV/7 and Decision XXV/5 as detailed in the following table:

Decision XXIV/7	Decision XXV/5
• Commercially available	• Commercially available
• Technically proven	• Technically proven
• Environmentally sound	• Environmentally sound
• Efficacy	• Easy to use
• Health, Safety & Environmental	• Safe use – flammability & toxicity
• Cost effectiveness	• Economically viable & cost effective
• High ambient temperatures	• High ambient temperatures
• High urban densities	• High urban densities

- The importance of avoiding too much repetition and bringing focus on what is either new or of growing importance.

- Recognition that some sectors (specifically refrigeration, air conditioning and foam) have data which allow for the characterisation of a Business-As-Usual (BAU) case and related mitigation scenarios.

- Recognition that other sectors (specifically solvents, fire protection and medical uses) do not have reliable data from which relevant mitigation scenarios can be derived or for which mitigation scenarios were not derived.

- Recognition that Decision XXV/5 seeks to generate an analysis of the Article 5 and non-Article 5 implications of avoiding high GWP alternatives to Ozone Depleting Substances

As a result, the following chapter layout has been followed:

***Chapter 1* ‘Executive Summary’**

***Chapter 2* ‘Introduction’**

…which provides background information to the Decision, the composition of the Task Force and the Structure of the Report.

***Chapter 3* ‘Emerging trends in alternative selection as they impact BAU determination’**

…which provides information on the trends in alternative selection within the refrigeration, air conditioning and foam sectors by sub-sector and the basis for those trends with reference to information previously contained in the Decision XXIV/7 Report and also as updated in the relevant Annexes to this Report.

***Chapter 4* ‘Factors influencing the specific BAU scenarios for Article 5 and non-Article 5 regions ’**

…which details the current assessment of consumption by each sector and sub-sector covered in Chapter 3 and the regulatory and other influences expected to impact the BAU development in the period to 2030, including the availability of funding.

***Chapter 5* ‘Identification of relevant mitigation scenarios compared to Business-As-Usual’**

…which considers the drivers for accelerated reductions in both Article 5 and non-Article 5 parties including technology availability, factors influencing cost, market drivers, funding sources and related issues.

***Chapter 6* ‘Environmental benefits associated with selected mitigation scenarios’**

…which assesses the impact in ozone and climate terms of changes in cumulative consumption (potential emissions) in the period to 2030 in both Article 5 and non-Article 5 Parties including comparison on a sector-by-sector basis.

***Chapter 7* ‘Information on alternatives to ODS in the fire protection sector’**

…which provides information on the trends in alternative selection within the fire protection sector with reference to information previously contained in the Decision XXIV/7 Report and also as updated in the relevant Annexes of this Report.

***Chapter 8* ‘Information on alternatives to ODS in solvent uses”**

…which provides information on the trends in alternative selection within the solvents sector with reference to information previously contained in the Decision XXIV/7 Report and also as updated in the relevant Annexes of this Report.

***Chapter 9* ‘Information on alternatives to ODS in medical uses’**

…which provides information on the alternatives available for medical uses and the implications of technology choices.

***Annexes* ‘Updated information on alternatives previously reported under Decision XXIV/7’**

…which provides an updated presentation of the information previously contained in the Decision XXIV/7 Report.

‘Specific summary on Refrigeration and Air Conditioning options in high ambient conditions’

….in response to requests from several Parties to see more explicit coverage of the high ambient condition challenges and solutions

3 Emerging trends in alternative selection as they impact BAU determination

Since much of the material presented in the Decision XXIV/7 Report remains largely unchanged, it has not been presented again in the body of this Report. It can, however, be found in updated form in the relevant Annexes to this Report (see Chapter 10); this chapter also contains an updated table of refrigerant alternatives (with latest R-number designations). Despite the decision to relegate this detailed information, it was still believed to be appropriate to provide a summarised list of alternatives at the outset of this chapter with cross-reference to the potential sectors of use. This table, which first appeared in XXIV/7 and has been fully updated, is shown on the following page.

The following sections now briefly describe the trends in refrigerant selection by specific sector.

3.1.1 Domestic Refrigeration

Regarding the refrigerants used in new appliances the share of HC-600a is further increasing. The USA market now includes several products applying HC-600a using a reduced charge of 57 g as required by UL. It is worth mentioning that many Article 5 countries are increasingly using HC-600a now, a trend that already started in the late 1990s. However, globally there is still a substantial amount of HFC-134a used in the domestic refrigeration sub-sector. Other than HFC-134a and HC-600a any other refrigerant or combination of refrigerants (blends) has a marginal fraction in the total use.

It is feasible to use HFC-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 HFC-134a and it has lower flammability characteristics than HC-600a. The lower flammability makes a possible application easier in countries that have strong reservations related to the application of the flammable HC-600a. Due to cost disadvantage, and investment requirements for product development, HFC-1234yf suffers significant disadvantages. Given the lack of activity by manufacturers, is not likely to displace HC-600a or HFC-134a.

It is also feasible to use R-513A in domestic refrigeration. There is no information about investigation work being developed with this refrigerant

Concerning not-in-kind technologies, magnetic refrigeration has been cited in literature various times, but it can be concluded that it was found that it is not close to commercialization.

3.1.2 Commercial refrigeration

Stand-alone equipment

HFC-134a and R-404A are still the dominant refrigerants for stand-alone equipment; in Europe, based on the update of the regulation on fluorinated substances, R-404A will be banned for use in new equipment as of 1 January 2020.

R-407F (GWP 1800) and R-407A (GWP 2100) are intermediate refrigerant blends currently in Europe and in the US to replace R-404A or HCFC-22.

HC-600a and HC-290 are the two hydrocarbons used for small commercial equipment. HC-600a is chosen for smaller refrigeration capacities such as water fountains. Ice machines and small display cases use HC-290. The uptake of HCs is significant for small commercial equipment with refrigerant charges varying from 15 g to 1.5 kg.

R-744 is mainly used in vending machines and bottle coolers; the technology is operating well, but is technically challenging and few companies have been able to develop efficient and compact systems.

Condensing units

HFC-134a, R-404A and, to a small degree, R-410A are HFCs of choice for condensing units. HFC-134a is chosen for small capacities and evaporation temperatures >-15°C. R-404A (or sometimes R-410A) is chosen for larger capacities for all temperature levels. As to stand-alone equipment, R-407A or R-407F is chosen to replace R-404A in Europe, but the difference of prices could still lead to charging R-404A in new condensing units. Temperature glide and higher compressor discharge temperatures are problems presented by R-407A and R-407F.

Several low GWP blends have been developed by refrigerant manufacturers in order to replace R-404A. The energy efficiency of those new blends are in general 5% to 8% better than R-404A without system optimisation.

Centralised systems

R-744 cascade systems have taken a significant uptake in Europe with about 1,600 stores equipped.

For large European commercial refrigeration operations HFC-134a has been used at the medium-temperature level cascading with R-744 direct systems for the low temperature level.

For cold climates, R744 is used at both temperature levels. R-744 clearly is an important option for centralised systems in future commercial refrigeration, especially in cascade systems with another refrigerant at the medium temperature level or in trans-critical systems.

Hydrocarbons are used in about 100 centralised systems in Europe, either with HC-290 or HC-1270, without that any significant commercial expansion took place during the last couple of years. HCs in large centralised systems will have a limited market share mainly due to safety issues.

HC-290 or HC-1270 are efficient in both medium and low-temperature stages of commercial refrigeration equipment. The additional costs are related to containment and safety. The refrigerant charge limit, directly associated with regulations and/or standards (depending upon the country), forms a barrier. The competition with R-744 as a low GWP option has limited the expansion of HCs in centralised systems.

R-717 is used in indirect systems for large capacity industrial systems but in very few commercial centralized systems. There is no significant driver to the spreading of R-717 in commercial refrigeration.

R-452A has been tested as an alternative to R-404A and is being evaluated in the United States.

For low GWP HFCs, the situation is similar to what has been previously mentioned for condensing unit. Several lower flammability blends (class 2L) have GWPs varying from 200 to 300 and can be used at the medium-temperature and low temperature levels. Furthermore, HFC-1234yf or HFC-1234ze can be applied as the primary refrigerant in cascading systems with R-744 at the low temperature. Non-flammable blends that provide reduced GWP (e.g. R-450A, R-513A with GWP<600) and high efficiency are also being considered as options. Their main attractiveness is that they do not require any safety measures as they are falling under safety class A1.

3.1.3 Transport refrigeration

Trucks, trailers and intermodal containers.

The refrigerant of choice for transport refrigeration systems within non-Article 5 countries are HFCs, mainly R-404A, R-407C and more recently HFC-134a (especially in new vessels and intermodal containers) and R-410A (especially on trucks and cruise ships).

R-404A has become a preferred choice for practically all trailers and large trucks. HFC-134a is used in small trucks and vans, because they can utilise automotive components. Testing of low-GWP alternatives is in progress elsewhere, but no option seems viable in the short term. The main issue is that the performance of R-404A is difficult to meet (especially its low discharge temperature). Although R-410A outperforms R-404A, it has higher pressures (requires technology change for most manufacturers).

Testing and trials with R-452A have been performed by some manufacturers.

Current and previous tests with trucks using R-744 suggest that introduction of R-744 will be possible when more efficient compressors with more than one compression stage, which are under development, will be commercially available.

In contrast to trucks and trailers, intermodal containers use HFC-134a in most cases and R-404A in some. The reasons for choosing HFC-134a could have been the global availability of HFC-134a, and lower cost per kg, otherwise R-404A (or today R-410A) would be more suitable.

Initial field tests with small fleets of containers using R-744 have started. R-717 is deemed unacceptable in all truck, trailer and intermodal container applications because of toxicity and material compatibility.

Vessels

The majority of the existing fleet (80%) use HCFC-22, which can be replaced by R-417A or R-422D. Other HFC alternatives, namely R-410A, R-407C and R-427A, require modifications. Modern cruise ships use R-410A and HFC-134a for air conditioning. Where refrigeration is needed for provision rooms or process cooling, R-404A is mainly used. HFC-23 is used for freezing at -60 °C and below (mainly for fish preservation).

R-717 and R-744 have been applied to some extent aboard marine vessels (RTOC, 2010). For European fishing vessels highly efficient R-717 / R-744-cascade systems are the systems of choice, using approximately 6% less energy (Schwarz et al., 2011).

3.1.4 Large size (industrial) refrigeration)

Over 90% of the large industrial refrigeration installations use R-717. R-717 is not widely used in smaller systems, where there is HCFC and HFC consumption, because suitable compressors are not available. Toxicity is an additional concern for R-717 in light industrial applications. Low GWP-alternatives to HCFCs include R-717, which is already widely used, hydrocarbons, R-744 for low temperature (freezing) and other speciality applications as well as air for very low temperatures (currently lower than -60 °C) and (possibly in future) unsaturated HFCs; although the anticipated higher cost of unsaturated HFCs will probably prevent their application in systems with large refrigerant charges.

Hydrocarbons are not widely used, other than in situations where safety measures are already required, e.g. in a petrochemical plant or for compact chillers.

R-744 is used with excellent efficiency in systems as the low temperature stage to a cascaded upper R-717 system especially in the food industry where the refrigerant has to evaporate in freezing equipment in the factory. In colder climates R-744 is energy efficient as the sole refrigerant.

In some Article 5 countries, HCFC-22 is being used, but most heat pumps commercialised today make use of R-410A, HFC-134a, R-407C, HC-290, HC-600a, R-717, R-744. The majority of new equipment uses R-410A. For replacing HCFC-22 by a non-ODS there are no technical barriers. The main parameters in the selection of alternatives when switching over from HCFC-22 are cost effectiveness, economic impact, safe use and easiness of use. Replacements such as HFC-32 and other low-GWP HFC blends such as R444B are under way to become commercial available.

HFC-32 is expected that products for water heating heat pumps will follow soon on a large scale.

Low GWP HFC blends are under way to become commercially available. The success of these blends will depend on the price competitiveness of the equipment compared to other alternatives, based on the same capacity and efficiency.

3.1.5 Water heating heat pumps

In some Article 5 countries, HCFC-22 is being used, but most heat pumps commercialised today make use of R-410A, HFC-134a, R-407C, HC-290, HC-600a, R-717, R-744. The majority of new equipment uses R-410A. For replacing HCFC-22 with a non-ODS alternative there are no technical barriers. The main parameters in the selection of alternatives when switching over from HCFC-22 are cost effectiveness, economic impact, safe use and easiness of use. Replacements such as HFC-32 and other low-GWP HFC blends such as R-444B are under way to become commercially available.

R-744 water heating heat pumps have been developed and commercialised mainly in Japan and are used for water heating. R-717 has also been used in a small number of reversible heat pumps and absorption heat pumps. The higher toxicity requires specific trained personnel, has specific use limitations and safety requirements. These cost impacts and use limitations limit the practical use.

HFC-32 is expected in products for water heating heat pumps that will follow soon on a large scale.

Low GWP HFC blends are under way to become commercially available. The success of these blends will depend on the price competitiveness of the equipment compared to other alternatives, based on the same capacity and efficiency.

3.1.6 Air conditioning

Small self-contained (window, portable, through-the-wall, packaged terminal)

As detailed in TEAP (2013), R-407C and R-410A have been used in a large proportion of SSC ACs following the transition from HCFC-22. They are therefore deemed to be the baseline option.

The application of HC-290 and HC-1270 in these systems is discussed in detail in TEAP (2013). Portable type units are widely available using HC-290 and window units are now in production in Asia. The additional cost is negligible and typically needs less material (copper and aluminium) than HCFC-22 or R-410A systems they are therefore can be considered as an economically viable option. Due to their higher flammability additional requirements are normally needed but limitations are not applicable for the majority of products, which have small capacity and corresponding low refrigerant charge.

TEAP (2013) reported that it is feasible to use HFC-32 in SSC ACs and production is likely to begin soon. Since the design is almost the same as or even needs less material (copper and aluminium) than R-410A then it is reasonable to state that the option is economically viable and there are no limitations to ease of use.

The mixtures R-446A, R-447A, R-444B and “DR5” are feasible to use in SSC ACs, although there is no production currently planned with any of them. The other implications associated with them, such as economic viability as R-410A and ease of application are likely to be comparable to HFC-32.

Information regarding the use of R-744 in this type of equipment was provided in TEAP (2013), where only niche type products are available (i.e., ECUs). Estimated costs are likely to be around double that of the baseline products and therefore not considered economically viable in most cases. This is particularly the case for high ambient climates.

Mini-split (non-ducted)

R-407C is used in a portion of split ACs (in the transition from HCFC-22 in non-Article 5 countries) whereas R-410A is used in most where HCFC-22 is not used. As such this is considered the baseline option.

HC-290 has been used in split ACs for many years on a limited scale but now with some companies developing and producing them on a larger scale, whilst HC-1270 is also gaining attention. Positive efficiency characteristics were discussed in detail in TEAP (2013). The use of HCs is technically proven and numerous HC-290 production lines are currently being completed, mainly in China. Based on experience, HC-290 has negligible additional cost and typically needs less material (copper and aluminium) than HCFC-22 or R-410A systems and is considered to be economically viable. In general, HC-290 and HC-1270 in split ACs is suitable for use in densely populated urban areas. In general, they are easily used for smaller and medium capacity systems, whilst larger capacity models require additional safety features that necessitate an additional safety feature. The main implication is that the service sector needs to be suitably trained in order to handle flammability.

It is feasible to use HFC-32 in split ACs, for example, where R-410A is already used. Most Japanese companies have stopped manufacturing R-410A products and have commercialised R32 mini-split products demonstrating they are technically and economical proven. It is considered suitable for use in high density urban areas and the only implication in terms of ease of use is related to the need to suitably train the service sector to handle lower flammable refrigerants..

R-446A, R-447A and DR-5 are feasible for use in split ACs, for example, where R-410A is already used. Energy efficiency is favourable and testing and trialling is underway in many countries (TEAP, 2013). The cost implications are considered minor, except the price of refrigerant may increase the cost. Nevertheless, split systems with R-446A and R-447A are likely to be economically viable as well as suitable for use in densely populated urban areas. In general they are deemed easy to use although due to lower flammability, the service sector would require necessary training.

R-444B is feasible to use in split ACs, for example, to replace HCFC-22 or R-407C, trials are ongoing and efficiency is comparable (TEAP, 2013). The cost should be comparable to that of HCFC-22 and R-407C but could be greater due to the refrigerant cost but nevertheless economically viable. It is not unsuitable for use in high density urban areas and it is otherwise easy to use except the need to training of the service sector in the handling of lower flammable refrigerants.

Multi-split, split (ducted) and dDucted split commercial and non-split air conditioners

R-407C and R-410A may be considered as the baseline options for all of these sub-categories of ACs. To a lesser extent, HFC-134a is used but mainly in regions with high ambient conditions.

The use of R-744 in all of these sub-categories is limited to northern climates where temperatures below 30 ^{o}C dominate. It is not suitable for high temperature climates due to the inability or excessive cost necessary to achieve desired efficiencies. Due to these higher cost implications, the use of R-744 can seldom be considered economically viable.

Although feasible in a small proportion of situations, HCs are not used in multi-split and some types of ducted systems due to charge size limitations in occupied spaces (TEAP, 2013). Due to charge amount limitations, they are not easily applicable and require expert consideration as to suitability of cases.

It is feasible to use HFC-32 in most types of multi-split and ducted ACs (TEAP, 2013). The cost should be equivalent or lower to R-410A. Nevertheless, at least for small and medium systems it is likely to be economically viable and probably suitable for regions with high ambient temperatures (although there are conflicting views on the implications for satisfying this). There are no reasons to make it unsuitable for use in densely populated regions. It would be easily applied, although necessary consideration is needed to provide suitable training for the service sector to handle the lower flammability aspects.

In principle, it is feasible to use the mixtures R-446A, R-447A, R-444B, DR-5, ARM-71 and ARM-32c in multi-split and ducted AC systems, for example, where R-410A or R-407C is already used and where HFC-32 could be used (TEAP, 2013). These refrigerants are suitable for regions with high ambient temperatures and there are no reasons to suggest they would be unsuitable for use in densely populated regions. Necessary consideration is needed to provide suitable training for the service sector to handle the flammability aspects. Further, it should be noted that these zeotropic blends, especially those with a notable temperature glide, can show performance degradation in reversed cycle mode due to the difficulties in optimising the heat exchanger for both heating and cooling mode.

3.1.7 Chillers

Positive displacement chillers

Positive displacement chillers include those with reciprocating piston, screw, and scroll compressors.

R-407C, R-410A and HFC-134a are widely used in positive displacement chillers and can be considered as the baseline options.

R-717 is used fairly widely in reciprocating and screw chillers for refrigeration and air conditioning, is well proven for a variety of applications and provides excellent efficiency (TEAP, 2013). In terms of regions with high ambient temperatures, R-717 chillers can and are used, although the very high discharge temperatures need to be accommodated for through inter-stage and oil cooling. Whether these chillers can be suitable for use in densely populated urban areas depends upon national regulations.

R-744 is now used in reciprocating chillers by different manufacturers, with good efficiency whilst operating at ambient temperatures not exceeding the critical temperature (around 30 °C), There is no reason for them to be unsuitable in densely populated urban environments.

Both HC-290 and HC-1270 chillers are produced by a number of manufacturers in Europe and other regions. There are no reasons why HC-290 and HC-1270 would not be suitable for use in densely populated areas. In principle they are easy to use, provided engineers have the capability of considering flammability aspects and that the service sector is appropriately trained to handle flammable refrigerants.

HFC-1234yf and HFC-1234ze(E) are suitable for chillers and have been trialled in systems in Europe, with good efficiency (TEAP, 2013). Due to high critical temperatures, they will perform well in warm climates. There is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle lower flammable refrigerants.

It is feasible to use HFC-32 in positive displacement chillers with equivalent energy efficiency to the baseline options (TEAP, 2013). Some manufacturers are developing models. There is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle lower flammable refrigerants.

The blends R-444B, R-446A, R-447A and DR-5 could be used as replacements for HCFC-22, R-407C or R-410A in positive displacement chillers that employ reciprocating or scroll compressor technologies. Chiller applications can be more suitable for the use of zeotropic blends as the glide can yield benefits when the heat exchangers are designed accordingly. It is not known whether any manufacturers are developing equipment with these alternative refrigerants.

R-513A is feasible for use in positive displacement chillers and can be used in existing HFC-134a technologies with minor modifications (TEAP, 2013), whilst maintaining adequate efficiency. R-450A is also feasible and there is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle lower flammable refrigerants.

Centrifugal chillers

HFC-134a is used widely in various capacities of centrifugal chillers and is considered to be the baseline refrigerant.

It is not practical to use R-410A and HFC-32 in centrifugal chillers. The compressor efficiency is not as high as one with HFC-134a or other low pressure refrigerants such as HFC-1234ze(E). R-717 is seldom used in centrifugal chillers and R-744 is not used in such machines (TEAP, 2013). HCs are used to a limited extent in centrifugal chillers typically within certain petro-chemical industries (TEAP, 2013), but are not considered further here. R-718 (water) chillers are in use in several installations in Europe and are now commercially available in Japan. The cost at large-scale production and thus the economic viability is not clear to date.

HFC-1234yf and HFC-1234ze(E) are considered suitable for medium pressure centrifugal chillers and are likely to give comparable efficiency to HFC-134a. HCFC-1233zd(E) is considered as a key alternative in low pressure centrifugal chillers, and should produce efficiency levels, slightly better than HCFC-123, both at moderate and high ambient temperatures. It is being trialled in chillers by some manufacturers.

3.1.8 Mobile Air Conditioning

Car

Dependent on the country, the preferred option is to keep going with HFC-134a or to shift to HFC-1234yf. The uptake of HFC-134a replacement refrigerants did not occur as expected, neither for HFC-1234yf nor for R-744, considered a second option, part of the reason was delay in the introduction of ”new models” in the context of the regulation.

The interest in and development of R-744 in this sub-sector declined significantly around 2009-2010, as car manufacturers and suppliers concentrated their efforts on HFC-1234yf. In 2013 there has been a renewed interest in R-744 MACs, with several German OEMs announcing their intention to develop such systems. However, to date no global OEM has installed R-744 for automotive air-conditioning. The main barriers for R-744 systems have been issues such as costs, reliability and servicing aspects.

Hydrocarbons are efficient refrigerants and, like other refrigerants, have to be chosen according to their condensing and evaporating pressures. Safety concerns are a clear and strong barrier against the use of HCs in cars. The sales of HC blends for car AC systems for the aftermarket will continue in some countries, but this does not constitute a global trend and will not receive the support of any carmaker. In conclusion, HCs are not at present a global option for car AC systems.
Low-GWP non-flammable blends have been proposed, in particular AC-5 and AC-6, which are currently being evaluated by an SAE International Cooperative Research Program.

HFC-1234yf , even if slightly flammable, is seen as the global solution for the car industry, and it is now being implemented in several models, especially in Europe,

German car manufacturers in 2012 raised again the issue of HFC-1234yf flammability and postponed its introduction in their assembly lines, until a separate safety assessment would have been conducted. Since then, two separate studies have been completed. Another Cooperative Research Program by the SAE confirmed previous conclusions that HFC-1234yf could be used safely for automotive air conditioning. Germany's Federal Motor Transport Authority KBA concluded that while HFC-1234yf was inherently more dangerous than HFC-134a in severe conditions, there was not enough evidence for an immediate action under the European product safety law. The KBA strongly recommended further investigations of the HFC-1234yf use and confirmed the car producer responsibility for the safety of their products. .Due to remaining safety concerns, some German OEMs work on introducing R-744 by 2017.

Public transport

Currently, the two dominant refrigerants are HFC-134a and R-407C in developed countries and HFC-134a and HCFC-22 in developing countries.

R-744 has been developed in Germany since 1996 by one company. There are over 60 busses operating with R744 MAC in Europe, with over 50 buses in Germany alone. Clear trend is the combination of the MAC with a heat pump function for energy saving heating in colder seasons with already 15 systems installed in buses in Europe. In Europe, several trials with R-744 MAC in trains have been done during the last years, with promising results.

The HFC-1234yf development for car AC systems will have direct consequences for bus and train AC systems currently operated on HFC-134a. The shift can be done, based on first lessons learned in the car industry. For train AC systems, the use of R-407C or the use of new blends containing the chemicals HFC-1234yf, uch as R-513A, or HFC-1234ze could be proposed in the near future.

In Germany, the air cycle (Brayton-Joule) technology has been installed on 67 ICE trains with 536 air cycle systems.

While the current HFCs could be used for a long period in train and bus niche applications, the shift from these high-GWP refrigerants to alternatives will be related to the overall developments in stationary AC systems.

Table 3-1 summarises the application of each alternative within the respective subsectors as discussed above.

Table 3-1 Application of each alternative in the refrigeration and air conditioning subsectors

GWP	0	1	3 – 5	4	4	6	6	290	330	490	490	600	630	716	1330	1410	1370	1700	1820	2100	2100	3700
	R-717	R-744	HC-290, HC-1270	HC-600a	HFC-1234yf	HFC-1234ze(E)	HCFC-1233zd(E)	“L-40”	R-444B	“L-41”	“DR-5”	R-450A	“XP-10”	HFC-32	R-448A	R-449A	HFC-134a	R-407C	R-407F	R-407A	R-410A	R-404A
Domestic refrigeration				C	F							F	F				C					
Commercial refrigeration																						
— Stand alone equipment		C	C	C	L	F		F	F	F	F	F	F	F	L	F	C	F	F	F	F	C
— Condensing units		L	L	F	F			F	F	F	F	F	F	F	L	F	C	F	F	F	F	C
— Centralised systems	L	C	L		F			F	F	F	F	F	L	F	L	F	C	F	C	C	F	C
Transport refrigeration		C	C		F			F	F	F	F	F	F	F	F	F	C	F	F	F	C	C
Large size refrigeration	C	C	L		F			F	F	F	F	F	F	F	F	F	F	C	C	C	C	C
Air conds and heat pumps																						
— Small self contained		L	C		F				F	F	F	F	F	L	F	F	C	C	F	F	C	F
— Mini-split (non-ducted)		L	C						F	L	F	F	F	C	F	F	F	C	F	F	C	F
— Multi-split		L							F	L	F	F	F	L	F	F	F	C	F	F	C	F
— Split (ducted)		F	F						F	F	F	F	F	L	F	F	F	C	F	F	C	F
— Ducted split comm. & non-split		F	L						F	F	F	F	F	L	F	F	C	C	F	F	C	F
— Hot water heating HPs	C	C	C	C	F	F		F	F	F	F	F	F	L	F	F	C	C	F	F	C	F
— Space heating HPs	C	C	C	L	F	F		F	F	F	F	F	F	L	F	F	C	C	F	F	C	C
Chillers																						
— Positive displacement	C	C	C		L	L		F	F	L	F	L	L	L	F	F	C	C	F	F	C	C
— Centrifugal			L		L	C	C										C					
Mobile air conditioning																						
— Cars		F	F		C							F	F				C					
— Public transport		F			L							F	F				C	C			C	

“C” indicates current use on a commercial-scale
“L” indicates limited use such as for demonstration, trials, niche applications, etc
“F” indicates use is potentially feasible on a commercial scale, based on fluid characteristics

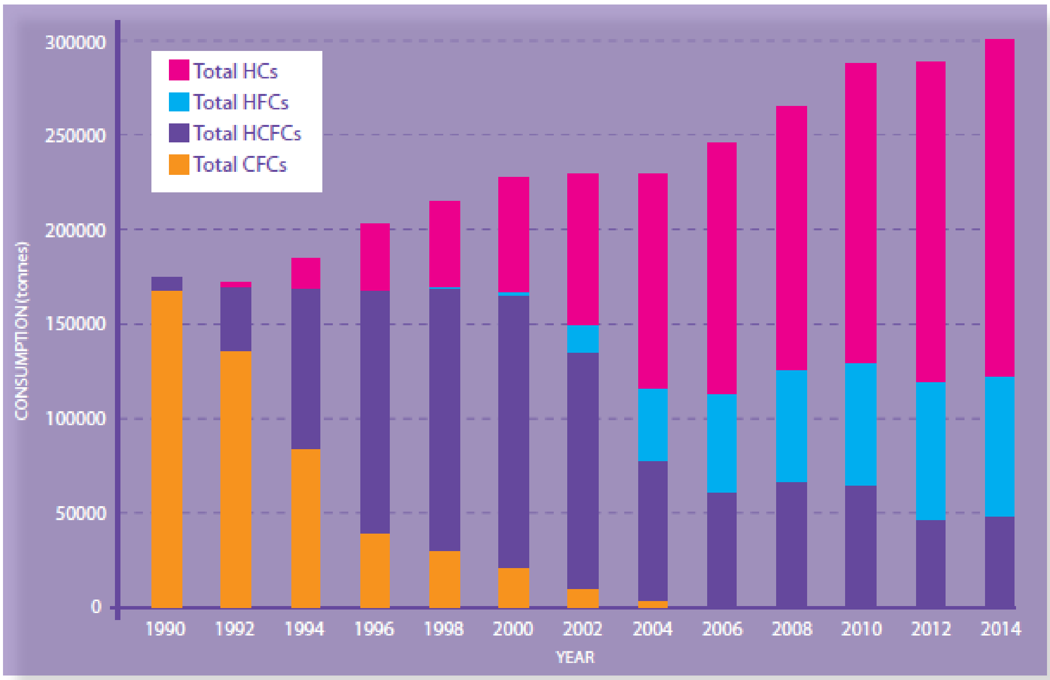
3.2 Foams

The foam sector has made significant strides in addressing the phase-out of ozone depleting substances since the signing of the Montreal Protocol in 1987. The availability of hydrocarbons at an early stage of the transition period has made it that a genuine low-GWP and cost-effective alternative has been available for large parts of the foam sector throughout that period, even at the time of the phase-out of CFCs in non-Article 5 Parties. Therefore, the account of the transition history since 1987 in the polyurethane and phenolic product sectors is dominated by whether a specific foam sub-sector could adopt hydrocarbon technologies or not. There have been a number of reasons cited over the period to explain why hydrocarbon solutions were not appropriate. These have included:

- The flammability risks associated with the production/deposition process
- The flammability risks associated with product installation and use
- The higher gaseous thermal conductivity leading to poorer thermal efficiency of the foam
- The cost of flame-proofing measures for production processes in relation to the size of the manufacturing plant (lack of economies of scale)
- Local health & safety regulations
- Local regulations on volatile organic compounds (VOCs)
- Waste management issues

Some of these have largely been discounted in more recent times, but others continue to be of importance and some are even growing in significance (e.g. waste management issues) as hydrocarbon blown foams reach end-of-life. Nevertheless, the market penetration of hydrocarbon technologies has had a substantial impact as shown by the graph below:

Global Trends in Blowing Agent Consumption by Type (1990-2014)



The dominance of the hydrocarbon technologies is even greater than it appears from the graph, since the blowing efficiency of hydrocarbon blowing agents is considerably better than the CFCs and HCFCs that were replaced. This means that the amount of foam blown by the 170,000 tonnes of hydrocarbons predicted to be used in the foam industry in 2014 will be 30-40% greater than would be achieved by the same quantity of CFCs. The optimisation of hydrocarbon technologies over the years has also resulted in improvements in thermal performance through improved cell structure, thereby negating some of the earlier concerns about poorer thermal efficiency. It can be seen that the other major groups of blowing agents being used for the polyurethane and phenolic foam sectors at this point are HCFCs (in Article 5 Parties) and HFCs (in non-Article 5 Parties).

In the Extruded Polystyrene sector, the main low-GWP and cost-effective alternative has been CO_2 itself. Again, the main challenge throughout has been to understand why this solution could not be universal in its application. Reasons have included:

- Processing difficulties with CO_2 and even CO_2/HCO or CO_2/HC blends
- The higher gaseous thermal conductivity leading to poorer thermal efficiency of the foam
- Costs of conversion - including licensing constraints resulting from patents
- Loss of processing flexibility ruling out some board geometries completely

For these reasons considerable proportions of the extruded polystyrene (XPS) industry have remained using HCFCs and HFCs rather than CO_2. This will be explained further in section 5.8.

In the intervening years, the search for low-GWP, high performance blowing agents without the limitations of hydrocarbons and CO_2 has been continuing. For the first time, the emergence of unsaturated HCFCs and HFCs (often commercially referred to as HFOs) seems to be offering a level of performance which not only allows the replacement of blowing agents with high-GWPs such as HCFCs and saturated HFCs, but also threatens to replace some elements of the hydrocarbon and CO_2-blown sectors, based primarily on improved thermal properties. However, although the situation is becoming clearer with these technologies, there are still some uncertainties over the overall system cost and the global availability. Limited commercial availability has already been established for HFO-1234ze(E) (gaseous blowing agent) and HFO-1233zd(E) (liquid blowing agent). Pilot scale production of HFO-1336mzzm(Z) is expected in late 2014, with full commercialisation in 2016. However, in the first instance, this availability is likely to be targeted mostly in markets within non-Article 5 Parties where the requirement for improved thermal efficiency is best identified. Even in these markets, it is expected that blowing agent blends will become predominant, especially where unsaturated HCFCs and HFCs can be blended with hydrocarbons to obtain better thermal performance with minimum system cost increase.

Other blowing agents are also emerging as potential replacements for HCFCs and HFCs. These include a group of oxygenated hydrocarbons (HCOs) which include methyl formate and methylal. Recent analyses of approved projects within the Multilateral Fund Secretariat shows that up to 5,000 tes of methyl formate and 300 tonnes of methylal can be expected by the time of project completion in 2015. These are generally seen as less flammable than the hydrocarbons themselves, although the significance of those differences can often depend on local product codes and the regulatory frameworks governing foam manufacture. Again, there is a growing tendency to see these used as components of tailored blends where they can contribute to overall performance criteria.

For the XPS sector, the emergence of gaseous unsaturated HFCs such as HFO-1234ze also presents a significant opportunity to replace any remaining HCFCs, saturated HFCs and even CO_2 in some instances. However, cost remains a key issue and blending with oxygenated hydrocarbons (e.g. dimethyl ether) may well be required to deliver a commercially viable alternative technology.

In summary, the following table provides an overview of the blowing agent classes which have either previously offered, or are currently offering, alternatives to ozone depleting substances in the sectors being specifically considered in this chapter. The table has been simplified over that of previous years by the fact that the Arkema product previously described as AFA-1 has now been confirmed as HFO-1233zd(E), which aligns it with the existing Honeywell product.

Sector	CFCs	HCFCs	HFCs	HCs	HCOs	HFOs	CO_2-based
	ODS being replaced						
PU Appliances	CFC-11	HCFC-141b HCFC-22	HFC-245fa HFC-365mfc/227ea	cyclo-pentane cyclo/iso-pentane	Methyl[Δ] Formate	HFO-1233zd(E) HFO-1336mzzm(Z)	CO_2 (water)*[Δ]
PU Board	CFC-11	HCFC-141b	HFC-365mfc/227ea	n-pentane cyclo/iso pentane		HFO-1233zd(E) HFO-1336mzzm(Z)	
PU Panel	CFC-11	HCFC-141b	HFC-245fa HFC-365mfc/227ea	n-pentane cyclo/iso pentane		HFO-1233zd(E) HFO-1336mzzm(Z)	CO_2 (water)*
PU Spray	CFC-11	HCFC-141b	HFC-245fa HFC-365mfc/227ea			HFO-1233zd(E) HFO-1336mzzm(Z)	CO_2 (water)* Super-critical CO_2
PU In-situ/Block	CFC-11	HCFC-141b	HFC-245fa HFC-365mfc/227ea	n-pentane cyclo/iso pentane		HFO-1233zd(E) HFO-1336mzzm(Z)	CO_2 (water)*
PU Integral Skin	CFC-11	HCFC-141b HCFC-22	HFC-245fa HFC-134a		Methyl Formate Methylal		CO_2 (water)*
XPS Board	CFC-12	HCFC-142b HCFC-22	HFC-134a HFC-152a		DME	HFO-1234ze(E)	CO_2 CO_2/ethanol
Phenolic	CFC-11	HCFC-141b	HFC-245fa HFC-365mfc/227ea	n-pentane cyclo/iso pentane		HFO-1233zd(E) HFO-1336mzzm(Z)	

*CO_2(water) blown foams rely on the generation of CO_2 from reaction of isocyanate with water in the PU system itself
[Δ] Primarily in the commercial refrigeration sector (e.g. vending machines)

The next sections of this chapter briefly summarise trends in blowing agent choice by specific sector. More detailed reviews of options are found in the relevant Annexes to this report (see Chapter 10). These annexed items are updates of the original materials presented in Decision XXIV/7.

3.2.1 Polyurethane Appliance

3.2.1.1 Non-Article 5 Parties

In Europe and Japan, the dominant blowing agent choices have been hydrocarbon blends, even at the point of phase-out from CFC use in the early/mid 1990s. Cyclo-pentane was a favoured component of blends because of its contributions to improved thermal performance, but its lack of blowing efficiency in pure form and the impact of this on processing and cost often led to the blending with components such as iso-pentane or n-pentane. Therefore, cyclo-iso blends have been a common feature of the domestic appliance industry and still remain so.

In North America, the technology choice was driven in a different direction – partly by the overall size and design of refrigerators and partly because of safety and insurance concerns from a manufacturing perspective. Transitions from CFCs moved to HCFCs and then, primarily, to HFC-245fa. There has also been some use of HFC-134a in the sector and, more recently, the removal of patent restrictions has allowed for the introduction of HFC-365mfc/227ea blends. Therefore, the domestic appliance industry in this region remains largely dependent on high GWP HFCs.

For commercial appliances and more complex insulated containers, the blowing agent choices have been more varied, with greater reliance on lower flammability options. In some instances (e.g. in vending machines), this has encouraged the use of oxygenated hydrocarbons such as methyl formate and, to a lesser degree methylal. In addition, there has been widespread reliance on HCFCs and, more latterly high GWP HFCs.

Although there are no obvious pressures to change technologies in any of the regions referenced above, the emergence of unsaturated HFCs and HCFCs has generated particular interest in all regions. The main reason is that these molecules offer improved thermal insulating properties in an application where maximising thermal performance and minimising insulation thickness are desirable outcomes. Whether additional market pressures in North America relating to the continued use of high-GWP HFCs will add to the pressure to adopt blends containing the unsaturated molecules is not yet clear.

3.2.1.2 Article 5 Parties

Similar trends exist for in the highly populated Article 5 Parties where multi-national companies are often seeking to adopt global technology strategies. In some cases, the transition from HCFCs to alternatives has not yet occurred and there are opportunities to avoid high-GWP HFCs. However, the Multilateral Funs process does not direct influence over these technology choices, since funding is usually not provided. Instead it falls on individual Parties to negotiate a phase-out strategy with their industries. This matter is covered further in Chapter 4. Interest in unsaturated HFCs and HCFCs is expected to mirror the decisions made in non-Article 5 regions.

For those transitions covered under the Multilateral Fund, it has been possible to direct virtually all HCFC phase-out activities towards low-GWP alternatives including pre-blended hydrocarbon, methyl formate and methylal. Transitions will not be complete before 2015, at which point the full degree of coverage of these technologies will be more self-evident.

3.2.2 Polyurethane Boardstock

3.2.2.1 Non-Article 5 Parties

In virtually all non-Article 5 regions, hydrocarbons (typically a mixture of cyclo-pentane and iso-pentane) have been the dominant choice of blowing agent in the replacement of ozone depleting substances. Accordingly, this is reflected in the Business-As-Usual scenario used for this report. There may be some future interest in the evaluation of unsaturated HCFCs/HFCs, but the cost is likely to be prohibitive in this cost sensitive application unless space saving is at a premium.

3.2.2.2 Article 5 Parties

There is no significant manufacture of boardstock in Article 5 regions with the possible exception of China. However, where new capacity is installed, it is highly likely that the blowing agent of choice will once again be hydrocarbons.

3.2.3 Polyurethane Panels

3.2.3.1 Non-Article 5 Parties

For the continuous panel sector, hydrocarbons have also been the blowing agent of choice except where fire performance requirements have dictated otherwise. In these limited instances, high-GWP HFCs have been adopted. Increasingly the industry has found ways of optimising formulations to improve fire performance while still using hydrocarbons and the use of saturated HFCs has steadily decreased over the last five years. This is reflected in the Business-as-Usual scenario used for this report.

For discontinuous panel manufacture, there has been greater reliance on high-GWP HFCs as replacements for HCFCs in order to overcome flammability concerns during processing. Nevertheless, similar trends to those with continuous panels are now being observed as manufacturers become more skilled and experienced in managing hydrocarbons in production situations.

3.2.3.2 Article 5 Parties

There is a greater preponderance of discontinuous production in Article 5 regions because of the lack of concentrated demand to support continuous production facilities. This has ensured continued use of HCFCs in many small discontinuous panel manufacturing uses. Although oxygenated hydrocarbons (HCOs) such as methyl formate and methylal are also being considered for this sector, the uptake at present is still relatively low.

3.2.4 Polyurethane Spray

3.2.4.1 Non-Article 5 Parties

This remains one of the most challenging areas from a technical viewpoint, because of the processing risks associated with using hydrocarbons in field applications. As a result, HCFCs were replaced *en masse* by high-GWP blowing agents such as HFC-245fa (particularly in North America) and HFC-365mfc/227ea (particularly in Europe). Although unsaturated HCFCs/HFCs are seen as a future replacement, emerging concerns about the stability of the gaseous blowing agent (HFO 1234ze(E)) in certain low-pressure pre-blended formulations are placing some doubt on the ability of these technologies to reach their full potential. Accordingly, the Business-As-Usual scenario remains focused on high-GWP solutions for the moment.

3.2.4.2 Article 5 Parties

For similar reasons to those expressed for non-Article 5 regions, PU Spray foam in Article 5 regions remains highly reliant on HCFCs. If the concerns about unsaturated HCFCs/HFCs continue for any significant period of time, contractors and systems houses may need to investigate the possibility of moving to a high-GWP interim solution in order to exit from HCFC-141b use in a timely manner.

3.2.5 Polyurethane In-situ/Block

3.2.5.1 Non-Article 5 Parties

These products can be made by a variety of processes, including continuous, semi-continuous and discontinuous options. Although there is some sensitivity to the use of hydrocarbons in some discontinuous facilities (see comments on discontinuous panels), the majority of products in this sector have been able to adopt hydrocarbon technologies successfully. There are possibilities that methyl formate or methylal might be able to replace saturated HFCs in some of the remaining discontinuous processes, but this will ultimately depend on local regulations and practices. Accordingly, little change is predicted in this sector within the next 5-10 years within the Business-As-Usual scenario.

3.2.5.2 Article 5 Parties

Similar concerns exist for discontinuous processes in Article 5 regions. As is the case in the panel sector, these are more prevalent in Article 5 regions because of lack of economies of scale. There are also differences in product demand with thermo-ware being a particular requirement in Southern Asia and elsewhere. For these reasons HCFCs continue to remain the blowing agent of choice, although uptake of methyl formate and/or methylal is predicted within a number of HPMPs. The magnitude of this uptake is varied in the Mitigation Scenarios selected for foams, but the Business-as-Usual scenario reflects a fairly conservative estimate of market penetration, with the remainder going to high-GWP HFCs.

3.2.6 Polyurethane Integral Skin

3.2.6.1 Non-Article 5 Parties

In this non-insulating sector, CO_2(water) technologies play a significant role, particularly where skinning properties are not critical. However, in non-Article 5 regions, hydrocarbons have become increasingly accepted as reliable replacements for HCFCs that were used previously. There has been some small use of HFCs (typically HFC-134a or HFC-245fa), but this has been limited to specialist applications.

3.2.6.2 Article 5 Parties

Since the focus on technology optimisation has not been so prevalent in Article 5 regions except where multi-national clients (e.g. the automotive sector) have been involved, there has been a tendency to remain with HCFC technology while awaiting further developments. Transitions to high-GWP HFC alternatives remain the easiest technology option, although methyl formate and methylal are also appropriate options, which mitigate at least some of the flammability risks associated with other hydrocarbons. The Business-As-Usual scenario follows the path and timing of most current HPMPs in predicting the transition paths and timing.

3.2.7 Extruded Polystyrene (XPS)

3.2.7.1 Non-Article 5 Parties

Alongside PU Spray Foam, the extruded polystyrene sector represents one of the most challenging technological sectors of the market. Although CO_2 technology has been successfully adopted by some of the multi-national producers, it is not very versatile and remains unsuitable for certain product types, even when modified with HCOs such as di-methyl ether. While hydrocarbons have proved uniquely acceptable in Japan, the majority of other non-Article 5 production is now based on the use of high-GWP HFCs such as blends of HFC-134a and HFC-152a. Attempts to move away from these blowing agents in the short-term are made less likely because of parallel concerns with the brominated flame retardants widely used in XPS and other polystyrene products. Accordingly, the Business-As-Usual scenario is relatively conservative in its outlook for further transition.

3.2.7.2 Article 5 Parties

Extruded polystyrene manufacture has grown substantially in a number of Article 5 regions over the last 10 years. Much of the manufacture has been based on HCFC technologies, since these are the most versatile options for a wide range of processing scales. For China, in particular, there are a large number of small plants and although there is some hope that a specifically tailored CO_2 technology can achieve widespread conversion, the outcome of an important pilot study is still awaited. As with the non-Article 5 assessment, the Business-As-Usual scenario is relatively conservative and does not anticipate early transitions.

3.2.8 Phenolic Foam

3.2.8.1 Non-Article 5 Parties

The technologies in use in non-Article 5 regions are almost universally based on hydrocarbon or 2-chloropropane blowing agents, since it has been found that the intrinsic fire properties of phenolic foams are more than sufficient to compensate for any blowing agent contribution to flammability. The only potential future transition might be to take advantage of the improved thermal properties of unsaturated HCFCs/HFCs, although this has not been postulated in the Business-as-Usual scenario for phenolic foam.

3.2.8.2 Article 5 Parties

There is very little production of phenolic foam in Article 5 regions with the exception of China. In keeping with the bulk of phenolic foam manufacture in non-Article 5 countries, all know production in China is already based on hydrocarbon technologies.

4 Factors influencing the specific BAU scenarios for Article 5 and non-Article 5 regions

4.1 Refrigeration and Air Conditioning – methods for developing demand estimates

In the case of refrigeration and air conditioning, one has to deal with a number of sub-sectors and sub-subsectors, each having several ODS alternatives. Considering that there is a preference to apply certain alternatives preference in specific equipment (and often under certain conditions), combined with the fact that the amounts in banks (present in the equipment) need recharging (i.e., servicing) over their entire lifetime (which is assumed to be 10-15 years), substantially complicates all matters for calculations.

The method used is a bottom-up method, where one has to define a starting point (i.e., the year 1990) where there is still a large amount of equipment (the installed base) in operation from the period 1975-1990. This amount will gradually disappear over the years, so that estimates for the demand after the year 2005 are dealing with estimates of numbers of equipment that have been manufactured after 1990. Choices for certain refrigerants made will therefore gradually increase in the total demand, consisting of both new manufacturing (charging) and servicing demand.

4.2 Article 5 Parties – Refrigeration and Air Conditioning

4.2.1 Decision XIX/6

The phase-down schedule under Decision XIX/6 is shown as follows:

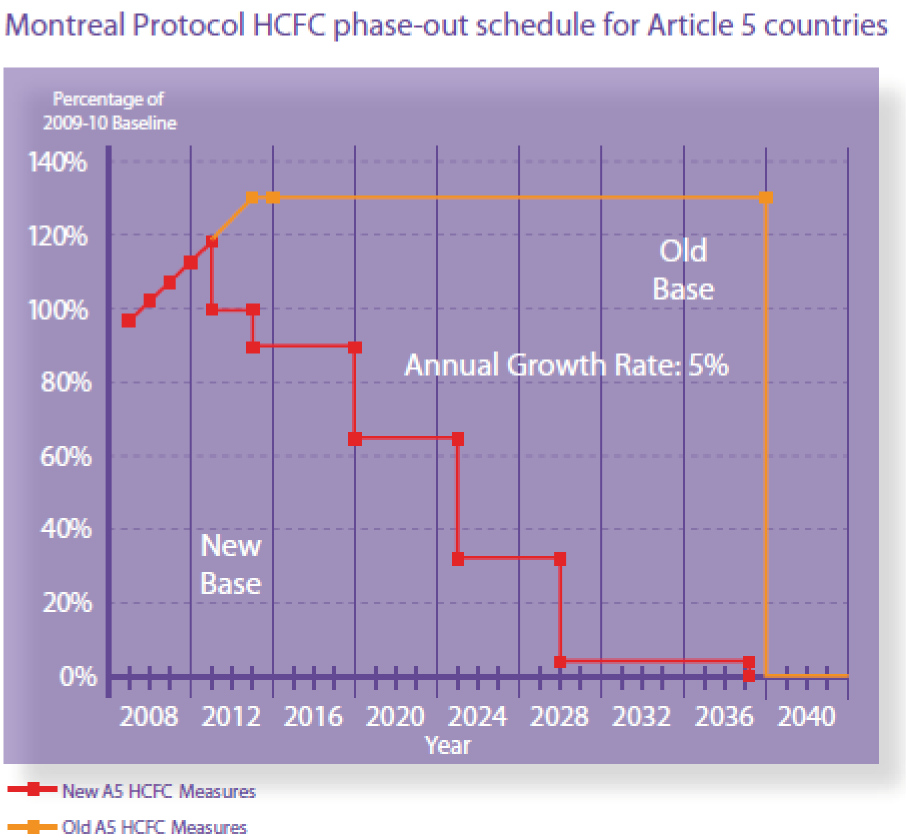


Figure 4-1 Schematic of the phase-down steps of Decision XIX/6 compared with earlier provisions

A major challenge created by the terms of Decision XIX/6 is that the freeze in 2013 is based on the average of the 2009 and 2010 consumption. This means that growth in the period from 2010 to 2012 needs to be offset in 2013. Figure 4-1 shows how the BAU would look for an annual growth rate of 5% during that period. This remains a challenge for both the RAC and foam sectors.

Decision XIX/6 on Adjustments for Annex C, Group I substances (HCFCs), mentions in its paragraphs:

(i) To encourage Parties to promote the selection of alternatives to HCFCs that minimize environmental impacts, in particular impacts on climate, as well as meeting other health, safety and economic considerations,

and

(ii) To agree that the Executive Committee, when developing and applying funding criteria for projects and programmes, and taking into account paragraph 6, give priority to cost-effective projects and programmes which focus on, inter alia on

(a) phasing-out first those HCFCs with higher ozone-depleting potential, taking into account national circumstances,

(b) substitutes and alternatives that minimize other impacts on the environment, including on the climate, taking into account global-warming potential, energy use and other relevant factors.

It implies that Parties should promote alternatives to HCFCs that minimise impacts on the climate, furthermore that the Executive Committee should give priority to cost effective projects and programmes, focusing on substitutes and alternatives that minimise impacts on the climate, taking into account the global warming potential and energy use of the alternatives.

In practice, the Executive Committee of the Multilateral Fund can have an influence on the choice of substitutes and alternatives in HCFC conversion projects, in particular for mass production of stationary air conditioning. This has been shown in projects approved in 2010-2012, where there has been an increasing preference to go to low-GWP alternatives, or in case where these alternatives could not be applied, to postpone conversion projects.

However, the conversion of existing stationary AC manufacturing is just one aspect. Many stationary air conditioning production facilities are new facilities and do not result from conversions as mentioned in Decision XIX/6. In other refrigeration and air conditioning sectors (mobile air conditioning, on-site erected commercial refrigeration units, large industrial refrigeration new plants) the choice of refrigerants normally is a choice for high-GWP HFCs (HFC-134a and HFC based blends).

A very large percentage of equipment in Article 5 countries is therefore equipped with HFCs, and the amount will grow following certain economic growth parameters. The amount of equipment that is being converted away from HCFC-22 to low-GWP alternatives represents a low share of the total number of refrigeration and air conditioning units produced.

4.2.2 Economic Growth Rates

The economic growth parameter is the important parameter to estimate BAU demand in developing countries. In the model, different economic growth percentages have been applied for certain Article 5 countries, with 7% growth per year in countries such as China. With its large consumption for HCFC-22, China is determining the total Article 5 demand to a significant degree.

4.2.3 BAU – Refrigeration and Air Conditioning

The BAU scenario for Article 5 countries for refrigeration and air conditioning does not take into account any policies or measures in the conversion to low-GWP alternatives. This BAU case can therefore be defined as unconstrained growth using economic growth parameters for the various Article 5 regions. The BAU scenario builds upon the trend from 2010-2015 in the establishment of the bank of refrigerants (via demand and leakage) in the different refrigeration and AC sub-sectors and is depicted in Table 4-1 below.

A5		
MAC	**All countries**	
	Use of R134a Servicing as usual	
Domestic	**All countries**	
CommRef **Transport** **Industrial**	**All countries**	
	(HCFC-22 replaced by and) new equipment lines on HFC-134a, R-404A, R-407A/C/F	
SAC		
	Usual practice of R-410A, R-407, some 134a	

Table 4-1 Assumptions for the Article 5 region BAU scenario

On the basis of the development of the demand for the various ODS replacements for the various sub-sectors (high GWP and of low GWP alternatives), the total demand in tonnes (and in GWP based CO_2 equivalent tonnes) can be calculated. Since the emphasis in the request in Decision XXV/5 is on ODS alternatives as a total (not split into the various sub-sectors of e.g. R/AC), the demand calculated can be split into the various high-GWP refrigerants and blends as well as low GWP refrigerants for the entire RAC sector, this for each of the years up to 2030.

Year/ Refrigerant type	2010	2015	2020	2025	2030
HFC-134a	54.4	110.4	183.5	287.2	209.9
R-404A/R-507	13.1	35.2	55.5	112.6	179.8
R-407C	16.5	58.6	105.6	167.5	246.5
R-410A	41	95.8	162.5	247.5	360.3
Low-GWP	22.4	33.7	48.8	68.9	98.5
T O T A L	**147.4**	**333.7**	**555.9**	**883.7**	**1295.0**

Table 4-2 Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2030 in Article 5 countries (ktonnes)

Year	2010	2015	2020	2025	2030
MAC	36.6	62.3	92.7	131.4	184.2
Domestic	16.0	23.3	31.0	44.1	62.3
Commercial	14.1	57.0	107.3	211.6	326.4
Industrial	20.7	31.3	47.9	68.0	95.5
Transport	1.7	3.2	5.1	7.9	11.5
Stationary AC	58.6	156.5	271.8	420.5	615.0
T O T A L	**147.4**	**333.6**	**555.9**	**883.7**	**1295.0**

Table 4-3 Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2030 in Article 5 countries (ktonnes)

Year/ Refrigerant type	2010	2015	2020	2025	2030
HFC-134a	70.7	143.5	238.5	373.3	532.9
R-404A/R-507	51.6	138.8	219.0	443.9	708.6
R-407C	26.8	95	171.1	271.3	399.3
R-410A	78.7	183.9	312.0	475.2	691.8
Low-GWP	0.06	0.14	0.25	0.42	0.68
T O T A L	**227.9**	**561.3**	**940.9**	**1564.1**	**2333.3**

Table 4-4 Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2030 in Article 5 countries (Mt CO_2 equivalent)

Year	2010	2015	2020	2025	2030
MAC	47.3	81.0	120.6	170.8	239.5
Domestic	16.9	21.7	24.7	31.5	38.8
Commercial	48.2	157.0	266.7	540.6	850.8
Industrial	3.3	10.4	27.2	46.9	73.1
Transport	5.2	9.5	13.8	20.6	29.3
Stationary AC	106.9	281.6	487.9	753.7	1101.7
T O T A L	**227.8**	**561.3**	**940.8**	**1564.1**	**2333.2**

Table 4-5 Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2030 in Article 5 countries (Mt CO_2 equivalent)

The following can be observed for Article 5 countries (based on no restrictions for the 2010-2030 demand, and assumed economic growth percentages):

- The demand for HFC-134a in Article 5 countries almost quadruples in 15 years, between 2015 and 2030, the most important subsector that uses HFC-134a being mobile air conditioning;
- The BAU scenario for R-404A and R-407C shows a growth in demand by a factor of 4-5 for the refrigerants R-404A, R-407C and R-410A mainly due to the external (growth) factors;
- Actually, the demand for low-GWP refrigerants grows by a factor of 3, mainly due to the fact that the application of low-GWP refrigerants is only assumed to occur in certain sub-sectors (e.g. the MAC and SAC sub-sectors);
- In Article 5 countries, the demand in tonnes for HFC-134a is estimated to remain higher than the demand for R-410A during the entire period 2015-2030;
- In tonnes, the total refrigerant demand increases by almost 400% between 2015 and 2030;
- The same tendencies in growth, both for the demand of the separate refrigerants (in sub-sectors) and for the total demand can be observed, if numbers are expressed in Mt CO_2 eq. In this case the total demand increases again by about 400% between 2015 and 2030.

4.3 Article 5 Parties - Foams

The term 'business as usual' (BAU) is assumed to consider only existing legislative steps agreed under the Montreal Protocol. For Article 5 Parties, the most significant regulatory framework from a foams perspective is Decision XIX/6 under the Montreal Protocol and the national legislation and programmes that have stemmed from it. The basic framework has already been addressed in Section 4.2.1. However, the following sub-sections set out the implications for the foam sector.

4.3.1 Polyurethane Foams

The dominant blowing agent for the polyurethane sub-sector in Article 5 Parties since the CFC phase-out has been HCFC-141b. Although some switches were made directly from CFCs to hydrocarbons in the appliance industry, lack of economies of scale prevented this approach in many regions. A survey conducted by the UN Multilateral Fund Secretariat in 2008[1] indicated that, of the 43 Article 5 Parties reporting the use of HCFC-141b, 20 were reporting annual consumption below 10 ODP tonnes (91 metric tonnes). The small scale and the wide spread of uses created an organisational challenge, which would require the full co-operation of polyurethane systems to address. Moreover, there would be a need to ensure that the widest possible range of technological options would be available.

An additional factor influencing the BAU in the polyurethane foam sector is the "worst first" focus of Decision XIX/6, which prioritises the higher ODP HCFCs for early replacement. This ensured that many of the HCFC-141b projects appeared on the Stage 1 HCFC Phase-out Management Plans (HPMPs). However, in view of the diffuse use patterns mentioned above and the organisational challenges arising, some projects were slow to be submitted for approval. This trend was often compounded by delays in finalising funding rules under the MLF. The outcome remains that, whilst most Stage 1 HPMPs have been submitted and approved, the implementation has been behind the schedule required to meet the 2013 freeze.

Although the general characterisation of the situation is one of diffuse HCFC-141b use patterns, there are a number of Article 5 Parties where major multi-national companies are significant HCFC-141b users. These are generally not eligible for funding under the Multilateral Fund, making the timing of phase-out plans the subject of negotiation between the companies and the relevant National Government. This will inevitably be factored into the Stage 1 (or Stage 2) HPMP, but it clearly leaves that Plan highly vulnerable to any changes in phase-out strategy in those operations.

4.3.2 Extruded Polystyrene Foams

The impact of multi-national company decision-making is even greater in the extruded polystyrene (XPS) sector where the ownership of manufacturing technology is relatively concentrated. In the absence of the 'worst-first' pressure associated with HCFC-141b and also the lack of obvious alternatives, the scheduling of transitions in this sub-sector has often been deferred until Stage 2.

This decision-making process belies the fact that the XPS sector is the most prevalent user of HCFCs within the foam sector. In many instances, deferring the transition to Stage 2 could jeopardise the ability of Article 5 Parties to meet their phase-down targets – especially the short-term targets such as the 2013 freeze and the 10% reduction by 2015.

In some Article 5 Parties, there has been a rapid growth in the production and use of XPS through small independent manufacturers. These are not generally beholding to the major multi-national technology holders but are reliant instead on the deployment of technologies by Implementing Agencies. One of the major options in this sector is small-scale CO_2 technology, but the

[1] Paper 54/54 submitted to the 54th Executive Committee Meeting in April 2008

demonstration project commissioned on this option will not report until November 2014. This leaves a level of uncertainty about the effectiveness of those transitions and their future timing.

4.3.3 Other Foams

There are few other foams in common use in Article 5 Parties. There has been minor use of phenolic foam in the past but, where this has occurred, transitions have already made to non ozone-depleting blowing agents. A similar trend has been seen in other thermoplastic foams such as polyethylene foam, where hydrocarbon has been the dominant replacement.

4.3.4 Factors influencing growth rates

Overall, the global financial slowdown precipitated in 2008 has dampened the demand for thermal insulation but not totally quenched it. It is typical for the investment cycles in construction projects to create a lag of around two years in market response. Accordingly, 2010 and 2011 were relatively depressed years for the construction sector. However, the drive for improved energy efficiency levels and the overall economic growth drivers in many Article 5 Parties meant that the growth rate of 5% assumed in Figure 4.1 for the period from 2010-2012 might not have been far from the truth as an average across the whole Article 5 grouping.

4.3.5 BAU - Foams

The series of factors highlighted in the previous few sections of this Report have led the authors to believe that the foam sector may have struggled to make its full contribution to the 2013 freeze and may still struggle to make its contribution to the 10% phase-down in 2015. Figure 4-2 illustrates how this might manifest itself based on the assumption that linear phase-down can be achieved in the polyurethane sector over the ten years to 2023.

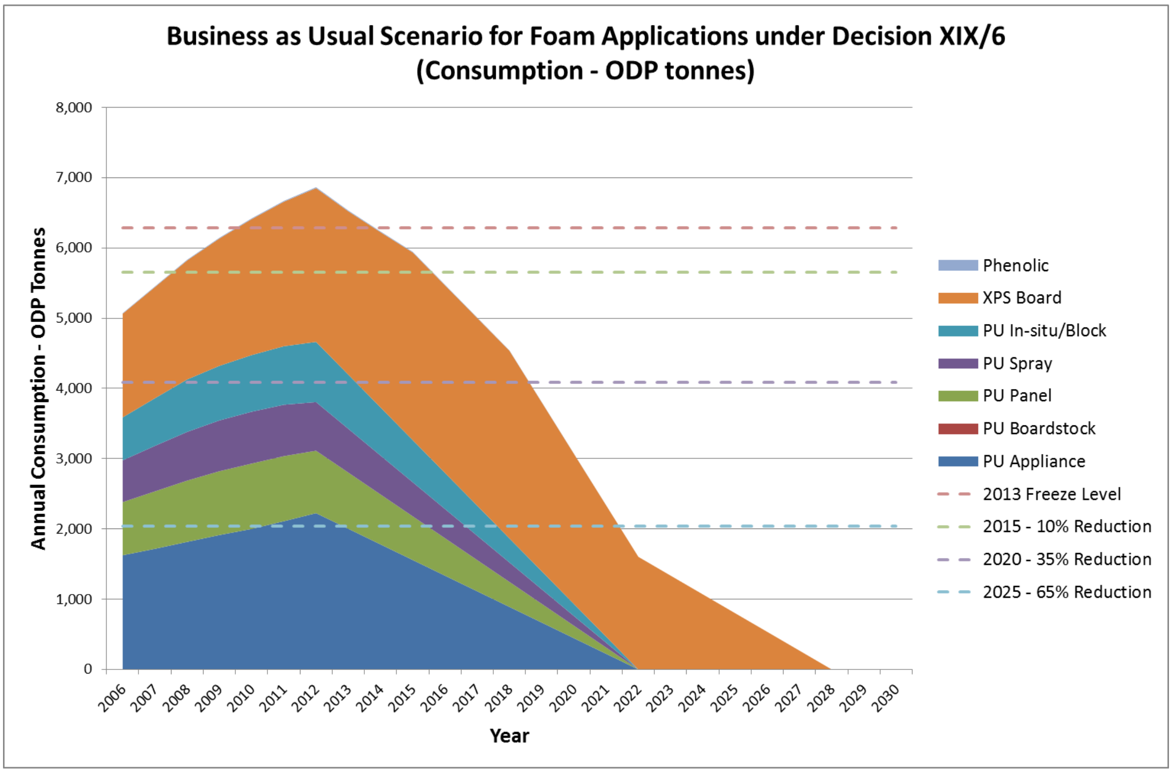


Figure 4-2 Business-as-Usual scenario for foams in Article 5 Parties (ODP tonnes)

The assumptions on which these conclusions are reached are set out in Table 4-6.

A5	
PU Appliance	**All countries**
ODS transitions complete by 2022*	Yes
% high GWP options by weight	10%
PU Boardstock	**All countries**
ODS transitions complete by 2022	Yes
% high GWP options by weight	20%
PU Panel	**All countries**
ODS transitions complete by 2022	Yes
% high GWP options by weight	20%
PU Spray	**All countries**
ODS transitions complete by 2022	Yes
% high GWP options by weight	100%/50%**
PU Insitu/Block	**All countries**
ODS transitions complete by 2022	Yes
% high GWP options by weight	20%
XPS Board	**All countries**
ODS transitions complete by 2028^	Yes
% high GWP options by weight	100%/50%**
Phenolic	**All countries**
ODS transitions complete by 2022	Yes
% high GWP options by weight	20%

* Assumes a 10 year linear phase down from peak in 2012
^ Assumes a 10 year linear phase down from peak in 2018
** Assumes 100% high GWP prior to 2017 and 50% high GWP from 2017 onwards

Table 4-6 Assumptions used for Business-as-Usual foam assessment in Article 5 Parties

Of course, the foam sector is not accountable in isolation for compliance with the Decision XIX/6 phase-down schedule and with the refrigeration and air conditioning sector accounting for two thirds of the HCFC consumption, as reported by the Mutilateral Fund Secretariat in 2008[1], it is likely that progress in the RAC field will be of more relevance to compliance than progress in the foam sector. That said, there is less pressure in RAC from the 'worst first' focus and the potential impacts on consumption are less immediate because of the on-going contribution of servicing demand.

The following two tables give further data on the BAU tonnage projections:

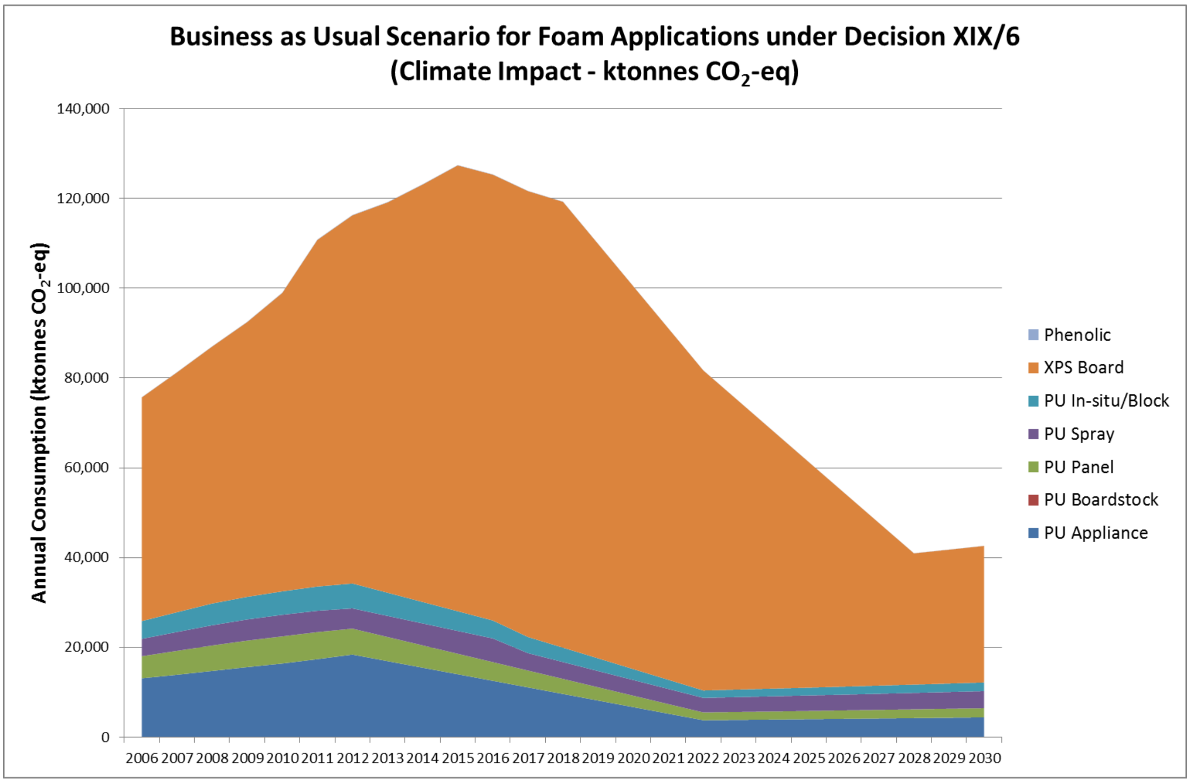
	A5 : BAU - Year in tonnes					A5 : BAU - Year in ktCO$_2$-eq				
	2010	*2015*	*2020*	*2025*	*2030*	*2010*	*2015*	*2020*	*2025*	*2030*
HCFC-141b	39,895	29,032	8,295	0	0	28,445	20,700	5,914	0	0
HCFC-142b	16,508	22,562	17,895	6,678	0	37,473	51,216	40,621	15,160	0
HCFC-22	17,436	23,345	18,118	6,678	0	31,036	41,555	32,251	11,887	0
HFC-245fa	354	2,171	3,841	4,986	5,504	361	2,214	3,918	5,085	5,615
HFC-365mfc/HFC-227ea	0	1,758	3,428	4,547	5,020	0	1,789	3,489	4,628	5,110
HFC-134a/HFC-152a	955	6,729	11,338	22,560	30,450	1,347	9,463	13,628	23,695	30,908
HFO/HCFO	0	0	10,996	23,296	31,081	0	0	77	163	218
Hydrocarbon	31,665	43,764	54,459	63,939	71,189	348	481	599	703	783
Other	0	0	0	0	0	0	0	0	0	0
Totals	***106,814***	***129,360***	***128,370***	***132,684***	***143,245***	***99,011***	***127,418***	***100,497***	***61,322***	***42,633***
% Growth		21.11%	-0.77%	3.36%	7.96%					
Average GWPs						927	985	783	462	298

Table 4-7 Current and future demand by blowing agent for ODS and their alternatives (BAU scenario) for the period 2010-2030 in Article 5 countries

	A5 : BAU - Year in tonnes					A5 : BAU - Year in ktCO_2-eq				
	2010	*2015*	*2020*	*2025*	*2030*	*2010*	*2015*	*2020*	*2025*	*2030*
PU Dom Appliance	42,004	46,192	45,202	47,548	52,497	12,135	10,304	4,522	2,346	2,590
PU Other Appliance	2,757	3,055	3,055	3,242	3,579	1,966	1,720	954	687	759
PU Reefers	3,100	3,294	3,294	3,496	3,860	2,309	1,993	1,226	975	1,077
PU Boardstock	175	192	192	203	225	2	2	2	2	2
PU Cont. Panel	2,689	2,788	2,788	2,959	3,267	1,254	1,013	567	413	456
PU Disc. Panel	7,908	7,583	7,583	8,047	8,885	4,797	3,559	1,980	1,431	1,580
PU Spray	7,653	7,306	7,306	7,753	8,560	4,794	5,079	3,494	3,440	3,798
PU Pipe-in-Pipe	4,764	5,039	5,039	5,347	5,904	3,378	2,820	1,564	1,127	1,244
PU Block	2,591	2,777	2,777	2,946	3,253	1,847	1,563	867	624	689
PF Block	101	117	117	124	137	72	66	37	26	29
Extruded Polystyrene	33,071	51,017	51,017	51,017	53,078	66,458	99,300	85,286	50,249	30,408
Totals	***106,814***	***129,360***	***128,370***	***132,684***	***143,245***	***99,011***	***127,418***	***100,497***	***61,322***	***42,633***

Table 4-8 Current and future demand by application for ODS and their alternatives (BAU scenario) for the period 2010-2030 in Article 5 countries

Before moving on to consider the non-Article 5 BAU scenario, it is worth reflecting on the climate contributions (potential emissions) of the Article 5 foams BAU case. This is shown in Figure 4-3 below:



4.4 Non-Article 5 Parties - Foams

In non-Article 5 Parties, the phase-out of HCFCs in the foam sector was achieved for the most part by 2010, with the XPS industry in North America being amongst the last to phase-out their use. The focus for non-Article 5 parties is therefore much more on the capability to make further transitions from the use of high-GWP HFCs, such as HFC-134a, HFC-245fa and HFC-365mfc.

In accordance with the specific requests of the Parties, the BAU case for non-Article 5 Parties has been modelled on the basis of an unconstrained scenario and does not include either the re-cast F-Gas Regulation or pending measures in other jurisdictions (e.g. the President's Climate Action Plan in the

USA). These are now quantitatively addressed in the Mitigation Scenarios contained within Chapter 5. However, the previously enacted F-Gas Regulation (2006) is considered as part of the BAU, since it would be difficult and highly theoretical to extract these impacts at this late stage. For this reason, the basic outlines of the legislative measures are also retained in this Chapter.

4.4.1 HFC legislation

4.4.1.1 European Union

On 20th May 2014, the re-cast F-Gas Regulation (EC 517/2014) was published in the Official Journal of the European Union confirming the agreement reached on 16th April 2014. This re-cast is an update of the original F-Gas Regulation (EC 842/2006) which entered into force in late 2006. The latest re-cast has significant implications for the Mitigation Scenarios in both RAC and foam areas. Figure 4-4 below shows the overall phase-down schedule:

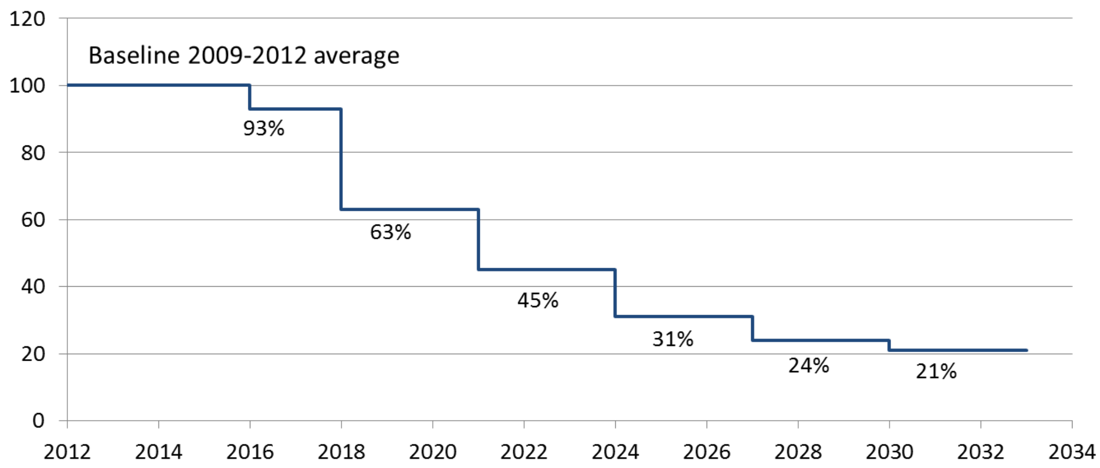


Figure 4-4 Final phase-down schedule for fluorinated gases in the EU

4.4.1.1.1 Refrigeration and Air Conditioning

Already in 2006, the MAC directive entered into force in the European Union, prohibiting the use of refrigerants with a GWP higher than 150 as of 2011 in new model cars, and as of 2017 in all new cars. The replacement of HFC-134a in new model cars has virtually not occurred, due to a large number of reasons. Some new cars currently (status April 2014) apply HFC-12434yf, but a large scale application of low GWP alternatives (GWP smaller than 150) is not expected before 2017. This is due to the fact that commercial availability of HFC-1234yf has been delayed, furthermore car manufacturers see some problems in the future with possible back-conversion to HFC-134a. The general expectation is that by 2017, all car manufacturers will apply a refrigerant solution with a GWP smaller than 150.

The 2014 re-cast F-gas Regulation 517/2014 sets a number of prohibitions for the placing of the market of products. These apply to HFCs or mixtures or blends that contain HFCs. It concerns the following:

Domestic refrigerators and freezers that contain HFCs with GWP of 150 or more	1/1/2015
Refrigerators and freezers for commercial use (hermetically sealed equipment) that contain HFCs with GWP of 2500 or more	1/1/2020
Refrigerators and freezers for commercial use (hermetically sealed equipment) that contain HFCs with GWP of 150 or more	1/1/2022
Stationary refrigeration equipment, that contains, or whose functioning relies upon, HFCs with GWP of 2500 or more (except equipment designed to cool products to temperatures below – 50 °C)	1/1/2020
Multipack centralised refrigeration systems for commercial use with a rated capacity of 40 kW or more that contain, or whose functioning relies upon, fluorinated greenhouse gases with GWP of 150 or more (except in the primary refrigerant circuit of cascade systems where fluorinated greenhouse gases with a GWP of less than 1500 may be used)	1/1/2022
Movable room air-conditioning equipment (hermetically sealed equipment which is movable between rooms by the end user) that contain HFCs with GWP of 150 or more	1/1/2020
Single split air-conditioning systems (containing less than 3 kg of fluorinated greenhouse gases), that contain, or whose functioning relies upon, fluorinated greenhouse gases with GWP of 750 or more	1/1/2025

This implies that for stationary refrigeration equipment fluorinated gases can be applied after 2020 that have a GWP smaller than 2500. Furthermore single split air conditioning systems can apply fluorinated gases with a GWP smaller than 750 (which would include the refrigerant HFC-32).

4.4.1.1.2 Foams

For foams, Figure 4-5 below illustrates the final position reached for various sectors and how these fit with the wider targets:

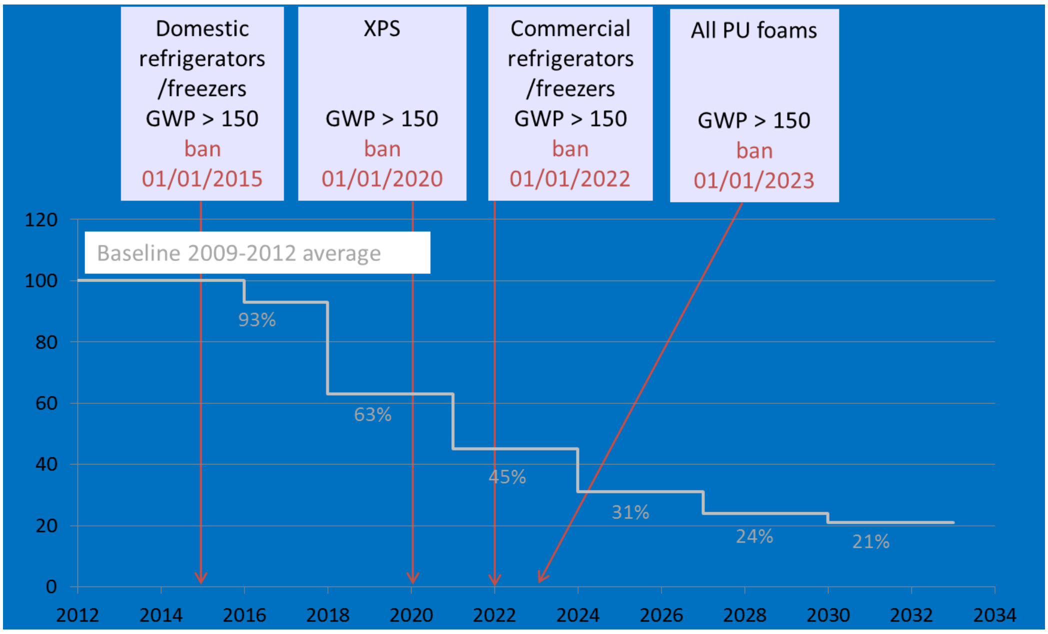


Figure 4-5 – The role of use-bans in foams in achieving phase-down targets

The decision to introduce a use-ban on high-GWP blowing agents in the XPS sector is viewed as particularly progressive. In some EU Member States, the bans are also augmented by taxation on

HFCs at varying levels. For the foams BAU case, the phase-out dates are assumed to be preceded by a five year linear phase-down in consumption.

4.4.1.2 North America

As already noted, the implementation of the President's Climate Action Plan in the USA has the potential to make impacts on the future consumption of HFCs in the country. In particular, it directs the US Environmental Protection Agency to use its authority through the Significant New Alternatives Program (SNAP) to encourage the adoption of solutions with lower climate impact by identifying and approving more benign chemicals while prohibiting certain uses of the most harmful chemical alternatives. These determinations by SNAP are expected to be made at use level and will not involve blanket bans or generic GWP cut-offs. Two subsequent proposed rules were published this year in July and August; the first rule proposes to add low-GWP refrigerants to the list of acceptable alternatives and the second rule proposes to prohibit certain high-GWP HFCs as alternatives in various end uses in the aerosols, refrigeration and air conditioning, and foam blowing sectors. It is expected that these rules will be finalized after consideration of public comments.

4.4.1.3 Japan

An amendment to the law was passed on 12th June 2013, which broadened and strengthened the approach to F-Gas management in Japan. Entitled the 'Act for Rationalised Use and Proper Management of Fluorocarbons'. It will become effective on 1st April 2015. It will require reporting of consumption of high-GWP F-gases in all areas of use. As a parallel activity, industries are expected to submit phase-down plans, which will be reviewed by the authorities before final schedules are agreed. Refrigerant handlers and users will also have requirements to report charging and recovery activities.

4.4.1.4 Other

Several non-Article 5 Parties are signalling an intent to lead on international negotiations in the area of F-Gases. It is not yet clear how this could influence further action in other non-Article 5 Parties, but some further pre-emptive activity can be expected.

4.4.1.5 Market drivers

Although many of the regulatory initiatives in non-Article 5 Parties are still focused on data gathering, reporting and voluntary commitments, the market signalling is clear. Increasingly, sectors and sub-sectors are recognising that delaying action will lead to further market pressure – particularly if competitive products have either been able to avoid from the outset, or move swiftly away from, high-GWP HFCs as a technology component. This may involve additional changes in product concepts, since it will concern an adaptation of manufacturing processes, leading to an automatic upgrade in technology and to the possible insertion of attractive consumer features.

4.5 Availability of alternatives

As can be concluded from Chapter 3 of this Report, there is no question that the emerging availability of high performance low-GWP solutions is providing new opportunities to consider alternatives with low climate impact, but is also slowing up the decision-making process while further clarity emerges on technical properties and cost. In the foam sector, those sub-sectors that could avoid high-GWP HFCs have already done so at the outset, with those remaining (e.g. XPS) being heavily dependent on such technologies until the scope of alternatives becomes clear. This is not expected much before 2018 in most regions.

4.5.1 BAU - Refrigeration and Air Conditioning

A BAU case (or scenario) for the calculation of the current and future demand for the period 2015-2030 has been defined, which assumes certain specific growth percentages for non-Article5 Parties as well as:

- the EU regulation in EU countries (new car MACs should be using substances with GWP < 150 as of 2017, the replacement of R-404A in new manufacture by blends such as R-407A/C/F, as of the year 2020);
- no control measures in other non-Article 5 Parties.

The BAU scenario for Non-Article 5 Parties for refrigeration and air conditioning does not take into account any policies or measures in the conversion to low-GWP alternatives in other countries than the EU. This BAU case can therefore be defined as unconstrained growth using economic growth parameters in other than EU non-Article 5 regions. The BAU scenario builds upon the trend from 2010-2015 in the establishment of the bank of refrigerants (via demand and leakage) in the different refrigeration and AC sub-sectors. The assumptions are summarised in Table 4-9 below:

BAU scenario		
nA5		
MAC	**EU**	**Other Countries**
2017	R134a = 0% for new eq., replaced by GWP1	
after 2017	No change in servicing	
CommRef Transport Industrial	**EU**	**Other Countries**
2020	R404A = 0% for new eq. replaced by R407	
after 2020	No change in servicing	

Table 4-9 Assumptions behind the RAC non-Article 5 Business-As-Usual Scenario

Year/ Refrigerant type	2010	2015	2020	2025	2030
HFC-134a	96.7	96.7	85.9	87.0	96.6
R-404A/R-507	38.7	42.2	32.6	28.6	28.2
R-407C	21.9	49.4	69.9	87.9	94.1
R-410A	51.4	119.4	147.3	189.4	229.3
Low-GWP	11.1	13.8	23.8	33.4	42.2
T O T A L	**219.8**	**321.5**	**359.5**	**426.8**	**490.4**

Table 4-10 Current and future refrigerant demand for (refrigerant) ODS alternatives (BAUscenario) for the period 2010-2030 in Non-Article 5 countries (ktonnes)

Year	2010	2015	2020	2025	2030
MAC	84.6	82.2	81.3	86.4	96.6
Domestic	3.7	3.5	3.2	3.6	4.1
Commercial	37.4	44.4	41.3	40.9	47.4
Industrial	15.7	19.2	20.8	23.9	27.8
Transport	2.2	2.7	2.7	2.9	3.2
Stationary AC	76.2	170.2	210.3	268.7	311.3
T O T A L	**219.8**	**321.5**	**359.5**	**426.8**	**490.4**

Table 4-11 Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2030 in Non-Article 5 countries (ktonnes)

Year/ Refrigerant type	2010	2015	2020	2025	2030
HFC-134a	125.7	125.6	111.7	113.9	125.6
R-404A/R-507	150.1	166.5	129.9	112.8	111.2
R-407C	35.4	80.1	113.2	142.4	152.4
R-410A	98.7	229.2	282.8	363.6	440.3
Low-GWP	0.03	0.04	0.04	0.05	0.07
T O T A L	**409.8**	**601.4**	**637.6**	**732.8**	**829.6**

Table 4-12 Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2030 in Non-Article 5 countries (Mt CO_2 equivalent)

Year	2010	2015	2020	2025	2030
MAC	110.3	106.8	96.6	96.8	107.0
Domestic	2.7	2.2	1.6	1.7	1.8
Commercial	133.2	152.6	143.5	129.0	129.5
Industrial	18.3	21.4	18.5	18.1	18.8
Transport	7.9	9.9	9.6	9.6	9.6
Stationary AC	137.4	308.5	382.9	485.7	562.9
T O T A L	**409.8**	**601.4**	**652.8**	**740.8**	**829.5**

Table 4-13 Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2030 in Non-Article 5 countries (kt CO2)

On the basis of the development of the demand for the various ODS replacements for the various sub-sectors (high GWP and of low GWP alternatives), the total demand in tonnes (and in GWP based CO2 equivalent tonnes) can be calculated. Since the emphasis in the request in Decision XXV/5 is on ODS alternatives as a total (not split into the various sub-sectors of e.g. RAC), the demand calculated can be split into the various high-GWP refrigerants and blends as well as low GWP refrigerants for the entire RAC sector, this for each of the years up to 2030.

The following can be observed in the case of Non-Article 5 Parties:

- The demand for HFC-134a in Non-Article 5 countries is relatively constant, with the phase-out for HFC-134a in MAC new equipment in Europe in 2017;
- The BAU scenario (which includes a phase-out in new manufacturing of stationary refrigeration equipment using HFCs with a GWP larger than 2500 in Europe by 2020) shows a 30% decrease in the demand for R-404A from 2010 to 2030;

- The BAU scenario (which implies increased use of R-407A/C/F instead of R-404A in Europe) shows a doubling of the demand between 2015 and 2030;
- As of 2013-2015, R-410A is the refrigerant that shows largest demand numbers, which demand, expressed in tonnes, forms almost 40% of the total HFC refrigerant demand;
- In tonnes, the total refrigerant demand increases by about 50% between 2015 and 2030;
- The same tendencies are visible for each of the refrigerants in Mt CO2 eq.
- In Mt CO2 eq., however, the total refrigerant demand increases by (only) 38% between 2015 and 2030. This smaller increase in Mt CO_2 eq. than in tonnes is due to the decrease in the contribution of R-404A with its very high GWP (in favour of R-407A/C/F) in the total amounts.

4.5.2 BAU – Foams

It is clear that the level of transitional pressure varies substantially by region within non-Article 5 Parties. The only jurisdiction where there is now a quantifiable mandatory approach to phase-down is in the European Union where the 2006 F-Gas Regulation sought to address some reporting and labelling issues for foams. However, there were no mandatory phase-downs within the various foam sub-sectors and the growth of HFC use has remained unconstrained by regulation, although market pressures have remained significant. For this reason the BAU scenario has no formal control measures in it but reflects a moderate growth in the period to 2030. The overall outcome for the sectors is shown in Tables 4-14 and 4-15:

	Non-A5 : BAU - Year in tonnes					Non-A5 : BAU - Year in ktCO$_2$-eq				
	2010	*2015*	*2020*	*2025*	*2030*	*2010*	*2015*	*2020*	*2025*	*2030*
HCFC-141b	0	0	0	0	0	0	0	0	0	0
HCFC-142b	16,665	0	0	0	0	37,830	0	0	0	0
HCFC-22	4,334	0	0	0	0	7,714	0	0	0	0
HFC-245fa	28,063	31,649	34,943	38,580	42,595	28,625	32,282	35,642	39,351	43,447
HFC-365mfc/HFC-227ea	9,609	9,042	9,983	11,022	12,169	10,039	9,346	10,319	11,392	12,578
HFC-134a/HFC-152a	24,230	32,819	35,400	39,085	43,153	22,259	37,375	40,088	44,261	48,867
HFO/HCFO	0	0	802	2,089	2,307	0	0	6	15	16
Hydrocarbon	121,999	130,414	144,775	176,158	194,492	1,342	1,435	1,593	1,938	2,139
Other	0	0	0	0	0	0	0	0	0	0
Totals	***204,900***	***203,924***	***225,904***	***266,933***	***294,716***	***107,808***	***80,437***	***87,647***	***96,957***	***107,048***
% Growth		-0.48%	10.78%	18.16%	10.41%					
Average GWPs						526	394	388	363	363

Table 4-14 Current and future demand by blowing agent for ODS and their alternatives (BAU scenario) for the period 2010-2030 in Non-Article 5 countries

	Non-A5 : BAU - Year in tonnes					Non-A5 : BAU - Year in ktCO$_2$-eq				
	2010	*2015*	*2020*	*2025*	*2030*	*2010*	*2015*	*2020*	*2025*	*2030*
PU Dom Appliance	31,253	34,251	37,893	42,739	47,187	12,175	13,725	15,152	16,734	18,475
PU Other Appliance	7,272	8,471	9,382	10,682	11,794	5,045	5,903	6,518	7,200	7,949
PU Reefers	2,521	2,795	3,086	3,407	3,761	1,698	1,803	1,991	2,198	2,427
PU Boardstock	69,227	77,814	87,195	110,363	121,850	2,459	2,929	3,248	3,741	4,130
PU Cont. Panel	21,128	19,325	21,379	24,066	26,571	7,386	6,225	6,873	7,594	8,384
PU Disc. Panel	13,788	13,691	14,282	15,768	17,409	12,481	12,555	12,685	14,005	15,463
PU Spray	10,463	11,430	12,619	13,933	15,383	10,726	11,667	12,881	14,222	15,702
PU Pipe-in-Pipe	2,718	2,518	2,780	3,069	3,389	1,179	1,099	1,213	1,340	1,479
PU Block	4,904	4,856	5,389	6,256	6,907	1,919	1,873	2,068	2,287	2,525
PF Block	939	900	996	1,130	1,248	362	342	378	417	461
Extruded Polystyrene	40,685	27,873	30,902	35,520	39,217	52,379	22,316	24,640	27,220	30,053
Totals	***204,900***	***203,924***	***225,904***	***266,933***	***294,716***	***107,808***	***80,437***	***87,647***	***96,957***	***107,048***

Table 4-15 Current and future demand by application for ODS and their alternatives (BAU scenario) for the period 2010-2030 in Non-Article 5 countries

Figure 4-6 provides a graphical assessment of the output from these assumptions for the period through to 2030.

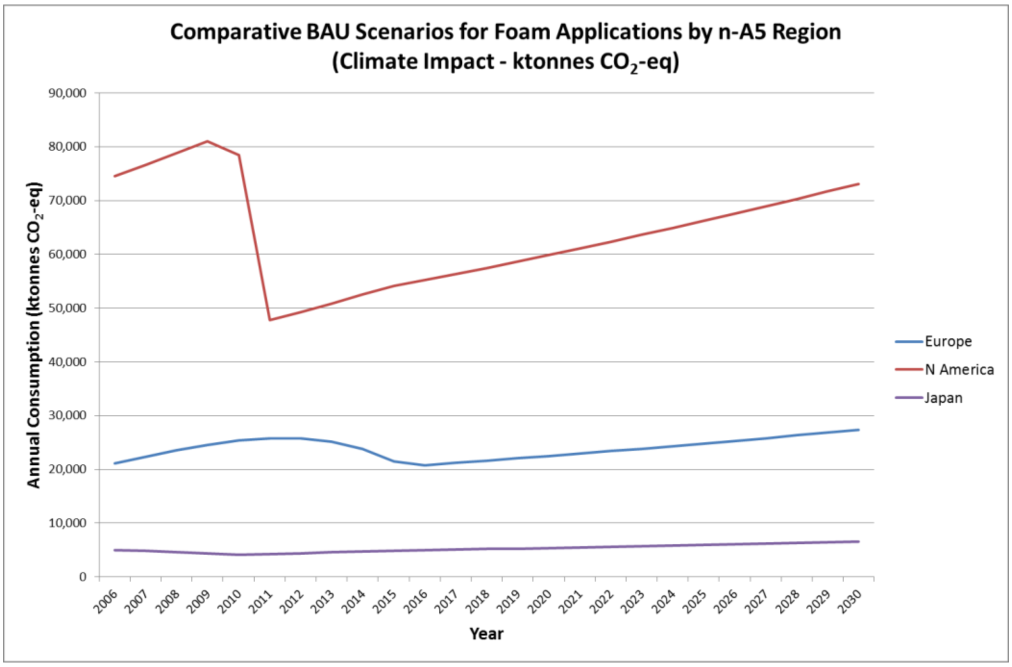


Figure 4-6 Business-as-Usual Scenario for foams in non-Article 5 Parties

The rather erratic profile for North America denotes the impact of the phase-out of HCFC use in the US extruded polystyrene industry in 2010. Nevertheless, North America remains by far the largest user of high-GWP HFCs amongst the non-Article 5 Parties as a result of decisions made in earlier transitions.

4.5.3 BAU – global summary for both foams and RAC

For the two major sectors reliant on HCFCs and HFCs, at least in part, it is important to bring some perspective to the BAU scenarios, which have been mapped out in this Chapter. Although comparisons can be made in both actual tonnages and ODP tonnes, the most meaningful from the perspective of this report is to assess the consumption (potential emissions) in climate terms (tonnes

CO_2-eq). Figure 4-7 does this and provides an assessment of the actual situation through to 2012 and then projections through to 2030 using the assumptions spelled out in earlier parts of this chapter.
It can be seen that consumption of refrigerants in RAC applications dwarfs the consumption as taking place in the various foam sub-sectors. It is also evident that the growth in Article 5 parties, if left unchecked, will have significant climate impact by 2030, especially if emission rates from installed equipment cannot be significantly limited to reduce on-going servicing demand. The graph indicates the value of considering possible action in Article 5 Parties to avoid increasing uptake in high-GWP alternatives to HCFCs.

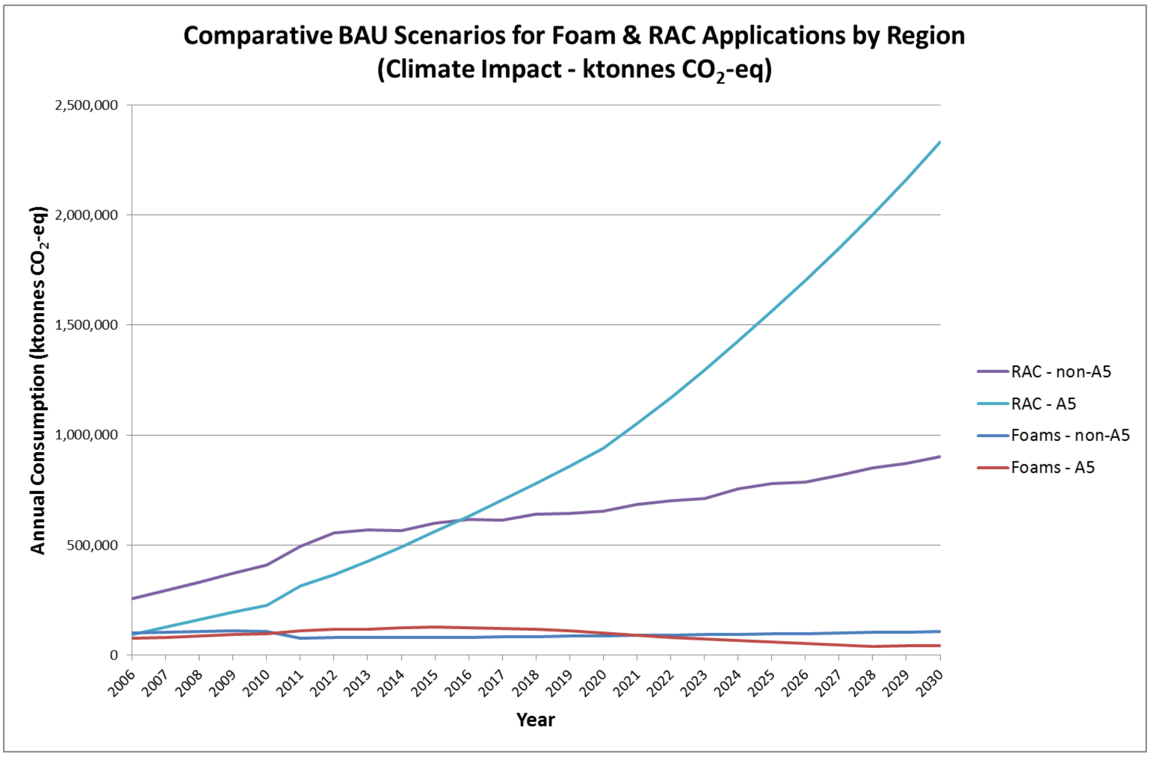


Figure 4-7 – Comparative BAU Scenarios for foams & RAC in Article 5 and non-Article 5 regions

5 Identification of relevant Mitigation Scenarios compared to Business-As-Usual

With significant levels of uncertainty about several factors influencing the choice of alternatives to ozone depleting substances and their replacements, it is undoubtedly challenging to develop meaningful scenarios for future trends in HCFC replacement and high-GWP HFC avoidance – especially when the period under evaluation extends to 2030. This chapter provides a narrative to some of the considerations that have been taken into account by the authors, prior to setting out the mitigation scenarios in Chapter 6.

5.1 Technical suitability

Although it is assumed that initial screening of alternatives will determine their suitability for the applications previously served by ODS, it is not always the case. The recent experience with the stability of unsaturated gaseous HFCs/HCFCs in certain low-pressure PU formulations in the United States of America, serves as a timely reminder that alternatives are unlikely to be absolute 'drop-in' replacements and, even with reformulation, are not guaranteed to meet the requirements of the application.

In addition to the specific capabilities of an alternative, it is increasingly the case that the range of applications served by a single alternative is reducing. This is partly because of the undeniable versatility of earlier technology options (e.g. CFCs), but the trend also reflects the fact that technological developments over the past 20 years have made the users of alternatives more discerning. There are now many more solutions available to choose from, but a need to apply greater scrutiny in decision-making to ensure continuing competitiveness in an increasingly globalised market.

5.2 Technology availability

5.2.1 Non-Article 5 Parties

Although many alternatives stem from chemistries that are already available within other sectors of use (e.g. hydrocarbons and oxygenated hydrocarbons (HCOs)), there is a need to ensure that the grade of product carries sufficient purity for the application in question. This is specifically the case for refrigerant and blowing agent applications where the presence of undesirable impurities can influence the thermodynamics and, in the case of foams, the surface chemistry of the system.

In other instances (e.g. the emergence of unsaturated HFCs and HCFCs), the molecules are themselves new. This creates a series of needs in order to validate the technology before commercial supply and use can be considered. These include:

- The characterisation of environmental criteria – such as GWP
- The assessment of human health toxicity and eco-toxicity
- The assessment of lifecycle impacts – including breakdown products
- The analysis of likely product take-up bearing in mind competitive solutions in the market place.
- The decision to invest in commercial scale plant and the lead-time required to build the necessary manufacturing facilities

The implication is that bringing new alternatives to market can take anything between two and five years depending on the starting position. Unless, an alternative is already well advanced in this process, it is unrealistic to seek to gain acceleration in the product's commercial introduction in any mitigation scenario. Accordingly, mitigation scenarios are often more about the level of market penetration than they are about the speed of technology introduction.

5.2.2 Article 5 Parties

For Article 5 Parties, there are still further considerations to be made. Most notably, a key question is whether there will be sufficient demand in the region to justify investment in manufacturing equipment or distribution infrastructure. Whilst the Executive Committee of the Multilateral Fund to a considerable amount, with assistance from the Implementing Agencies, endeavours to quantify demand and provide incentives for investment, the justification and prioritisation of such investment will be an important factor in determining whether there is a realistic prospect of availability of what might otherwise be preferred alternatives.

5.3 Defining the cost

It is self-evident that those applications with easy routes to substitution will have already instigated the necessary measures. The main reason for the continued use of HCFCs and/or the adoption of saturated HFCs is that either the technical requirements cannot be met by other alternatives or that the capital investment costs are prohibitive. In the remaining sectors of RAC and foam, the level of disaggregation in the market is high, making it rare to find economies of scale that can be leveraged to allow investment in the expensive capital equipment often needed to manage issues such as increased flammability. Ultimately it is 'cost per unit of production' that is the barrier to transition rather than the absolute investment cost itself. That said, life-cycle costing reveals that improved energy efficiency from replacement of equipment and/or refrigerant/blowing agent can make the overall abatement cost look attractive. Indeed, many climate studies will confirm that the replacement of high-GWP refrigerants and blowing agents can be very cost-effective. The challenge, however, is that the investment and subsequent savings are often de-linked.

The other challenge related to the use of climate abatement costs as a measure of cost-effectiveness in a global study is that the carbon intensity of energy will vary significantly by region making it difficult to assess the cost/benefit relationship in a meaningful way.

5.3.1 Non-Article 5 Parties

In non-Article 5 Parties, the bulk of HCFC use is already avoided and, where economies of scale do not exist, high-GWP solutions have often been the alternatives of choice. In several non-Article 5 jurisdictions there is no absolute pressure to make any further transitions and certainly no binding time-scale. Therefore, it is unlikely that costly transitions will be made unless and until equipment is due for replacement for other reasons.

Since a forced transition will always be substantially more expensive, it is impossible to place a meaningful range of cost, since each project situation will be unique. Such forced transitions are beginning to emerge in Europe, where the revised F-Gas Regulation has created more stringent phase-down targets across the industry sectors in question. Japan is in the mid-ground, where there is no absolute transition schedule, but the moral and market pressure for transition is high.

5.3.2 Article 5 Parties

In Article 5 regions, the schedule for transition is dictated to a large extent by Decision XIX/6. However, the choice of alternative is not prescribed in this process, especially for those projects not eligible for Multilateral Fund support. It is therefore perfectly legitimate, even if not environmentally desirable, to transition from an HCFC to a high-GWP alternative in order to minimise the capital cost of the project. Where the performance of a high-GWP alternative is demonstrably better than low-GWP options, or the low-GWP solution is not yet available, the drive to high-GWP alternatives, even if only for the short-term, is often irresistible.

Evidence is emerging that an over-ambitious ODS mitigation strategy can actually jeopardise the delivery of climate benefits. This has played out in practice in some instances, where the “worst first” strategy for HCFC-141b has forced inclusion in Stage 1 HPMP transitions where alternatives are not yet in place. A good example of this is in the PU Spray Foam sector where high-GWP solutions have been adopted in lieu of the arrival low-GWP solutions. The only safeguard has been a signed commitment by the enterprise for those projects supported under the Multilateral Fund to make a further transition to low-GWP solutions as soon as they are available. These dynamics are notoriously difficult to model in any mitigation scenario.

Of course, there are also investments in both sectors that are not transitional at all and, in the absence of proven low-GWP alternatives, will trends towards high GWP solutions. This is true both in the RAC and foam sectors, particularly where technology selections in non-Article 5 regions are following a similar path.

5.4 Funding sources

Section 5.3 has highlighted the fact that it is virtually impossible to pin down a realistic range of transition costs for any technology sector, since the real cost is so dependent on circumstances unrelated to the technology itself. The only general conclusion that can be drawn is that a less hurried approach is liable to lead to lower costs.

Whilst the cost question may be very difficult to fathom, the funding element is much simpler to address, since the funding mechanisms are clearer.

5.4.1 Non-Article 5 Parties

Although there are no funds available for non-Article 5 transitions under the Montreal Protocol, investments can be justified on the basis of the saving in carbon emissions. This analysis delivers the ‘so-called’ abatement cost, but needs to be assessed carefully since it should be based on emissions avoided rather than consumption avoided. That said, over a long enough period, it is certainly valid to consider consumption as potential emissions. Indeed, for refrigeration and air conditioning equipment, the cumulative servicing charge over the life-time of a piece of equipment reflects the emission and is likely to be considerably greater than the initial equipment charge.

The high-GWP of many refrigerants and foam blowing agents makes this assessment quite powerful in justifying transitions. Most climate strategies will consider that abatement investment costs up to US$ 50/tonne CO_2-eq would be reasonable. For a refrigerant on foam blowing agent of, say, 1000 GWP, this would support an investment of US$ 50/kg. Since most refrigerant transitions are in the US$ 6-10/kg range with some transitions being as low as US$ 1-2/kg, there seems little barrier to making wholesale conversions. However, there are very few jurisdictions where such projects can be monetised in this way, with California being one of few exceptions. Even then, the case for seeking to avoid refrigerant emissions seems compelling based on wider climate criteria.

5.4.2 Article 5 Parties

The funded transitions under the Multilateral Fund are much more explicit about investment thresholds and it seems that transitions to low-GWP refrigerants would fall within these thresholds provided that reliable low-GWP alternatives can be identified. It should be noted that this is not only a matter of capital cost, but also of incremental operating costs. Therefore issues such as energy efficiency can play a key role in determining the efficacy of proposed alternatives.

In the foam sector, the economy of scale issue is particularly acute. In 2008, the Multilateral Fund Secretariat paper presented to the 54^{th} Executive Committee meeting (paper 54/54) highlighted the fact that HCFC-141b and HCFC-142b use was typically associated with countries which had overall uses of less than 10ODP tonnes per year. In responding to this, the MLF has provided a funding threshold of just under US$ 8/kg for blowing agent conversion, but has also allowed a 25% premium (just under US$ 10/kg) to support the preferential introduction of low-GWP alternatives. However, it should be noted that these are funding thresholds and not assessed costs. It is well known that many enterprises are co-funding transitions from various sources to ensure that they make the most logical transition in order to remain competitive in the global market.

5.5 Other issues

The previous sections of this Chapter have highlighted a number of factors, which can influence the speed and extent of technology transition. It is clear from this assessment that not all of the drivers for more rapid transition are yet aligned.

5.5.1 Non-Article 5 Parties

In the non-Article 5 regions, it is clear that the regulatory framework developed in Europe around the revised F-Gas Regulation will stimulate further focus on transitions out of high-GWP solutions such as saturated HFCs. However, the consequences of those transitions are, as yet, uncertain – particularly where the low-GWP technologies are not yet fully proven. Even so, the framework is rigid enough to justify including the revised F-Gas regulation within the BAU baseline.

In other regions, there seems more reluctance to put such prescriptive regulatory frameworks in place and it is not yet clear whether transitions will be driven without them. The President’s Climate Action Plan and the Japanese amended law on the proper use of fluorinated gases may have some impact, but they are undoubtedly softer than the European approach.

5.5.2 Article 5 Parties

The implementation of Decision XIX/6 was always understood to be a vehicle for promoting appropriate consideration of climate aspects when transitioning out of HCFCs. In some sectors, this seems to have been effective, but ultimately the decisions are driven by confidence in the low-GWP alternatives. There are still a number of pilot projects outstanding on these technologies (notably CO_2 in XPS and pre-blended hydrocarbons for PU foams), which still need to deliver positive outcomes before mitigation strategies can be enforced.

6 Environmental benefits associated with selected Mitigation Scenarios

Taking into account the content of Chapter 5, the Task Force has developed two mitigation scenarios covering RAC and foams in both Article 5 and non-Article 5 regions. The following sections deal with the assumptions made and the predicted environmental outcomes arising.

6.1 Article 5 – Refrigeration and Air Conditioning

6.1.1 Mitigation Scenarios

Two mitigation scenarios have been selected in refrigeration and air conditioning for introducing low GWP replacements, i.e. mitigating high GWP replacements compared to the BAU scenario as given in Chapter 4, separately for Article 5 and Non-Article 5 countries. It concerns a variation in dates for the prohibition of the use in new manufacturing of certain high GWP ODS alternatives. The sectors considered are refrigeration (including commercial, industrial and transport refrigeration), mobile air conditioning and stationary air conditioning. This type of approach is to some degree comparable with the approach in the European revised F-gas regulation. Table 6-1 summarises the assumptions used for Mitigation Scenario 1.

A5	
MAC	**All countries**
2022	R134a = 0 for neq eq. No change in servicing
Domestic	**All countries**
2025	R134a = 0 for new eq.
CommRef Transport Industrial	**All countries**
2025	R404A =0 for new eq. Replaced by R407

Table 6-1 Assumptions behind the RAC Article 5 Mitigation Scenario 1

When adding up the demands for the various sub-sectors the amounts for MIT-1 can be determined as given in Tables 6-2 and 6-3 for Article 5 countries.

Year/ Refrigerant type	**2010**	**2015**	**2020**	**2025**	**2030**
HFC-134a	54.4	110.4	183.5	230.5	275.1
R-404A/R-507	13.1	35.2	55.5	91.3	130.3
R-407C	16.5	58.6	105.6	188.7	296.0
R-410A	41	95.8	162.5	247.5	360.3
Low-GWP	22.4	33.7	48.8	125.6	233.3
T O T A L	**147.4**	**333.7**	**555.9**	**883.7**	**1295.0**

Table 6-2 Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-1 scenario) for the period 2010-2030 in Article 5 countries (ktonnes)

Year/ Refrigerant type	2010	2015	2020	2025	2030
HFC-134a	70.7	143.5	238.5	300.0	376.6
R-404A/R-507	51.6	138.8	219.0	360.1	513.6
R-407C	26.8	95	171.1	305.7	479.5
R-410A	78.7	183.9	312.0	475.2	691.8
Low-GWP	0.06	0.14	0.25	0.67	1.04
T O T A L	**227.9**	**561.3**	**940.9**	**1441.7**	**2043.5**

Table 6-3 Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-1 scenario) for the period 2010-2030 in Article 5 countries (Mt CO_2 equivalent)

The following can be observed for Article 5 countries (where there are now more restrictions for the 2010-2030 demand, namely, a ban on HFC-134a in MACs as of 2022, and a ban on the use of R-404A by 2025):

- The demand for HFC-134a in Article 5 countries increases by a factor of 2.5 in 15 years, between 2015 and 2030, where the lower growth is due to changes in mobile air conditioning;

- The MIT-1 scenario for R-404A and R-407A/C/F still shows large growth for the refrigerants R-404A (smaller than in the BAU scenario), R-407A/C/F and R-410A, mainly due to the external (growth) factors;

- Actually, the demand for low-GWP refrigerants now grows by a factor of 7, mainly due to the fact that the application of low-GWP refrigerants is assumed in several sub-sectors, including the MAC sector that presents a high growth;

- In the Article 5 countries, the demand in tonnes for R-410A (the same as in the BAU scenario) is now larger than the demand for HFC-134a;

- In tonnes, the total refrigerant demand increases again by almost 400% between 2015 and 2030 (the same amounts for BAU and MIT-1);

- The same tendencies in growth, both for the separate refrigerant demand numbers (sub-sectors) and for the total demand, expressed in Mt CO_2 eq. can be observed.

- Due to a somewhat higher demand for low-GWP refrigerants, the total demand expressed in Mt CO_2 increases not that much as in the BAU scenario (365 instead of 415 % over the period 2015-2030).

For the second mitigation scenario, the Article 5 approach has followed the same approach as might be expected in the non-Article 5 regions. This is a relatively aggressive approach, especially in view of the rapid growth that is anticipated in the Article 5 region. In this respect, it is probably at the limit of what is currently achievable given some of the issues discussed in Chapter 5. Table 6-4 sets out the main assumptions applied:

MIT 2 scenario		
A5		
MAC	**All countries**	
2017	R134a = 0% for new eq. replaced by GWP1	
after 2017	No change in servicing	
Domestic	**All countries**	
2020	R134a = 0% for neq eq. replaced by GWP1 No change in servicing	
CommRef Transport Industrial	**All countries**	
2020		R404A = 0% for new eq. replaced by GWP ≤ 300 No change in servicing
2030	80% CO_2 Eq. of sale R404A retrofit by GWP ≤ 300 (Retrofit - 80%)	
SAC	**All countries**	
2020	R404A = 0% replaced by GWP ≤ 700	

Table 6-4 Assumptions behind the RAC Article 5 Mitigation Scenario 2

When adding up the demands for the various sub-sectors the amounts for MIT-2 can be determined as given in Tables 6-5 and 6-6 for the Article 5 countries.

Year/ Refrigerant type	2010	2015	2020	2025	2030
HFC-134a	54.4	110.4	150.0	196.2	218.3
R-404A/R-507	13.1	35.2	52.7	71.9	44.8
R-407	16.5	58.6	94.6	118.1	79.8
R-410A	41.0	95.8	139.0	164.7	95.9
Low-GWP	22.4	33.7	119.6	332.8	856.2
T O T A L	**147.4**	**333.7**	**555.9**	**883.7**	**1295.0**

Table 6-5 Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-2 scenario) for the period 2010-2030 in Article 5 countries (ktonnes)

Year/ Refrigerant type	2010	2015	2020	2025	2030
HFC-134a	70.7	143.5	195.0	255.1	283.8
R-404A/R-507	51.6	138.8	207.9	283.3	176.9
R-407	26.8	95.0	153.2	191.3	129.2
R-410A	78.7	183.9	267.0	316.2	184.2
Low-GWP	0.06	0.14	11.6	52.6	171.0
T O T A L	**227.9**	**561.3**	**834.7**	**1098.5**	**945.1**

Table 6-6 Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-2 scenario) for the period 2010-2030 in Article 5 countries (Mt CO_2 equivalent)

The following can be observed for Article 5 countries (where there are now similar restrictions for the 2010-2030 demand as in Non-Article 5 countries, namely, a ban on HFC-134a in MACs as of 2017, and a ban on the use of R-404A and R-410A by 2020):

- The demand for HFC-134a in Article 5 countries still increase between, between 2015 and 2030 (by a factor of 2), due to the high growth and the remaining in the period 2020-2030.

- The MIT-2 scenario shows increases in the demand for R-404A and R-407C until 2025, after that a decrease in demand occurs (this is due to the external (growth) factors, while the change in the bank of low-GWP refrigerant changes gradually);

- Actually, the demand for low-GWP refrigerants now grows enormously, in particular after 2017, and is about two thirds of the total by the year 2030;

- In tonnes, the total refrigerant demand increases again by almost 400% between 2015 and 2030 (the same amounts for BAU, MIT-1 and MIT-2);

- The same tendencies in growth, both for the separate refrigerant demand numbers (sub-sectors) and for the total demand, expressed in Mt CO_2 eq. can be observed.

Owing to a much higher demand for low-GWP refrigerants, the total refrigerant demand, expressed in Mt CO_2 eq., increases much less than in the MIT-1 scenario. There is a growth of about a factor of 2 between the years 2015 and 2025, after which a decrease occurs in the amount expressed in Mt CO_2 eq. of about 15% (compared to the year 2025), while the demand in tonnes increases by 45%.

6.1.2 Impact assessment of Mitigation Scenarios

The MIT-1 scenario will result in savings in the demand of HFC-134a and R-404A, while increasing the demand of R-407 (A/C/F). This will not result in major savings in the years 2020-2030. Table 6-9 shows the impact. It will result in less than 10% influence on the total amount of CO_2 eq estimated for 2025 and slightly more for the amounts estimated for 2030.

The MIT-2 scenario has a much bigger influence on the amounts of refrigerants used in terms of tonnes of CO_2 eq., 25% of the total estimated for 2025 can be avoided, and this will increase to more than 50% in the year 2030.

Even under the MIT-2 scenario Article 5 countries are expected to see a growth in demand of about 80% between 2015 and 2030.

Year	2010	2015	2020	2025	2030
BAU	227.9	561.3	940.9	1564.1	2333.3
Reductions					
MIT-1	0	0	0	122.5	289.7
MIT-2	0	0	106.2	465.6	1388.2

Table 6-7 Current and future total demand of refrigerants for the period 2010-2030 in Article 5 countries for the BAU (Mt CO_2 equivalent) and savings for the MIT-1 and MIT-2 scenarios (Mt CO_2 equivalent)

It needs to be mentioned that the impact of phasing in low-GWP alternatives cannot be totally estimated in the period 2020-2030, since many measures in manufacturing are taking place as of 2020, and will not have full impact after the servicing part on HFCs has been phased out. However, Figure 6-1 illustrates graphically the overall impact of the Mitigation Scenarios against the BAU scenario outlined in Chapter 4.

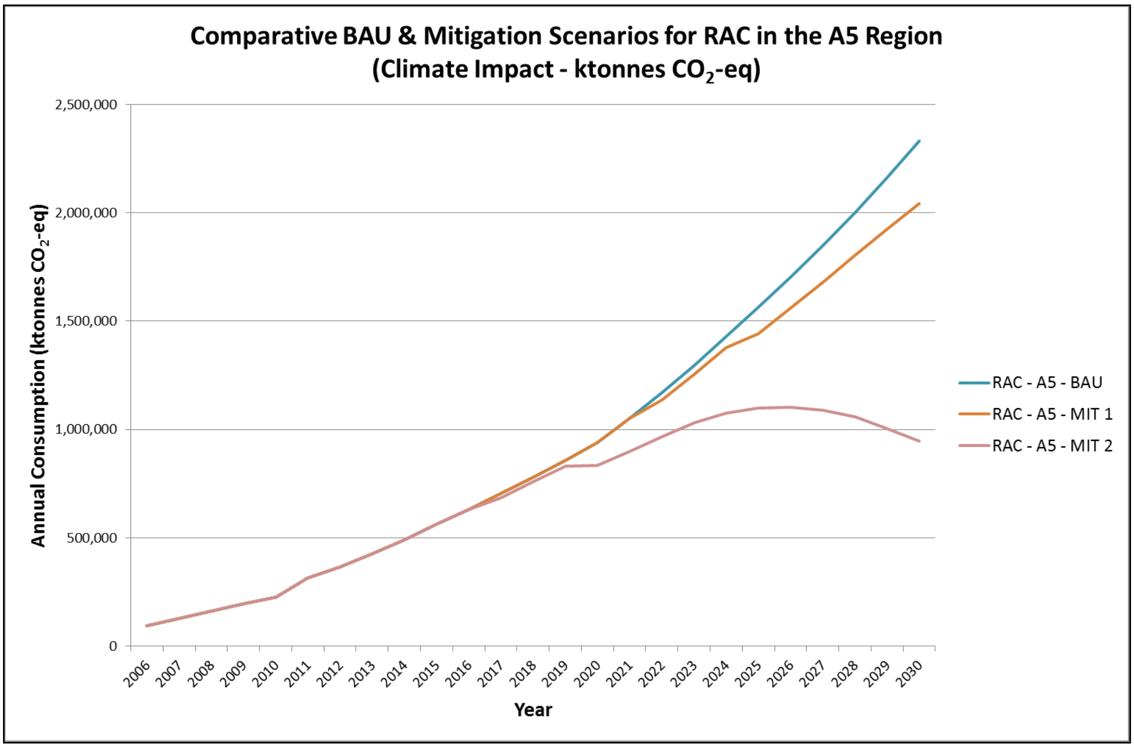


Figure 6-1 Impact of Mitigation Scenarios for RAC in the Article 5 Regions

6.1.3 Economic factors

Decision XXV/5 asks to focus on the economic costs of various scenarios to phase down high GWP alternatives to ODS. Economic costs will consist of changes in manufacturing processes and the possible impact on employment, on higher operating costs in the case of lower energy efficiency, on re-engineering system designs, on capital costs involved in the conversion to low GWP substances as well as on possible higher costs involved in the servicing sector.

The Task Force, at this stage, assumes that there will be no additional operating costs involved, that servicing practices are likely to be more complicated (but cannot attach numbers to this aspect), so that the actual economic costs for which a range can be derived would solely be the conversion of the manufacturing operations.

In order to determine indicative amounts for the change to low GWP refrigerants in Article 5 countries, it is necessary to look at the amounts used in manufacture (i.e., the change in manufacture) going from the BAU scenario to the MIT-1 and MIT-2 scenario.

In the tables above, the amounts are given for the BAU, the MIT-1 and the MIT-2 scenario of high GWP and low GWP refrigerants for MACs, commercial, industrial, transport, and domestic refrigeration and stationary air conditioning. These are the sectors that use R-404A (507), R-407A/C/F, R-410A and HFC-134a.

The refrigerant demand as presented in the tables concerns both servicing and manufacturing. The demand for R-404A and R-410A can come from manufacturing lines that have been newly established or that have been converted from the use of HCFC-22 (between 2015 and 2020, as assumed in the spreadsheet calculations).

Costs can be determined for a period of e.g. 2017-2022 for the MIT-1 or MIT-2 scenario, using the manufacturing amounts (the capacity in tonnes per year, which can be translated to average units per year) of the various refrigerants mentioned above. In this case the 2015 consumption has been taken as the reference point, assuming that this would form a sort of cut-off date, and that new capacity for high GWP alternative applications, to be established after this date, should not be considered.

If one assumes a total consumption of high GWP alternatives (HFCs) in the year 2015 of about 300,000 tonnes, used in Article 5 countries in the refrigeration and air conditioning sector, the following indicative numbers for conversion costs could be determined. In this case one could apply a 60% share of manufacturing and a 40% share of servicing, since it concerns growing sub-sectors in all cases (in a stable situation the servicing percentage would be higher).

For all conversions to low GWP alternatives it is difficult to assume narrow costs ranges. Several studies, including the XXIV/7 Task Force report, assume costs that may be low for some conversions, but are often higher than US$ 15-65/ kg. On the basis of experience in converting certain manufacturing to low GWP ODS alternatives under the Multilateral Fund, costs could be assumed in the range of US$ 6-18 per kg, but could easily be a factor of 3 higher in certain sub-sectors. It will be clear that, for a conversion from R-404A (507) to R-407A/C/F costs will be relatively low and can be assumed in the range of US$ 1-3.

Sector	**Conversion to**	**Amount (tonnes)**	**Manufacturing conversion (tonnes)**	**Costs (US$ million)**
MAC	Low GWP	75,000	45,000	405-810
Refr.sectors	R-407A/C/F	90,000	54,000	54-162
Stationary AC		135,000		0
Total				**459-972**

Table 6-8 Costs for the MIT-1 scenario in Article 5 countries

Sector	**Conversion to**	**Amount (tonnes)**	**Manufacturing conversion (tonnes)**	**Costs (US$ million)**
MAC	Low GWP	75,000	45,000	270-810
Refr.sectors	Low GWP	90,000	54,000	324-972
Stationary AC	Low GWP	135,000	81,000	486-1458
Total				**1080-3240**

Table 6-9 Costs for the MIT-2 scenario in Article 5 countries

In this case, it is not important whether or not the conversion would take place in multinationals or domestically owned companies.

If funding in the case of multinationals would not be considered, this would completely change the picture. However, at this stage the Task Force does not have any reliable data to make any more detailed calculations that would take this into account.

Roughly spoken, if the conversion would take place during a period of 5-6 years, it would concern an amount of US$ 100-160 million per year in the case of the MIT-1 scenario and an amount of US$ 180-650 million per year in the case of the MIT-2 scenario.

The amount in the range of US$ 180-650 million per year, during a period of 5-6 years would save 100-470 Mt CO_2 equivalent in demand per year (compared to BAU) in the period 2020-2025 (this is not equal to a saving in emissions in that same period).

It needs to be clearly stated that this amount is based upon the 2015 manufacturing amounts to be converted, with a cut-off date for e.g. the year 2015. This may turn to be not realistic in practice, if one would have to depart from the amounts predicted for the year 2020, total costs will again substantially decrease and could easily be 60-70% higher (compare the numbers in the BAU scenario for Article 5 countries).

6.2 Article 5 - Foams

6.2.1 Mitigation Scenarios

As with RAC, two mitigation scenarios have been selected for foams. Both are based on a potential acceleration of the achievable HCFC phase-out date and a reduction in the high-GWP uptake cited in the BAU scenario (Table 4-4). The following two tables provide the assumptions in full:

MIT 1 scenario	
A5	
PU Appliance	**All countries**
ODS transitions complete by 2020	Yes
% high GWP options by weight	5%
PU Boardstock	**All countries**
ODS transitions complete by 2020	Yes
% high GWP options by weight	10%
PU Panel	**All countries**
ODS transitions complete by 2020	Yes
% high GWP options by weight	10%
PU Spray	**All countries**
ODS transitions complete by 2020	Yes
% high GWP options by weight	25%
PU Insitu/Block	**All countries**
ODS transitions complete by 2020	Yes
% high GWP options by weight	10%
XPS Board	**All countries**
ODS transitions complete by 2026	Yes
% high GWP options by weight	25%
Phenolic	**All countries**
ODS transitions complete by 2020	Yes
% high GWP options by weight	10%

Table 6-10 Assumptions adopted for Mitigation Scenario 1 in the Article 5 foams sector

It can be seen that Mitigation Scenario 1 foresees an accelerated phase-out of HCFCs in the polyurethane foam sector by 2020 and in the XPS sector by 2026.

MIT 2 scenario	
A5	
PU Appliance	**All countries**
ODS transitions complete by 2018	Yes
% high GWP options by weight	0%
PU Boardstock	**All countries**
ODS transitions complete by 2018	Yes
% high GWP options by weight	0%
PU Panel	**All countries**
ODS transitions complete by 2018	Yes
% high GWP options by weight	0%
PU Spray	**All countries**
ODS transitions complete by 2018	Yes
% high GWP options by weight	0%
PU Insitu/Block	**All countries**
ODS transitions complete by 2018	Yes
% high GWP options by weight	0%
XPS Board	**All countries**
ODS transitions complete by 2024	Yes
% high GWP options by weight	0%
Phenolic	**All countries**
ODS transitions complete by 2018	Yes
% high GWP options by weight	0%

Table 6-11 Assumptions adopted for Mitigation Scenario 2 in the Article 5 foams sector

Mitigation Scenario 2 is viewed as having an aggressive substitution deadline for all polyurethane foams of 2018 with the additional challenge of ensuring that all alternatives are low-GWP. For extruded polystyrene the target date for HCFC phase-out is 2024 – four years ahead of the BAU scenario and only four years later than the requirements of the revised F-Gas regulation in Europe. Accordingly, Mitigation Scenario 2 is viewed as amongst the most progressive options available to the foam sector. Even then, its impact, when compared with the potential contribution from the RAC sector is relatively minimal, as is revealed in the following section.

6.2.2 Impact Assessment of Mitigation Scenarios

Tables 6-12 and 6-13 show the impact for foam Mitigation Scenarios in terms of blowing agent:

	A5 : MIT-1 - Year in tonnes					A5 : MIT-1 - Year in ktCO_2-eq				
	2010	*2015*	*2020*	*2025*	*2030*	*2010*	*2015*	*2020*	*2025*	*2030*
HCFC-141b	39,895	25,921	0	0	0	28,445	18,482	0	0	0
HCFC-142b	16,508	22,530	13,356	2,226	0	37,473	51,143	30,319	5,053	0
HCFC-22	17,436	23,229	13,356	2,226	0	31,036	41,348	23,774	3,962	0
HFC-245fa	354	2,102	2,556	2,822	3,115	361	2,144	2,607	2,878	3,178
HFC-365mfc/HFC-227ea	0	1,689	2,142	2,365	2,612	0	1,719	2,181	2,408	2,658
HFC-134a/HFC-152a	955	6,693	10,798	15,839	18,236	1,347	9,422	13,465	18,418	21,008
HFO/HCFO	0	0	31,825	47,973	55,439	0	0	223	336	388
Hydrocarbon	31,665	47,047	62,510	70,538	78,175	348	518	688	776	860
Other	0	0	0	0	0	0	0	0	0	0
Totals	***106,814***	***129,211***	***136,544***	***143,989***	***157,577***	***99,011***	***124,775***	***73,256***	***33,830***	***28,092***
% Growth		20.97%	5.68%	5.45%	9.44%					
Average GWPs						927	966	537	235	178

Table 6-12 Current and future demand by blowing agent for ODS and their alternatives (MIT-1 scenario) for the period 2010-2030 in Article 5 countries

	A5 : MIT-2 - Year in tonnes					A5 : MIT-2 - Year in ktCO$_2$-eq				
	2010	*2015*	*2020*	*2025*	*2030*	*2010*	*2015*	*2020*	*2025*	*2030*
HCFC-141b	39,895	21,130	0	0	0	28,445	15,066	0	0	0
HCFC-142b	16,508	18,920	8,313	0	0	37,473	42,949	18,871	0	0
HCFC-22	17,436	19,480	8,313	0	0	31,036	34,674	14,798	0	0
HFC-245fa	354	1,987	430	475	524	361	2,027	439	484	535
HFC-365mfc/HFC-227ea	0	1,574	0	0	0	0	1,602	0	0	0
HFC-134a/HFC-152a	955	7,630	6,383	6,524	7,203	1,347	10,759	9,001	9,198	10,156
HFO/HCFO	0	1,871	35,537	52,612	58,088	0	13	249	368	407
Hydrocarbon	31,665	52,334	68,464	77,067	85,089	348	576	753	848	936
Other	0	0	0	0	0	0	0	0	0	0
Totals	***106,814***	***124,927***	***127,442***	***136,678***	***150,903***	***99,011***	***107,666***	***44,110***	***10,899***	***12,033***
% Growth		16.96%	2.01%	7.25%	10.41%					
Average GWPs						927	862	346	80	80

Table 6-13 Current and future demand by blowing agent for ODS and their alternatives (MIT-2 scenario) for the period 2010-2030 in Article 5 countries

Figure 6-2 shows the incremental climate savings achieved for Mitigation Scenarios 1 and 2 against the BAU baseline.

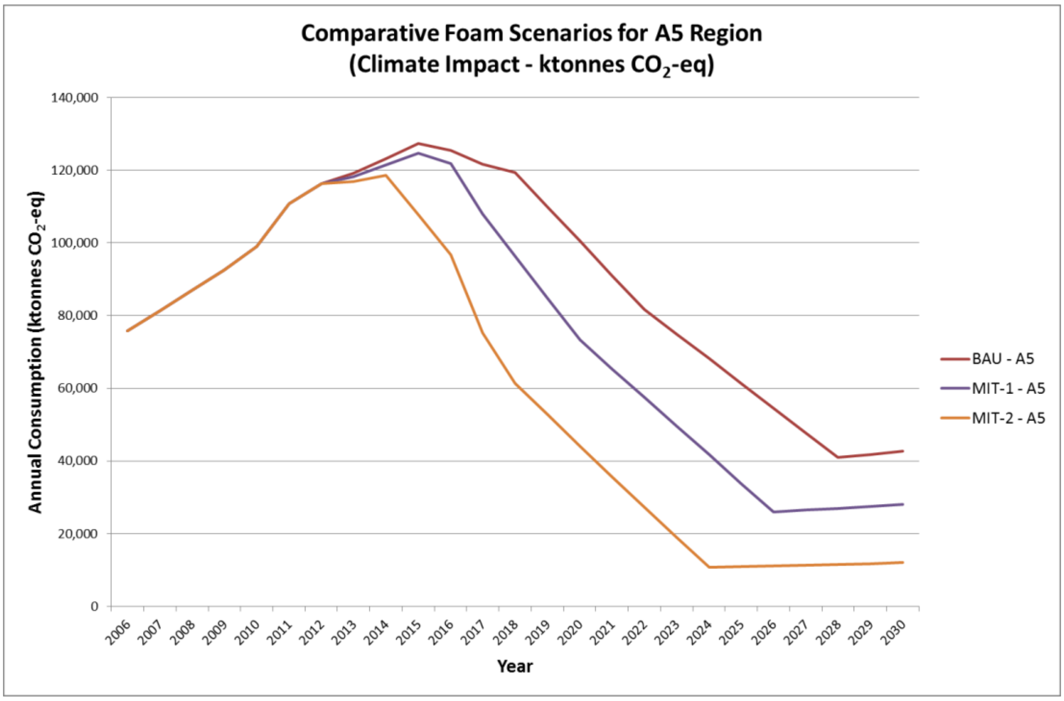


Figure 6-2 Impact of Mitigation Scenarios for foams in the Article 5 regions

6.2.3 Economic factors

As has already been pointed out in Chapter 5 and in other parts of this report, the acceleration of phase-out dates is likely to increase the cost of transitions, since it makes it less likely that costs can be allocated against other drivers such as equipment renewal. In the case of foams, the range of processes involved and the variation in size of the manufacturing facilities makes it very difficult to quantify transitional costs in absolute terms. A detailed review of foam projects under the Multilateral Fund shows cost effectiveness valuations ranging from < US$ 2/kg up to US$ 150/kg.

6.3 Non-Article 5 countries Refrigeration and Air Conditioning

6.3.1 Mitigation Scenarios

For reasons already covered in earlier sections of this report, the drivers for conversion in non-Article 5 regions are often very different from those in Article 5 regions and may result as much from market pressures as from regulatory stimuli.

Mitigation Scenario 1 for non-Article 5 regions is as follows:

MIT 1 scenario		
nA5		
MAC	EU	Other Countries
2017	R134a = 0% for new eq. replaced by GWP1	
after 2017	No change in servicing	
Domestic	EU	Other Countries
2020	R134a = 0% for new eq., replaced by GWP1 No change in servicing	
CommRef Transport Industrial	EU	Other Countries
2020		R404A = 0% for new eq. repalced by R407C No change in servicing
2030	80% CO2 Eq. of sale R404A retrofit by GWP ≤ 300 (Retrofit - 80%)	
	usual practice	

Table 6-14 Assumptions adopted for Mitigation Scenario 1 in the non-Article 5 RAC sector

When summarising the demands for the various sub-sectors the amounts for MIT-1 can be assessed as given in Tables 6-15 and 6-16 below for Non-Article 5 countries.

Year/ Refrigerant type	2010	2015	2020	2025	2030
HFC-134a	96.7	96.7	64.8	47.5	32.1
R-404A/R-507	38.7	42.2	25.0	10.3	5.0
R-407C	21.9	49.4	69.3	91.4	102.7
R-410A	51.4	119.4	147.3	189.4	229.3
Low-GWP	11.1	13.8	61.5	99.8	145
T O T A L	**219.8**	**321.5**	**367.9**	**438.4**	**514.1**

Table 6-15 Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-1 scenario) for the period 2010-2030 in Non-Article 5 countries (ktonnes)

Year/ Refrigerant type	2010	2015	2020	2025	2030
HFC-134a	125.7	125.6	84.2	61.8	45.9
R-404A/R-507	150.0	166.5	98.5	47.7	19.5
R-407C	35.4	80.1	112.3	148.0	166.3
R-410A	98.7	229.2	282.8	363.6	440.3
Low-GWP	0.03	0.04	5	8	11
T O T A L	**409.8**	**601.4**	**582.8**	**629.1**	**683.0**

Table 6-16 Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-1 scenario) for the period 2010-2030 in Non-Article 5 countries (Mt CO_2 equivalent)

The following can be observed for Non-Article 5 countries (where the main change is in MACs and in the ban of the use of R-404A as of 2020 in non-EU countries):

- The demand for HFC-134a in Non-Article 5 countries decreases by a factor of 3, between 2015 and 2030, due to the MAC new equipment phase-out of HFC-134a in 2017;

- The demand for R-404A (apart from some servicing) virtually disappears by the year 2030;

- This MIT-1 scenario (which includes increased use of R-407A/C/F instead of R-404A) shows an increase of a factor two in the demand for R-407C between 2015 and 2030;

- As of 2013-2015, R-410A remains the refrigerant that shows the largest demand, which, in tonnes, is almost 40% of the total demand for all HFC refrigerants;

- In tonnes, the total refrigerant demand increases by about 50% between 2015 and 2030, but this now includes a much larger portion of low-GWP refrigerants (low GWP fluorocarbons, non-fluorocarbons), in the year 2030 almost 30% of the total in this scenario consists of low GWP refrigerants;

- The same tendencies are visible for each of the refrigerants in Mt CO_2 eq.

- In Mt CO2 eq., however, the total refrigerant demand increases by (only) 14% between 2015 and 2030. This smaller increase in Mt CO_2 eq. than in tonnes is due to the decrease in the contributions of R-404A with its very high GWP (in favour of R-407C and other low-GWP refrigerants), and due to the phase out of high-GWP refrigerant in MAC applications.

For Mitigation Scenario 2 (MIT-2), the assumptions made are as follows:

<table>
<tr><th colspan="3">MIT 2 scenario</th></tr>
<tr><th colspan="3">nA5</th></tr>
<tr><th>MAC</th><th>EU</th><th>Other Countries</th></tr>
<tr><td>2017</td><td colspan="2">R134a = 0% for new eq.
replaced by GWP1</td></tr>
<tr><td>after 2017</td><td colspan="2">No change in servicing</td></tr>
<tr><th>Domestic</th><th>EU</th><th>Other Countries</th></tr>
<tr><td>2020</td><td colspan="2">R134a = 0% for neq eq.
replaced by GWP1
No change in servicing</td></tr>
<tr><th>CommRef
Transport
Industrial</th><th>EU</th><th>Other Countries</th></tr>
<tr><td>2020</td><td></td><td>R404A = 0% for new eq.
replaced by GWP ≤ 300
No change in servicing</td></tr>
<tr><td>2030</td><td>80% CO_2 Eq. of sale
R404A retrofit by GWP
≤ 300 (Retrofit - 80%)</td><td></td></tr>
<tr><th>SAC</th><th>EU</th><th>Other Countries</th></tr>
<tr><td>2020</td><td colspan="2">R404A = 0% replaced by GWP ≤ 700</td></tr>
</table>

Table 6-17 Assumptions adopted for Mitigation Scenario 2 in the non-Article 5 RAC sector

The application of these MIT-2 assumptions leads to the determination of consumption shown in Tables 6-18 and 6-19 below.

Year/ Refrigerant type	**2010**	**2015**	**2020**	**2025**	**2030**
HFC-134a	96.7	96.7	63.9	46.0	29.2
R-404A/R-507	38.7	42.2	25.0	10.3	5.0
R-407	21.9	49.4	52.5	34.3	13.2
R-410A	51.4	116.7	116.3	62.6	24.3
Low-GWP	11.1	13.8	115.7	287.5	480.8
T O T A L	**219.8**	**318.8**	**373.4**	**440.7**	**552.5**

Table 6-18 Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-2 scenario) for the period 2010-2030 in Non-Article 5 countries (ktonnes)

Year/ Refrigerant type	**2010**	**2015**	**2020**	**2025**	**2030**
HFC-134a	125.7	125.6	83.0	59.8	37.9
R-404A/R-507	150.1	166.5	98.5	47.7	19.5
R-407	35.4	80.1	85.0	55.5	21.4
R-410A	98.7	229.2	223.4	120.2	46.6
Low-GWP	0.03	0.04	33.6	119.2	200.6
T O T A L	**409.8**	**596.3**	**523.5**	**402.4**	**326.0**

Table 6-19 Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-2 scenario) for the period 2010-2030 in Non-Article 5 countries (Mt CO_2 equivalent)

The following can be observed for Non Article 5 countries (where the main change can now be observed in stationary air conditioning, next to MACs, and also in the ban of the use of R-404A in favour of only low-GWP refrigerants):

- The demand for HFC-134a in Non-Article 5 countries decreases by a factor of 4, between 2015 and 2030;
- The demand for R-404A (apart from some servicing) virtually disappears by the year 2030, moreover, also the demand for R-407C now decreases substantially over the period 2015-2030;
- As of 2013-2015, the demand for R-410A sharply decreases, to about 25% of the 2015 value in the year 2030;
- In tonnes, the total refrigerant demand increases by about 50% between 2015 and 2030, but this now includes a very high portion of low-GWP refrigerants (low GWP fluorocarbons, non-fluorocarbons), in the year 2030 the share of low-GWP is assumed to be more than 85% of the total.
- In Mt CO_2 eq., the total refrigerant demand now decreases by almost 50% between 2015 sand 2030. This (sharp) decrease in Mt CO_2 eq. than in tonnes is due to the decrease in the contributions of R-404A, R-410A as well as HFC-134a in the various types of applications.

6.3.2 Impact assessment of Mitigation Scenarios

The MIT-1 scenario will result in savings in the demand of HFC-134a and R-404A, while increasing the demand of R-407A/C/F. This will not result in major savings in the years 2020-2030. Table 6-18 shows the impact. It will result in less than 15% influence on the total amount of Mt CO_2 eq. estimated for 2025 and about the same for the amounts estimated for 2030.

The MIT-2 scenario has a bigger influence on the amounts of refrigerants used in terms of tonnes of CO_2 eq. Almost 20% of the total estimated for 2020 in the BAU can be avoided, and this will increase to about 55% in the year 2025 and 65% in the year 2030. The decrease in the saving percentage after 2025 is mainly due to the impact of stationary air conditioning manufacturing and servicing demand.

Under the MIT-2 scenario, non-Article 5 countries are expected to see a decrease in demand of about 45% between 2015 and 2030.

Year	**2010**	**2015**	**2020**	**2025**	**2030**
BAU	409.3	601.4	637.6	732.8	829.6
Reductions					
MIT-1	0	0	54.8	103.7	146.6
MIT-2	0	5.1	114.1	330.4	503.6

Table 6-20 Current and future total demand of refrigerants for the period 2010-2030 in Non Article 5 countries for the BAU (Mt CO_2 equivalent) and savings for the MIT-1 and MIT-2 scenarios

It needs to be mentioned that the impact of phasing in the various low-GWP alternatives cannot be totally estimated during the period 2020-2030, since many measures in manufacturing are taking place as of 2020, and will not have full impact after the servicing part on HFCs has been phased out.

The situation is summarised graphically in Figure 6-3 below:

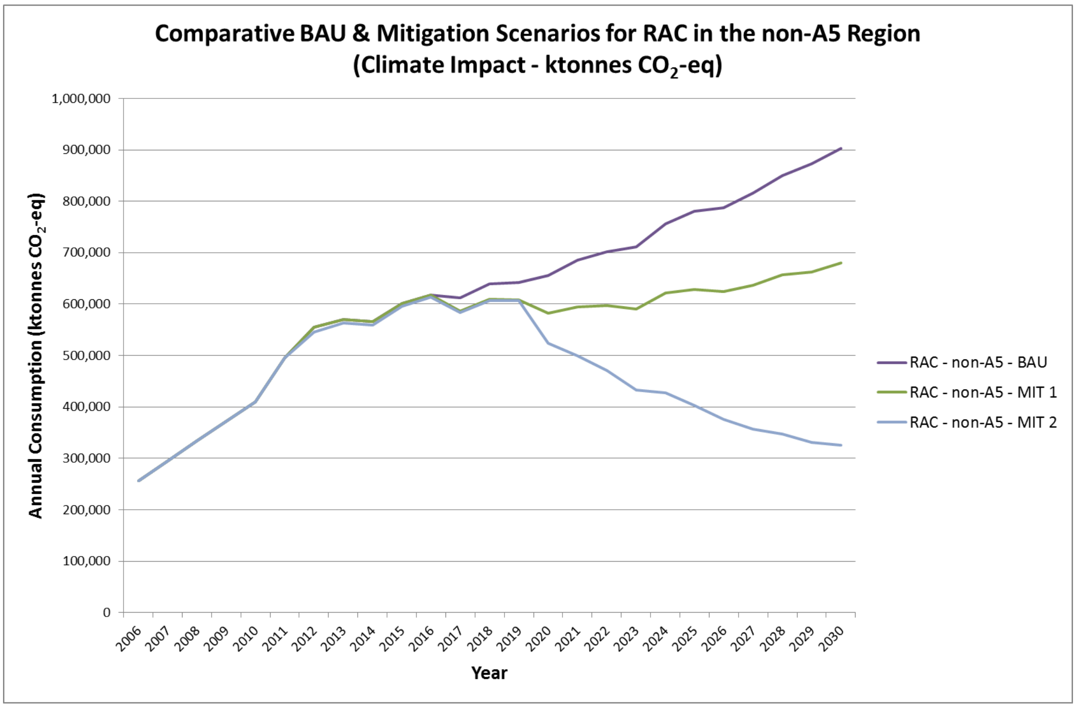


Figure 6-3 Impact of Mitigation Scenarios for RAC in the non-Article 5 regions

6.3.3 Economic Factors

In order to determine indicative amounts for the change to low GWP refrigerants in Non-Article 5 countries, it is again necessary to look at the amounts used in manufacture (i.e., the change in manufacture) going from the BAU scenario to the MIT-1 and MIT-2 scenario.

In the tables above, the amounts are given for the BAU, the MIT-1 and the MIT-2 scenario of high GWP and low GWP refrigerants for MACs, commercial, industrial, transport, and domestic refrigeration and stationary air conditioning. These are the sectors that use R-404A (507), R-407A/C/F, R-410A and HFC-134a.

The refrigerant demand as presented in the tables concerns both servicing and manufacturing. The demand for R-404A and R-410A will come from manufacturing lines that have been newly established; there may be some that were converted from the use of HCFC-22 in the 1990-2000's.

Costs can be determined for a period of e.g. 2017-2022 for the MIT-1 or MIT-2 scenario, using the manufacturing amounts as done in section 7-2 for Article 5 countries.

Also in the case of non-Article 5 countries, the 2015 consumption has been taken as the reference point, assuming that this would form a sort of cut-off date, and that new capacity for high GWP alternative applications, to be established after this date, should not be considered.

If one assumes a total consumption of high GWP alternatives (HFCs) in the year 2015 of about 300,000 tonnes, used in non-Article 5 countries in the refrigeration and air conditioning sector, the following indicative numbers for conversion costs could be determined. It happens to be so that the demand for high GWP alternatives to ODS is more or less equal in both Article 5 and non-Article 5 countries.

Also in the case of Non-Article 5 countries one could apply a 60% share of manufacturing and a 40% share of servicing, since it concerns growing sub-sectors in all cases (in a stable situation the servicing percentage would be higher).

The refrigerant demand as presented in the tables concerns both servicing and manufacturing. The demand for R-404A and R-410A will come from manufacturing lines that have been newly established; there may be some that were converted from the use of HCFC-22 in the 1990-2000's.

Costs can be determined for a period of e.g. 2017-2022 for the MIT-1 or MIT-2 scenario, using the manufacturing amounts as done above for Article 5 countries. Also in the case of non-Article 5 countries, the 2015 consumption has been taken as the reference point, assuming that this would form a sort of cut-off date, and that new capacity for high GWP alternative applications, to be established after this date, should not be considered.

If one assumes a total consumption of high GWP alternatives (HFCs) in the year 2015 of about 300,000 tonnes, used in non-Article 5 countries in the refrigeration and air conditioning sector, the following indicative numbers for conversion costs could be determined. It happens to be so that the demand for high GWP alternatives to ODS is more or less equal in both Article 5 and non-Article 5 countries. Also in the case of non-Article 5 countries one could apply a 60% share of manufacturing and a 40% share of servicing, since it concerns growing sub-sectors in all cases (in a stable situation the servicing percentage would be higher).

For all conversions to low GWP alternatives costs are assumed to be in the range of US$ 6-18 per kg, for a conversion from R-404A (507) to R-407A/C/F costs are assumed to be in the range of US$ 1-3.

Sector	**Conversion to**	**Amount (tonnes)**	**Manufacturing conversion (tonnes)**	**Costs (US$ million)**
MAC	Low GWP	75,000	45,000	270-810
Refr.sectors	R-407A/C/F and low-GWP (EU countries)	55,000	33,000 (18,000 in non-EU)	108-324
Stationary AC		135,000		0
Total				**378-1134**

Table 6-21 Costs for the MIT-1 scenario in Non-Article 5 countries

Sector	**Conversion to**	**Amount (tonnes)**	**Manufacturing conversion (tonnes)**	**Costs (US$ million)**
MAC	Low GWP	75,000	45,000	270-810
Refr.sectors	Low GWP	55,000	33,000	198-594
Stationary AC	Low GWP	175,000	105,000	630-1890
Total				**1098-3294**

Table 6-22 Costs for the MIT-2 scenario in Non-Article 5 countries

When comparing the numbers, even with different consumption in the commercial and stationary air conditioning sectors, it is not surprising that the range derived for the costs is not much different since the assumption for low GWP conversion costs is the same.

At this stage the Task Force does not have any reliable data to make more detailed calculations that would take the effect of multinational or domestic operation into account.

Roughly speaking, if the conversion would take place during a period of 5-6 years, it would concern an amount of US$ 60-230 million per year in the case of the MIT-1 scenario and an amount of US$ 200-650 million per year in the case of the MIT-2 scenario.

The amount in the range of US$ 200-650 million per year, during a period of 5-6 years would save 110-330 Mt CO_2 equivalent in demand per year (compared to BAU) in the period 2020-2025 (this is not equal to a saving in emissions in that same period).

6.4 Non-Article 5 Parties – Foams

6.4.1 Mitigation Scenarios

The final scenarios to be assessed in this Chapter are those relating to the manufacture of foams in non-Article 5 regions. As seen in Chapter 4, the Business-as-Usual scenario is relatively unconstrained with only the European region having any formal regulatory framework requiring positive action. For Mitigation Scenario 1 (MIT-1), the following assumptions are made:

MIT 1 scenario		
nA5		
PU Appliance	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2025
Completion of Linear Phase-down	2020	2030
PU Boardstock	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2025
Completion of Linear Phase-down	2020	2030
PU Panel	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2025
Completion of Linear Phase-down	2020	2030
PU Spray	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2025
Completion of Linear Phase-down	2020	2030
PU Insitu/Block	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2025
Completion of Linear Phase-down	2020	2030
XPS Board	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2025
Completion of Linear Phase-down	2020	2030
Phenolic	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2025
Completion of Linear Phase-down	2020	2030

Table 6-23 Assumptions adopted for Mitigation Scenario 1 in the non-Article 5 foam sector

It can be seen that linear phase-downs are envisaged in all foam sub-sectors and all regions no later than 2030. The European targets for polyurethane foams are also brought forward from 2023 to 2020.

The resulting consumption table is shown in Table 6-24.

	Non-A5 : MIT-1 - Year in tonnes					Non-A5 : MIT-1 - Year in ktCO$_2$-eq				
	2010	*2015*	*2020*	*2025*	*2030*	*2010*	*2015*	*2020*	*2025*	*2030*
HCFC-141b	0	0	0	0	0	0	0	0	0	0
HCFC-142b	16,665	0	0	0	0	37,830	0	0	0	0
HCFC-22	4,334	0	0	0	0	7,714	0	0	0	0
HFC-245fa	28,063	31,649	30,193	32,737	0	28,625	32,282	30,796	33,392	0
HFC-365mfc/HFC-227ea	9,609	9,042	2,784	2,075	0	10,039	9,346	2,466	1,635	0
HFC-134a/HFC-152a	24,230	32,819	23,096	25,499	0	22,259	37,375	32,565	35,954	0
HFO/HCFO	0	0	13,378	16,140	45,078	0	0	94	113	316
Hydrocarbon	121,999	130,414	153,490	187,000	233,508	1,342	1,435	1,688	2,057	2,569
Other	0	0	0	0	0	0	0	0	0	0
Totals	***204,900***	***203,924***	***222,939***	***263,450***	***278,585***	***107,808***	***80,437***	***67,610***	***73,151***	***2,884***
% Growth		-0.48%	9.32%	18.17%	5.75%					
Average GWPs						526	394	303	278	10

Table 6-24 Current and future demand by blowing agent for ODS and their alternatives (MIT-1 scenario) for the period 2010-2030 in non-Article 5 countries

For the Mitigation Scenario 2 (MIT-2), the dates are brought forward still further as shown in Table 6-26. This leads to the following assessment of consumption for non-Article 5 regions:

	Non-A5 : MIT-2 - Year in tonnes					Non-A5 : MIT-2 - Year in ktCO$_2$-eq				
	2010	*2015*	*2020*	*2025*	*2030*	*2010*	*2015*	*2020*	*2025*	*2030*
HCFC-141b	0	0	0	0	0	0	0	0	0	0
HCFC-142b	16,665	0	0	0	0	37,830	0	0	0	0
HCFC-22	4,334	0	0	0	0	7,714	0	0	0	0
HFC-245fa	28,063	31,649	29,916	1,229	0	28,625	32,282	30,515	1,253	0
HFC-365mfc/HFC-227ea	9,609	9,042	2,322	0	0	10,039	9,346	1,964	0	0
HFC-134a/HFC-152a	24,230	32,819	23,096	768	0	22,259	37,375	32,565	1,083	0
HFO/HCFO	0	0	14,011	40,684	45,078	0	0	98	285	316
Hydrocarbon	121,999	130,414	153,523	193,159	214,701	1,342	1,435	1,689	2,125	2,362
Other	0	0	0	0	0	0	0	0	0	0
Totals	***204,900***	***203,924***	***222,868***	***235,839***	***259,778***	***107,808***	***80,437***	***66,830***	***4,746***	***2,677***
% Growth		-0.48%	9.29%	5.82%	10.15%					
Average GWPs						526	394	300	20	10

Table 6-25 Current and future demand by blowing agent for ODS and their alternatives (MIT-1 scenario) for the period 2010-2030 in non-Article 5 countries

MIT 2 scenario		
nA5		
PU Appliance	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2020
Completion of Linear Phase-down	2020	2025
PU Boardstock	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2020
Completion of Linear Phase-down	2020	2025
PU Panel	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2020
Completion of Linear Phase-down	2020	2025
PU Spray	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2020
Completion of Linear Phase-down	2020	2025
PU Insitu/Block	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2020
Completion of Linear Phase-down	2020	2025
XPS Board	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2020
Completion of Linear Phase-down	2020	2025
Phenolic	**EU**	**Other Countries**
Commencement of Linear Phase-down	2015	2020
Completion of Linear Phase-down	2020	2025

Table 6-26 – Assumptions adopted for Mitigation Scenario 2 in the non-Article 5 foam sector

In this instance, no further acceleration is thought possible in Europe, but additionally a five year acceleration is postulated for other non-Article 5 regions to bring the phase-out date forward to 2025. The environmental impact of these two Mitigation Scenarios is considered in the next section.

6.4.2 Impact Assessment of Mitigation Scenarios

The ability to accelerate phase-outs in all non-Article 5 regions of the world is measured against the benchmarks set by the revised F-Gas Regulation. However, most commentators see the 2020 deadline for the XPS sector as particularly challenging – especially as a minimum target.

Figure 6-4 illustrates the gains arising from these additional measures.

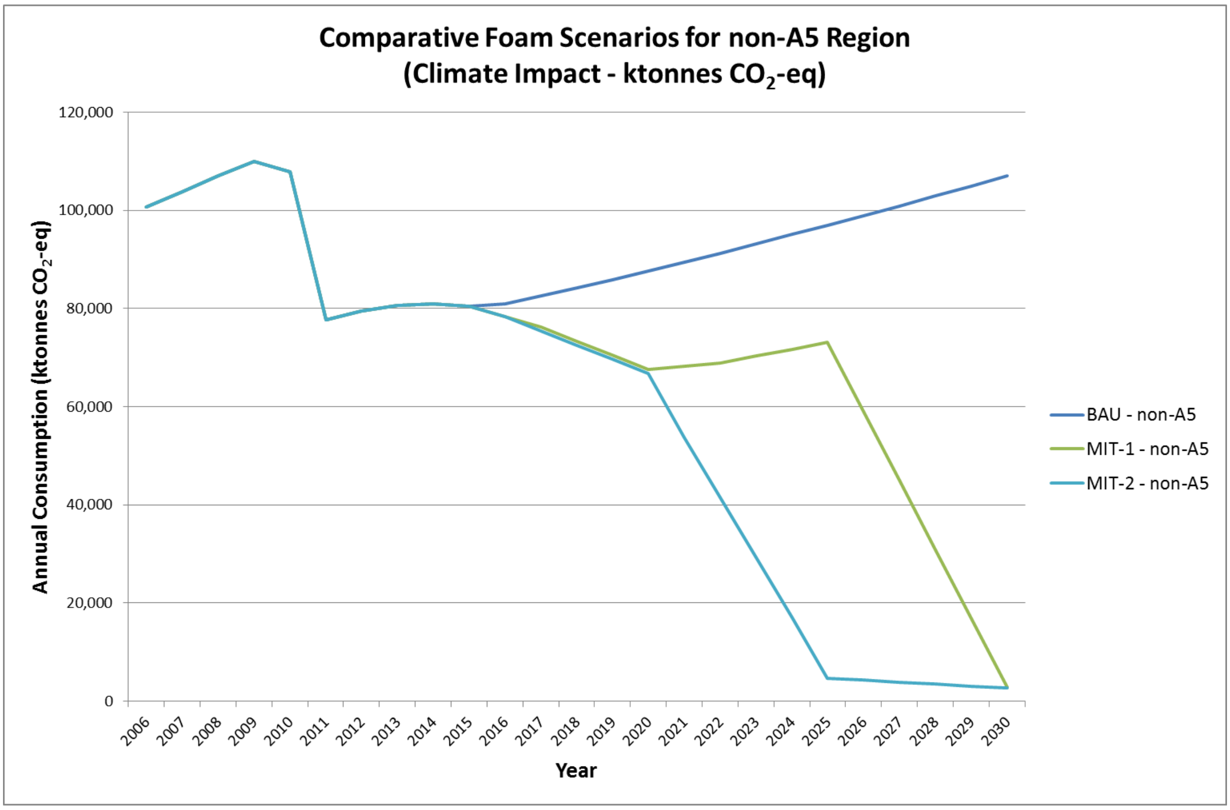


Figure 6-4 Impact of Mitigation Scenarios for foams in the non-Article 5 regions

6.4.3 Economic factors

The transitional cost data for phase-outs in the foams sector is very sparse in practice, since few transitions have been made in the post-ODS era. In preparing its revision of the F-Gas Regulation, the European Commission conducted a number of studies in order to determine the costs associated with transition. Amongst these was the Öko Recherche study, which looked in depth at some of the foam sectors, including XPS. The outcome of that work proved controversial and stimulated substantial discussion, most of which was around the assumptions adopted. Again, the key question is whether the costs of the transition have to be taken in full against the blowing agent transition or whether the costs can be defrayed more widely in instances where equipment upgrading was anticipated in any event. Rather than become embroiled in that discussion once more, the Task Force would prefer to draw attention to the fact that the range of possible scenarios makes a single figure, or even a tight range, impossible to establish.

7 Information on alternatives to ODS in the fire protection sector

7.1 Introduction

This section addresses the requirements of "Decision XXV/5: Response to the report by the Technology and Economics Assessment Panel on information on alternatives to ozone-depleting substances (Decision XXIV/7, paragraph 1). The Halons Technical Options Committee (HTOC) has provided these responses at the request of the Task Force addressing the Decision.

The production and consumption of halons used in fire protection ceased in non-Article 5 Parties on January 1, 1994 and ceased elsewhere on January 1, 2010. The production and consumption of HCFCs for use in fire protection continues. Ozone depleting substances (ODS) used as fire extinguishants possess unique efficacy and safety properties that serve as a basis of fire protection systems where the application of water (by hose stream or sprinkler heads), dry chemical agents, or aqueous salt solutions is problematic, especially in high-value commercial electronics environments and in military systems, to name only two of many applications where such systems had many serious technical disadvantages.

Development of alternatives to ODS fire extinguishing agents, beginning in the late 1980s, has progressed steadily and is now relatively mature. Interest remains, however, in development of new alternatives that offer further advancements in efficacy, safety, and environmental characteristics.

The HTOC Technical Note 1 provides the most up-to-date assessment of ODS use in fire protection, and the status of commercially available, technically proven alternatives.

7.2 Response to Question 1(a)

7.2.1 Commercially available, technically proven alternatives to ODS for total flooding fire protection using fixed systems

The Commercially available, technically proven alternatives to ODS for total flooding fire protection using fixed systems remain unchanged from those fully described in the TEAP response to Decision XXIV/7 subsection 6.2.1 (TEAP, 2013). They are:

a) Halocarbon agents:
FK-5-1-12
HFC-23
HFC-125
HFC-227ea

b) Inert Gas agents
IG-01
IG-100
IG-55
IG-541

c) Carbon dioxide (for use in unoccupied areas only)

d) Water Mist technologies

e) Inert Gas generators

f) Fine solid particles

Although the above alternatives are available in both Article 5 and non-Article 5 Parties, their use pattern depends on the hazard threat to be protected against as well as local regulations and relative costs.

High ambient temperatures do not affect the use patterns of these agents. However, extremely low ambient temperatures such as those found in arctic regions or the outside of aircraft at high altitude do. Extremely low temperatures pose significant challenges for currently commercialised alternatives seeking to replace halon in these environments. They are also challenged by other constraints in civil aviation, such as space and weight limitations because all the alternatives require more agent to suppress a fire than the halon being replaced.

Other halocarbon agents are in the early stages of testing and development. However, due to the lengthy process of testing, approval and market acceptance of new fire protection equipment types and agents, it is not anticipated that these agents can have any appreciable impact in the near-term. Phosphorous tribromide (PBr_3) has been commercialised for use as a fire extinguishant in one small aircraft engine application but it is not being considered for any other application at this time owing to its toxicity and corrosiveness.

7.2.2 Commercially available, technically proven alternatives to ODS for local application fire protection using portable systems

The commercially available, technically proven alternatives to ODS for local application fire protection using portable systems remain unchanged from those fully described in the TEAP response to Decision XXIV/7 subsection 6.2.2. They are:

a) Halocarbon agents
   HFC-236fa
   HFC-227ea
   FK-5-1-12
b) Carbon dioxide
c) Dry chemical
d) Straight stream water
e) Fine water spray
f) Aqueous salt solutions
g) Aqueous film-forming foam

Two chemicals are at an advanced stage of testing and development and may be commercialised as fire extinguishing agents in the future. These are:

h) FK-6-1-14
i) 2-Bromo-3,3,3-trifluoropropene
   Note, civil aviation is trying to meet the International Civil Aviation Organisation's (ICAO) 31st December 2016 deadline for the replacement of halon handheld portable extinguishers using this agent. The required regulatory process for commercialisation / manufacturing in Europe (Registration, Evaluation, Authorisation and Restriction of Chemicals - REACH registration) has been completed and in the United States the required listing as acceptable under the Significant New Alternatives Policy (SNAP) program and approval under the Toxic Substances Control Act (TSCA) has just begun. If successful, from a performance and environmental perspective, this agent will likely be the most effective replacement for halon 1211 applications. However, according to its manufacturer, the agent is anticipated to be at least double the cost of other clean agent alternatives, and will require stabilisers to maintain the material in long-term storage. For these reasons, the agent is only likely to fill the needs of niche applications where its lower weight and superior fire protection performance justify the higher cost.

For local, non-portable, applications such as the protection of floating roof tank rim seals, CF_3I (iodotrifluoromethane) has re-emerged as an acceptable alternative for halon 1211 or halon 2402.

Although the above alternatives are available in both Article 5 and non-Article 5 Parties, their use pattern depends on the hazard threat to be protected against as well as local regulations and relative costs. Of concern are reports of the introduction of some clean agent portable extinguishers in some Article 5 Parties that are not rated by internationally recognised testing laboratories.

High ambient temperatures do not affect the use patterns of these agents.

7.3 Response to Question 1(b)

The principle chemical alternatives to ODS are HFCs and a fluoroketone. According to the manufacturers, usage and growth of their agents is as follows:

A) HFCs

The split of HFC sales for fire protection between Article 5 and non-Article 5 Parties is approximately 70:30.

Sector Growth: HFC Sales for fire protection according to one manufacturer are:

US: flat
Middle East: growing
Asia Pacific: growing
Latin America: flat
Europe: flat

B) Fluoroketone

The split of fluoroketone sales for fire protection between Article 5 and non-Article 5 Parties is approximately 50:50.

Sector Growth: Fluoroketone sales for fire protection according to the manufacturer are:

Sales continue to grow substantially in Europe, the Middle East, Africa, North America and South East Asia. In addition, sales are increasing in Latin America.

7.4 Response to Question 1(c)

The HTOC is of the opinion that it is not possible to report or even estimate values in response to the question posed.

The production of clean agent alternatives for use in fire extinguishing systems and portable fire extinguishers is performed by very few manufacturers, all of whom treat the information on their historical, present and projected production and costs as proprietary. The required factual data is thus not available. So, without a clear understanding of these production levels and costs there is no basis on which to assess the economic costs and implications and environmental benefits of avoiding high GWP alternatives to ozone depleting substances, and doing so may result in data that is misleading.

It should be noted that all of the alternative systems have their own sets of characteristics such as effectiveness, cost, weight, space and environmental properties to name a few. System cost is one of the most important considerations in system selection. In cases where space and weight are not limiting factors, there is recent, but limited, information that in some parts of the world inert gas systems can be cost competitive with halocarbon systems, a heretofore unanticipated situation. The HTOC is continuing its investigation into this development, which may provide additional clarity on market penetration options for low environmental impact agents in the future.

7.5 Response to OEWG questions By Parties

7.5.1 Status of currently available alternatives for Civil Aviation

Halons are used for fire suppression on civil aircraft in:

- Lavatory trash receptacle extinguishing systems;
- Handheld extinguishers;
- Engine nacelle/auxiliary power unit (APU) protection systems; and
- Cargo compartment extinguishing systems.

All new installations of fire extinguishing systems for engines and cargo compartments use halon 1301, and all new installations of handheld extinguishers use halon 1211. With the exception of lavatory trash receptacles, there has been no retrofit of halon systems or portable extinguishers with available alternatives in the existing worldwide fleet of aircraft.

Lavatory Trash Receptacle

Research and testing has shown that there are suitable alternative suppression systems (using HFC-227ea or HFC-236fa) available for this application that meet the criteria for space and weight, the toxicological factors, and cost the same or less than the halon systems being replaced. Data from one lavatory extinguisher manufacturer shows that the vast majority of new production aircraft are now installed with non-halon systems. In addition, some airlines are replacing existing halon 1301 lavex systems with these halon-free alternatives during scheduled maintenance operations.

Handheld Extinguishers

Two non-ODS alternatives, HFC-227ea and HFC-236fa (and also one ODS - HCFC Blend B), have successfully completed all of the required handheld UL and Minimum Performance Standard tests and are commercially available. These alternatives have increased space and weight characteristics and environmental concerns. Qualification and installation certification by airframe manufacturers and regional authorities is needed prior to airline use. Based on these issues airframe manufacturers have chosen not to pursue qualification and installation certification for these alternatives.

As mentioned above in subsection 7.2.2 i), testing of a “low GWP” unsaturated HBFC known as 3,3,3-trifluoro-2-bromo-prop-1-ene or 2-BTP that has the potential of lower space and weight impact compared to other alternatives, continues. If approved, this agent could be commercialised in the next few years to meet aviation needs for a handheld extinguisher replacement for in production aircraft after December 31, 2016, and may be a possible candidate for evaluation in engine nacelles/APUs as well.

Engine and APU Compartment

HFC-125 has been used successfully as an alternative to halon for engine fire protection on US military aircraft developed since the early 1990s. In addition, HFC-125 is currently being developed for use on a military derivative of a large commercial aircraft (Boeing 767; military derivative KC-46). HFC-125 has increased space and weight characteristics that present installation and environmental concerns. Based on these issues, airframe manufacturers have chosen not to pursue qualification and installation certification for HFC-125 in engines/APUs.

Both low/non-GWP fire fighting agents that have been tested by approval authorities for engine and APU applications have failed. One failed the low temperature live-fire test and the other failed the large-scale live-fire test. The civil aviation industry has come to the conclusion that they need to take a different approach to finding a halon 1301 replacement for engine and APUs. They are going to pool their resources to develop a single agent/approach and have formed the Engine/APU Halon

Alternatives Research Consortium (IC). The IC consists of aircraft OEMs, fire extinguishing suppliers & distributors, a chemical company, airline operators, an engine manufacturer, an aviation industry group and representation from the US military. The IC has mapped out a 3 phase approach: Phase I (administrative start-up) is scheduled to run until mid-to-late 2014. Phase II (requirements development) is estimated to be another 12 months (will commence once Phase I is complete) and Phase III (selection of the winning agent/approach) follows thereafter, but has no time-scale assigned as yet. The first task for the IC is to appoint an independent Managing Entity, to manage International Property (IP) rules and agreements which are needed before Phase II (Technical Definition of the Statement of Work) can take place. Currently the air framer team is reviewing a Service Agreement and Statement of Work that will formally engage the Managing Entity for launch of Phase I activities.

Cargo Compartments

In passenger aircraft the cargo compartments are typically located below the passenger cabin, or occupy both the main and lower deck on freighter aircraft. Fire control is effected by depressurising the main deck cargo compartment, reaching the landing site and landing as quickly as possible before the fire re-establishes itself. In the case of a fire in the lower deck cargo compartment, a rapid discharge of halon is deployed into the protected space to suppress the fire, which is followed by a discharge that is released slowly to maintain a concentration of halon to prevent re-ignition. The slow discharge is maintained until the plane has landed to protect against any reduction in the concentration of halon caused by ventilation or leakage.

Cargo compartment fire suppression systems must be able to meet the requirements of four fire tests. The system must be able to suppress a Class A deep-seated fire for at least 30 minutes and a Class A fire inside a cargo container for at least 30 minutes. The system must be able to extinguish a Class B fire (Jet-A fuel) within 5 minutes, and prevent the explosion of a hydrocarbon mixture, such as found in aerosol cans. In addition, the system must have sufficient agent/suppression capability to be able to provide continued safe flight and landing from the time a fire warning occurs, which could be in excess of 350 minutes, depending on the aircraft type and route planned.

To date, there have been no cases of halon 1301 replacement with an alternative agent in cargo compartments of civil aircraft. Testing of halocarbon agents has shown that they are not technically or economically feasible due to the space and weight requirements of maintaining the necessary high concentrations of these agents. A combination of water mist and nitrogen has been tested to and met the current performance requirements. Commercial development of a water mist/nitrogen cargo fire suppression system is in the early stages.

The International Coordinating Council of Aerospace Industries Associations (ICCAIA) has formed the Cargo Compartment Halon Replacement Working Group (CCHRWG) to begin to coordinate a single industry effort to find an alternative to halon 1301 in cargo bays.

7.5.2 The estimated installed base of HFCs in fire protection

HFC-227ea fire protection installed base

The following two papers have been identified that estimate emissions of HFC-227ea:

- Laube (Laube et al., 2010) used firn air samples collected in Greenland, from the North Greenland Eemian Ice Drilling project, NEEM, to reconstruct a history of atmospheric concentrations of HFC-227ea. The air trapped in the ice correlates back to the year when the ice formed. A depth of 80 meters in this case correlates to about 1993. They found very low concentrations at about 74 meters, indicating that prior to that time there was no appreciable source of emissions of HFC-227ea. They were able to reconstruct concentrations from 1995 until 2007. They provided estimates of the annual emissions that are needed to obtain the atmospheric concentrations they measured.

- Vollmer (Vollmer et al., 2011) used in situ measurements from the global monitoring sites of the Advanced Global Atmospheric Gases Experiment (AGAGE), the System for Observations of Halogenated Greenhouse Gases in Europe (SOGE), and Gosan (South Korea). They also use archived air from October 1973 – December 2010 from the Northern Hemisphere, which were collected at multiple stations in the USA, and from April 1978 – December 2010 from the Southern Hemisphere at Cape Grim. They found evidence of HFC-227ea in samples from the 1980s. The modeled global growth rate was 12% / yr. They also found evidence suggesting a more balanced emission pattern between the northern and southern hemispheres.

If fire protection was the only sector to use HFC-227ea, then it could be assumed that all of the emissions would come from the installed base and production and handling losses. However, HFC-227ea is used in meter-dosed inhalers (MDIs) and in foams. There may be other uses of HFC-227ea such as in aerosols and there will be production and handling losses. For the purposes of this estimate, the production and handling losses and other potential emissions uses are assumed to be 10% of the annual production. The annual amount of HFC-227ea used in MDIs has been estimated by (Noakes, 2014). For the purposes of this estimate, it is assumed that the annual emission of HFC-227ea is the same as the quantity used in MDIs in any given year. Ashford provided estimates of the annual emissions of HFC-227ea from the entire foam sector.

The (Laube et al., 2010) and (Vollmer et al., 2011) data represent the total global emissions of HFC-227ea. The fire protection amount was estimated by subtracting the three non-fire protection emissions: 1) MDI amounts estimated by (Noakes, 2014) the foam emissions estimated by (Ashford, 2014), and 3) the 10% production and handling loss / other potential emissive uses. It should be noted that there will be a lot of uncertainties associated with the various estimates and ultimately the final estimate of the size of the fire protection installed base. The final estimates should be considered order-of-magnitude estimates only. Assuming a 3% average emission rate from fire protection applications, the installed base from the period 2006-2010 is in the low tens of thousands of metric tonnes (30,000-50,000 MT range).

HFC-236fa installed base

As was the case for HFC-227ea, there are other non-fire protection uses of HFC-236fa. However, unlike HFC-227ea, there is little information available on the relative take-up of HFC-236fa in the fire protection market. There are portable extinguishers that have been commercialized to replace halon 1211 and there is also one other known small use for fire protection in United States auto racing, National Association for Stock Car Auto Racing, known as NASCAR.

The results of the total emissions of HFC-236fa provided in (Vollmer et al.), are only 160 MT in 2010 as compared with HFC-227ea total emissions of 2530 MT, more than one order of magnitude different. As it is not known how much of these emissions can be attributable to fire protection, the best that can be done is bound the issue. If the fire protection installed base is responsible for 90% of these emissions, and assuming a 4 % emission rate for portable extinguishers, the fire protection installed base in 2010 would be low thousands of metric tonnes (3000 - 4000 MT range), which is an order of magnitude less than for the HFC-227ea fire protection installed base. If the fire protection installed base is responsible for only 10% of these emissions, and again assuming a 4 % emission rate for portable extinguishers, the fire protection installed base in 2010 would be in the low to mid hundreds of metric tonnes (300-500 MT range), which is two orders of magnitude less than for the HFC-227ea fire protection installed base.

8 Information on alternatives to ODS in solvent uses

8.1 Introduction

This solvent chapter only describes updates compared to the Decision XXIV/7 Report (TEAP, 2013). HCFC solvents currently used are HCFC-141b and HCFC-225ca/cb with an ODP of 0.11 and 0.025/0.033 and a 100 year GWP of 713 and 120/586, respectively.

Solvents are widely used as process agents in a variety of industrial manufacturing processes although they are not contained in the final products to consumers. The main applications of solvents are metal cleaning where metal working oil, grease, pitch wax, etc are cleaned, electronics cleaning where flus is mainly cleaned, and precision cleaning where dust is mainly cleaned. Among ODSs controlled by Montreal Protocol, CFC-113 and 1,1,1-trichloroethane (TCA) use as solvents were banned in both of Article-5 and non-Article 5 Parties.

Several reports that describe the use of HCFCs in solvent applications have been published in the past. These include the IPCC TEAP Special Report, the TEAP Decision XXI/9 Task Force Report, XXIII/9 Task Force Report, XXIV/7 Task Force Report, and the Assessment Reports of CTOC and STOC.

Many alternative solvents and technologies developed for CFC alternatives since 1980s are the candidates for HCFC alternatives, which include, not- in kind technologies such as aqueous cleaning, semi-aqueous cleanings, hydrocarbon and alcoholic solvents, and in-kind solvents such as chlorinated solvents, and fluorinated solvents which include HFCs and HFEs with various levels of acceptance. HCFC-141b was already banned in non Article 5 Parties by 2010. HCFC-225 is going to be phased out in 2015. Thus, HCFC uses in non-Article 5 Parties are going to be phased out in near future, and a phase down of the HCFC uses in Article 5 Parties has just begun towards the phase out of HCFCs in 2025.

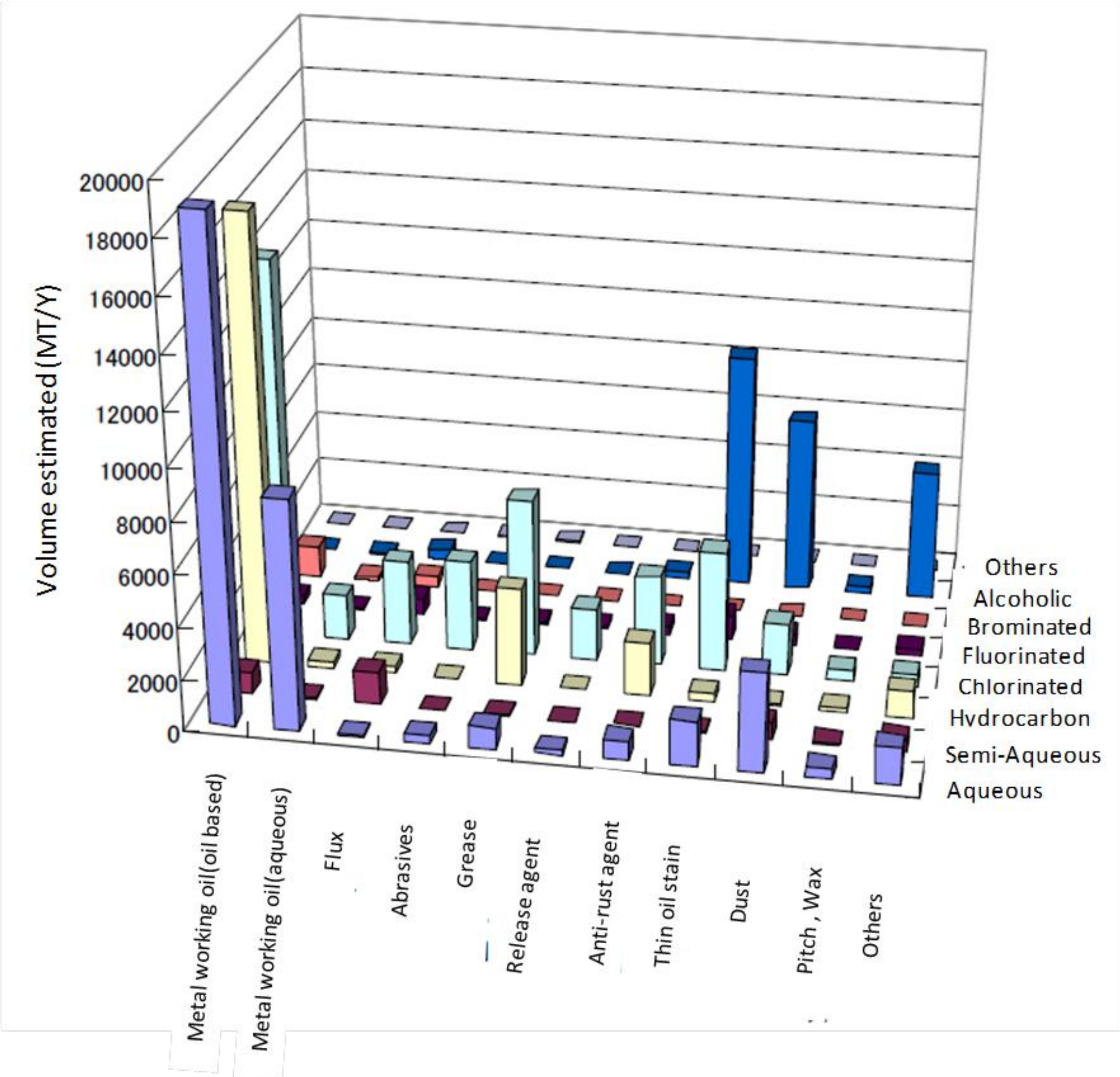
8.3 Response to Question 1(a)

8.3.1 Status in non-A5 Parties

So far, most of HCFCs uses have been replaced successfully by many other alternatives in non-Article 5 Parties, and the HCFCs demand is steadily shrinking. As an example, Figure 8-1 shows the supplied volume (estimated) of all kinds of solvent in each solvent application in 2007 market in Japan.

Although the data presented in the figure are old and estimated values, thus are not representing the total demand of Japanese market, they show the relative positioning of each solvent in each application very well.

From the figure, it is clear that the market share of fluorinated solvents, which includes HCFCs, HFCs and HFEs, had been already very small in 2007. Also, there are some other alternatives being used in each application where fluorinated solvents are used, although the required cleaning specification may be different.



Furthermore, unsaturated fluorochemical HFOs (hydrofluoroolefins) with zero ODP, and HCFOs (hydrochlorofluoroolefins) , CFOs (chlorofluoroolefins) and HBFOs (hydrobromofluoroolefins) with nearly zero ODP are said to be under development. They have ultra low GWP (<10) and are expected to replace HCFCS as well as high GWP-HFC and moderate GWP HFE solvents. Among them, HCFOs, CFOs and HBFOs are unique in their balanced solvency due to the presence of chlorine (or bromine) and fluorine atom in the molecule. If those with appropriate boiling points, low toxicity and enough stability to the practical use be on market, they may replace HCFCs totally in the future.

8.3.2 Status in Article 5 Parties

As shown in UNEP database, consumption and production amount of ODSs in Annex A and Annex B have been completely phased out in Article 5 Parties. Now, Article 5 Parties are moving forward to phase out HCFCs in an orderly fashion.

Although it is very difficult to obtain accurate figures of the total manufacture, imports and use of ODS solvents in Article 5 Parties, preferable alternatives have been identified throughout the world and are generally readily available except the unsaturated chemicals which are under development for commercialisation. So, to keep providing information and knowledge about what are the acceptable alternatives is quite important. A second major hurdle to be overcome is the economic considerations. However, the biggest problem is being able to identify the small- and medium-sized enterprises (SMEs) that, collectively, make up a major portion of the solvent market.

The selection of the alternative technologies to ODS solvents for Article 5 Parties should be:

- Aqueous/hydrocarbon-surfactant cleaning
- Organic solvent cleaning (with solvents less toxic than non-ozone-depleting halogenated solvents)
- Non-ozone-depleting halogenated solvents (TCE, PCE, HFO, HCFO, CFO)
- Organic solvent cleaning (with solvents more toxic than non-ozone-depleting halogenated solvents)
- Some fluorinated solvents with medium to high GWP (HFC, HFE)

However, SME who don't have enough investment tend to use chlorinated solvents as they are cheaply available and the existing facilities can be used with minimum modifications.

8.4 Solvents update

8.4.1 N-Propyl Bromide

A brominated solvent, n-propyl bromide was widely accepted as alternative for TCA, CFC-113, perchloroethylene and HCFCs because of the similar cleaning properties. However, there has been significant concern about the toxicity of n-propyl bromide. The American Conference of Governmental Industrial Hygienists (ACGIH) proposed the reduction of the TLV for n-propyl bromide from 10 ppm to 0.1 ppm in 2012, and finally released 2014 editions of TLVs® and BELs book that shows 0.1ppm of TWA for nPB. That indicates that nPB is not considered as the candidate for cleaning solvent any more due to the safety concerns.

8.4.2 Alternatives under development

Recently unsaturated fluorochemicals such as HFOs, HCFOs, CFOs and HBFOs have been proposed. They are a new class of solvents specifically designed with a low atmospheric lifetime. The unsaturated molecules are known to be unstable in the atmosphere and therefore they show these low atmospheric lifetimes.

HFOs with zero ODP and ultra-low GWP (<10) are being developed for the replacement of high GWP HFC and low or moderate GWP HFE solvents. They also could be candidates to replace HCFCs in certain solvent applications.

On the other hand, HCFOs (hydrochlorofluoroolefins) , CFOs (chlorofluoroolefins) and HBFOs (hydrobromofluoroolefins) have nearly zero ODP and ultra-low GWP (<10). They are unique in their balanced solvency due to the presence of chlorine (or bromine) and fluorine atom in the molecule. If those with appropriate boiling points, low toxicity and enough stability to the practical use have been developed, they are expected to totally replace HCFCs in the future.

9 Information on alternatives to ODS in medical uses

9.1 Metered Dose Inhalers

Inhaled therapy is essential for the treatment of asthma and chronic obstructive pulmonary disease (COPD). There are two main types of inhalers for the delivery of respiratory drugs: the metered dose inhaler (MDI) and the dry powder inhaler (DPI). The choice of the most suitable inhaler is a complex decision taken between doctor and patient.

CFC-propelled MDIs were historically the inhaled delivery device of choice as they were inexpensive, reliable and extremely effective. Under the Montreal Protocol, CFC phase-out in MDI manufacture is almost completed in non-Article 5 Parties and likely to be completed in Article 5 Parties in 2015.

Since 1994, the CFC propellant in MDIs has been gradually replaced with HFCs (HFC-134a and to a lesser extent HFC-227ea), and there are now HFC MDI alternatives available to cover all key classes of drugs used in the treatment of asthma and COPD. Approximately 630 million HFC MDIs (with an average 15g HFC/MDI) are currently manufactured annually worldwide, using about 9,400 tonnes of HFCs and accounting for a relatively small proportion of global HFC usage.

Dry powder inhalers, which do not require a propellant, provide a not-in-kind alternative to MDIs. DPIs fall into two categories: single-dose DPIs, which have been in use for more than 60 years, and multi-dose DPIs, which have been in use for more than 20 years. For single-dose DPIs, the drug is supplied in individual single-dose capsules that must be inserted into the reusable inhaler device, one at a time, by the patient before each use. Multi-dose DPIs, by definition, contain more than one dose of drug, typically supplied with enough for at least one month's treatment. There are two main types of multi-dose DPI, reservoir and multi-unit dose devices. Reservoir devices, which are not refillable, contain a bulk supply of drug (120-200 doses) from which individual doses are released with each actuation and inhaled by the patient. Multi-unit dose devices utilise individually prepared and sealed doses of drug: one type of refillable device uses 4-8 unit dose capsules loaded as a magazine of sealed blisters, with each blister delivering one dose of drug; the other type of non-refillable device contains a preloaded strip of 30-60 blister packed individual doses.

Other alternatives include nebulisers, which are used to inhale drug solutions and account for about 10 percent or less of the market on a dose basis. Another alternative recently launched is a propellant-free aqueous MDI. There are also some emerging alternatives in the earlier stages of development, commercialisation or marketing, such as an iso-butane propelled MDI.

9.1.1 Technical and economic assessment of alternatives to CFC MDIs

An analysis follows of the technical and economic feasibility of the two main alternatives to CFC-propelled MDIs, HFC MDIs and DPIs (Table 1). The criteria established in Decision XXV/5 are not universally relevant to alternatives to CFC MDIs. In particular, in addressing whether alternatives are environmentally sound, and in place of the less relevant energy efficiency, this assessment has considered the alternatives in relation to their greenhouse gas emissions and carbon footprint. This assessment has also considered whether the alternatives are suitable for regions with high humidity rather than regions with high ambient temperature. In addition, cost effectiveness has been interpreted to mean affordability rather than a comparison of the effectiveness of the alternatives in relation to their costs.

Using the criteria, a crude assessment of the technical and economic feasibility of alternatives to CFC MDIs is presented, taking into consideration differences between Article 5 and non-Article 5 Parties. For some criteria (in particular, environmentally sound, affordability), an assessment is made for each alternative *relative to CFC MDIs and to each other*. For example, DPIs can sometimes be less affordable than CFC MDIs or HFC MDIs. For other criteria (such as commercially available, technically proven), an assessment can be made independently because these criteria are more objective measures. A more detailed, descriptive assessment of alternatives to CFC MDIs is elaborated below, and should be read in conjunction with Table 9-1.

Assessment Criteria	Alternatives to CFC MDIs			
	HFC metered dose inhalers		Dry powder inhalers	
	Article 5 Parties	Non-Article 5 Parties	Article 5 Parties	Non-Article 5 Parties
Commercially available	◆ (yellow)[1]	◆ (green)	◆ (yellow)[1]	◆ (green)
Technically proven	◆ (green)	◆ (green)	◆ (green)	◆ (green)
Environmentally sound	◆ (yellow)[2]	◆ (yellow)[2]	◆ (green)	◆ (green)
Economically viable and affordable	◆ (green)	◆ (green)	◆ (yellow)[3]	◆ (yellow)[3]
Suitable for regions with high humidity	◆ (yellow)[4]	◆ (yellow)[4]	◆ (yellow)[4]	◆ (yellow)[4]
Suitable for safe use	◆ (green)	◆ (green)	◆ (green)	◆ (green)
Easily used	◆ (yellow)[5]	◆ (yellow)[5]	◆ (yellow)[5]	◆ (yellow)[5]

Table 9-1 Technical and economic assessment of alternatives to CFC MDIs

Legend: Column 1 lists the assessment criteria, and Columns 2-5 indicate the qualitative assessment for each listed alternative for Article 5 and non-Article 5 Parties, according to each criterion, using the following indicators:

◆ (green) Yes or More acceptable; ◆ (yellow) Not always or Less acceptable; ◆ (red) No or Unacceptable.

1. Not yet commercially available for all drug categories in China alone.
2. More environmentally sound than CFC MDIs but less than DPIs due to HFC emissions. Lower carbon footprint than CFC MDIs but more than DPIs due to HFC emissions.
3. Multi-dose DPIs can be less affordable than MDIs; single-dose DPIs can be more affordable than MDIs.
4. Older reservoir DPIs and some HFC MDIs can be affected by high humidity. Newer multi-dose DPIs function equally well in areas of high humidity.
5. DPIs can be easier for the patient to use because they do not require as much patient coordination as MDIs. However, DPIs have a minimum inspiratory effort, generally available to older children and adults, needed for proper use and drug efficacy. Either MDIs used with a spacer or nebulisers may be the only devices currently suited for treating the very young or patients with low inspiratory flow, and for treating acute attacks.

Commercially available— A range of HFC MDIs and DPIs are commercially available to cover all key classes of drugs used in the treatment of asthma and COPD. However, they are not yet widely available in China for all drug classes, where manufacturing transition to HFC MDIs is anticipated by the end of 2015 and widespread commercial availability probable by 2016-2017. In some regions, there can be more of one alternative (HFC MDI or DPI) used in preference to another. For example, the proportion of MDIs prescribed compared with DPIs varies considerably across Europe, with 70 percent of MDIs prescribed in the UK and only 10 percent in Sweden[2]. This is more to do with

[2] T. Hillman, F. Mortimer, N. S. Hopkinson, Inhaled drugs and global warming: time to shift to dry powder inhalers: Propellants in metered dose inhalers are powerful greenhouse gases, British Medical Journal. 2013; 346: f3359.

market factors and physician/patient practices and preferences than it is to do with commercial availability.

***Technically proven*—** There are now HFC MDI alternatives available to cover all key classes of drugs used in the treatment of asthma and COPD. Single-dose DPIs have been technically proven for more than 60 years, and multi-dose DPIs for more than 20 years. New drugs continue to be developed in the DPI format, sometimes exclusively. One multinational company, GSK, has been launching new respiratory drugs only as DPIs, although it continues to market 75 percent of its products in developing countries in HFC MDI format.

***Environmentally sound*—** Based on carbon footprint estimates, HFC MDIs have about 10 times less climate impact than CFC MDIs. DPIs have an even lower climate impact, about 100 times less than CFC MDIs and 10 times less than HFC MDIs[3]. The estimated carbon dioxide equivalent of a 2-puff dose of an HFC MDI (200g CO2eq.) is comparable to the climate impact of everyday items, such as a 330ml can of Cola (170g CO2eq.)[4]. HFC MDIs can account for a significant portion of the total carbon footprint of a country's health sector (e.g. 8 percent of the total carbon footprint of the UK's NHS)[5].

***Economically viable and affordable*—** Development costs for pharmaceutical companies for the transition of MDIs from CFCs to HFCs have been estimated to exceed US$1 billion, with investment still continuing. MLF funding approved by the Executive Committee of the Montreal Protocol has been US$52.2 million for projects mainly focussed on technology transfer to convert CFC MDI manufacture to HFC MDIs and institutional strengthening.

MDIs are inexpensive and reliable devices that are extremely effective for patients. Multi-dose DPIs made by multinationals in non-Article 5 Parties generally have a similar price to the equivalent dose of drug in an MDI made by multinationals in non-Article 5 Parties. The exception is salbutamol that is more expensive per dose in multi-dose DPIs. Multi-dose DPIs are generally more expensive than MDIs manufactured in Article 5 Parties.

Short-acting bronchodilators (e.g. salbutamol) are generally cheaper when in MDIs than in multi-dose DPIs. Nevertheless, Hillman *et al*. argued that because DPIs are more likely to be used correctly, a direct cost per dose analysis might overestimate the cost effectiveness of MDIs. Notwithstanding, they still conclude that DPIs will need to be cheaper if they are to be used more widely, particularly in emerging economies and health systems where patients pay for their own drugs.[6]

Single-dose DPIs are affordable, and available for the short-acting bronchodilator salbutamol. Patients buy the re-usable device once and generally use that device for about 12 to 24 months. Patients buy only the medicines (capsules) as needed. In Article 5 Parties, single-dose DPIs have the advantage that they permit low-income patients to avoid the expense of buying one month's therapy at a time (as necessary with MDIs and multi-dose DPIs). In India and Bangladesh, doctors prefer

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[3] *2010 Report of the UNEP Medical Technical Options Committee*, 2010 Assessment Report, pp.15-17. Rough estimates of carbon footprints of the manufacture and use of respiratory devices were provided by IPAC. Based on a 200-dose equivalence, the estimated carbon footprint of an CFC MDI is 150-200 kgCO2eq., HFC-227ea MDI 60-80 kgCO2eq., HFC-134a MDI 20-30 kgCO2eq., and of a DPI is 1.5-6.0 kgCO2eq.

[4] http://www.cokecorporateresponsibility.co.uk/big-themes/energy-and-climate- change/product-carbon-footprint.aspx

[5] T. Hillman, F. Mortimer, N. S. Hopkinson, Inhaled drugs and global warming: time to shift to dry powder inhalers: Propellants in metered dose inhalers are powerful greenhouse gases, British Medical Journal. 2013; 346: f3359.

[6] T. Hillman, F. Mortimer, N. S. Hopkinson, Inhaled drugs and global warming: time to shift to dry powder inhalers: Propellants in metered dose inhalers are powerful greenhouse gases, British Medical Journal. 2013; 346: f3359.

single-dose DPIs for the majority of their economically challenged patients. In India, for example, single-dose DPIs account for more than 50 percent of inhaled therapy.

***Suitable for regions with high humidity*—** Older reservoir multi-dose DPIs can suffer from water ingress in high humidity environments that leads to clumping of the powder formulation. Some HFC MDIs are also affected by high humidity. In both cases the issue can be partially addressed by supplying the device in a foil pouch opened on first use. Newer multi-dose DPIs function equally well in areas of high humidity, such as experienced in many Article 5 Parties. Single-dose DPIs can be more susceptible to humidity than some of the more recent multi-dose DPIs. However, an effective drug dose is likely to be delivered even with the effects of humidity, and pharmaceutical companies are working to improve blister pack technology and to ameliorate humidity problems.

***Suitable for safe use*—** The new MDIs and DPIs have been subjected to extensive regulatory assessments for safety, efficacy and quality. Clinical trials have shown HFC MDIs to have a safety and efficacy profile comparable to that of CFC MDIs. Furthermore, new HFC-containing MDIs may even provide improved performance resulting from more consistent dosing.[7] Evidence also indicates that DPIs are equally effective as MDIs for the treatment of asthma and COPD.[8]

***Easily used*—** DPIs can be easier for the patient to use because the drug delivery is effected by the patient's own inhalation, and they do not require as much patient coordination as MDIs. Studies[9] have shown that for many patients single- and multi-dose DPIs are easier to use correctly than MDIs. In some studies as many as 50 percent of patients cannot use an MDI efficiently, although issues of coordination can be overcome through use of a spacer device or breath-actuated inhaler. On the other hand, DPIs have a minimum inspiratory effort that is needed for proper use and drug efficacy. Therefore DPIs are generally used in older children and adults, but not in small children or patients with poor inspiratory flow. Indeed, either MDIs used with a spacer or nebulisers may be the only devices currently suited for treating the very young or the elderly and for treating acute attacks. It has been estimated that up to 30 percent of elderly COPD patients could not achieve satisfactory inspiratory flows through common DPIs[10]. There may be other individual patients for whom DPIs are also not suitable.

***Other and emerging technologies*—** Other alternatives include nebulisers, which account for about 10 percent or less of the market on a dose basis. Nebulisers are useful for treating acute attacks and patients with poor coordination. They are relatively expensive, most are not portable, and their use is often restricted to medical facilities or the patient's home. Nebulisers may play a more significant role in any shift away from MDIs, although currently there is a more limited range of modern drugs in solution formulation. Recently, a novel but expensive propellant-free aqueous MDI has been launched and marketed for a limited range of drugs. One company in Argentina is undertaking research and development to use isobutane as the propellant, planning to launch a salbutamol MDI in 2016. In the 1990s and early 2000s, a German company had also been developing isobutane-propelled salbutamol MDIs, although that work appears to have ceased. Previous studies have

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[7] Asthma patients to benefit from advancement in inhalers, *Business Recorder*, November 3, 2013, Pakistan.

[8] T. Hillman, F. Mortimer, N. S. Hopkinson, Inhaled drugs and global warming: time to shift to dry powder inhalers: Propellants in metered dose inhalers are powerful greenhouse gases, *British Medical Journal*. 2013; 346: f3359.

[9] Atkins, P.J., Dry powder inhalers: an overview, *Respir. Care.* 2005; 50; 1304-12; Timsina MP, Martin SP et al., Drug delivery to the respiratory tract using dry powder inhalers, *Int. J. of Pharmaceutics.* 1994, Vol 101, pp 1-13; Singh M and Kumar L., Randomized Comparison of a Dry Powder Inhaler and Metered Dose Inhaler with Spacer in Management of Children with Asthma, *Indian Paediatrics.* 2001; 38: 24-28; Zeng X Macritchie H B Marriott C Martin G P., Humidity-induced changes of the aerodynamic properties of dry powder aerosol formulations containing different carriers, *International Journal of Pharmaceutics.* 2007; 333: 45-55.

[10] W. Janssens, P. VandenBrande, E. Hardeman, E. De Langhe, T. Philps, T. Troosters and M. Decramer, Inspiratory flow rates at different levels of resistance in elderly COPD patients, *Eur. Respir. J.* 2008; 31: 78–83.

reported toxicological concerns for isobutane used in combination with a beta-agonist[11]. The development and regulatory timescales for new inhaled delivery systems are lengthy.

Conclusions— HFC MDIs, DPIs, nebulisers and other technologies are suitable technically and economically feasible alternatives to CFC MDIs for the treatment of asthma and COPD. HFC MDIs have a lower climate impact than CFC MDIs, but a higher climate impact than DPIs. HFC MDIs can be less affordable than DPIs (for single-dose DPIs in Article 5 Parties) and less easily used (more difficult to coordinate) than DPIs. DPIs can be less affordable than HFC MDIs (for salbutamol in multi-dose DPIs, and generally for multi-dose DPIs in Article 5 Parties) and less easily used (for patients with insufficient inspiratory flow and for treating acute attacks). As a result, HFC MDIs will remain an essential therapy for the foreseeable future, and completely avoiding high-GWP alternatives in this sector is not yet technically or economically feasible. By about 2025, it might become more technically and economically feasible to avoid the use of high-GWP alternatives such as HFC MDIs.

9.1.2 Current and future demand for ODS alternatives

Asthma and COPD are increasing in prevalence world-wide; the acceptance and use of inhalers are also increasing. These two factors combined mean that the overall numbers of inhalers used world-wide are also increasing, especially in Article 5 Parties.

The International Pharmaceutical Aerosol Consortium (IPAC)[12] provided IMS Health[13] market data of global inhaler usage from 2007-2012. Figure 9-1 summarizes the global sales in standard units[14] of all MDIs, CFC MDIs, HFC MDIs, DPIs and nebulized solution inhalants.

[11] Final report of the Safety Assessment of isobutane, isopentane, n-butane, and propane. *Int. J. Toxicology*, 1; 4: 127-142, 1982.

[12] The International Pharmaceutical Aerosol Consortium is a group of companies (Astrazeneca, Boehringer Ingelheim, Chiesi Farmaceutici, Glaxosmithkline, Teva) that manufacture medicines for the treatment of respiratory illnesses, such as asthma and COPD.

[13] IMS Health is a respected company that has been gathering and analyzing pharmaceutical market data for decades. IMS Health; IMS MIDAS granted IPAC permission to submit this data to MTOC/TEAP.

[14] A standard unit is defined by IMS as the number of dose units, such as the number of inhalations/puffs, tablets, the number of 5ml doses, or the number of vials, sold for a particular product. For standard unit comparisons of DPIs versus MDIs it is important to note that for DPIs: 1 puff (1 SU) = 1 dose, whereas in general for MDIs: 2 puffs (2 SUs) = 1 dose. Translating standard units into the absolute number of actual MDIs or DPIs can be complex because different devices provide a range of doses. A rough estimate is made for MDIs by dividing the SUs by 200 and for DPIs by 60.

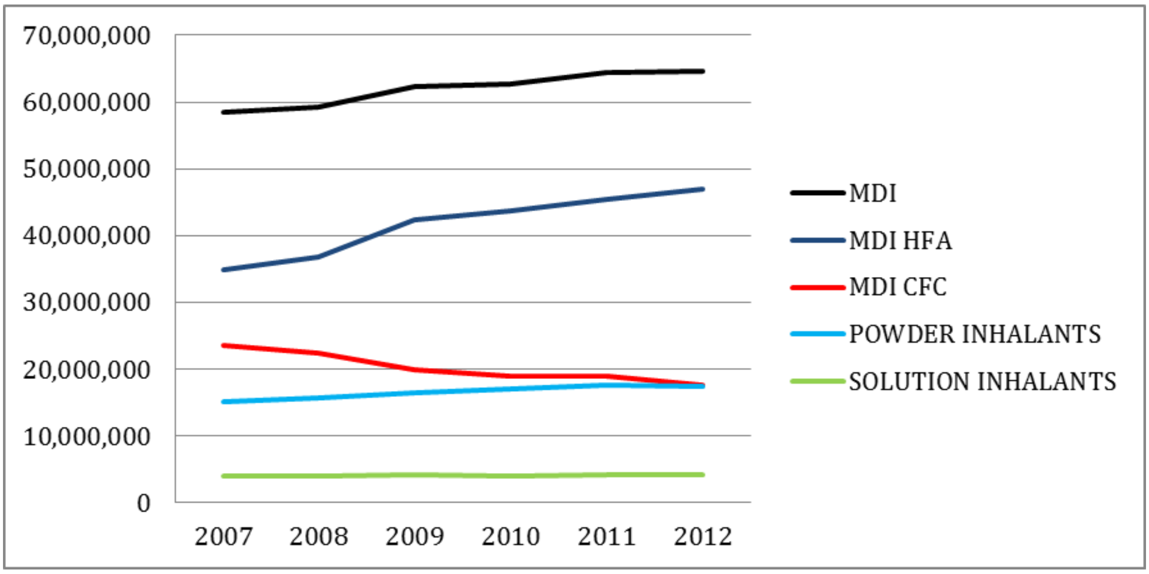

Figure 9-1 Global Standard Units (in 1000s) of total MDIs, CFC and HFC MDIs, DPIs and solution inhalants

World-wide usage of CFC MDIs is declining, and is less than either DPI or HFC MDI usage, based on dose equivalence. Meanwhile there has been an increased overall use of inhalers due to the increased use of both MDIs and DPIs. The data show an increase in the total consumption of all MDIs during this period (2.6 percent per annum), and an increase in the consumption of DPIs (2.9 percent per annum). DPIs accounted for around 32 percent of all inhaled medication, based on dose equivalence, and CFC MDIs for around 16 percent. In China, India, Latin America and Russia, total doses of inhaled medication are increasing more rapidly than in Europe and North America where they are increasing slowly or not at all. In North and Latin America and in Russia, DPI use is lower as a proportion of total doses of inhaled medication than the global average. Whereas, as previously reported[15], in some parts of Europe multi-dose DPIs account for more than 90 percent of inhaled therapy, and in India, single-dose DPIs account for more than 50 percent of inhaled therapy. Based on IMS market data, approximately 300 million DPIs are manufactured annually worldwide.

Based on HFC manufacturing industry estimates[16], approximately 630 million HFC based MDIs (with an average 15g/MDI) are currently manufactured annually worldwide, using approximately 9,400 tonnes of HFCs. HFC-134a makes up the major proportion of MDI manufacture (~8900 tonnes in 2014), with HFC-227ea accounting for about 5 percent (~480 tonnes in 2014). Under a business as usual model, global HFC demand in MDI manufacture (HFCs -134a and -227ea) has been estimated by industry for the period to 2025 (Figure 9-2). It is worthwhile noting that accuracy is likely to decline from 2018 onwards. This modelling does not allow, other than in the flattening of demand for HFC-227ea due to EU F-gas regulations[17], for any other regulatory impact. Neither does it allow for the on-going trend to smaller metered doses[18], which is likely to continue and may have a net effect of

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[15] *TEAP Progress Report*, May 2009, pp. 38-39, and *TEAP Progress Report*, May 2010.

[16] T.J. Noakes, Mexichem Fluor, United Kingdom, personal communications. HFC consumption data derived from this HFC industry source differs from that derived from IMS Health market data. For the purposes of this report, the “top-down” industry data has been used to derive HFC consumption.

[17] EU F-gas regulations prescribe, *inter alia*, reductions in HFCs permitted on the market in the EU from 2015 onwards. Reductions will apply to MDIs until 2018 onwards, after which MDIs are currently exempted from on-going HFC reductions.

[18] Some companies have reduced the size of the metering values on the canisters (to ~25 or 30µl) from an historically larger size (50-65µl) to deliver the same dose, allowing a reduction in the amount of propellant used

a 25-30 percent reduction in future HFC demand. Nevertheless, based on these predictions, global HFC demand for MDI manufacture is estimated to increase annually by 2 percent over the period.

HFC-134a accounts for 95 percent or more of total global demand for MDI manufacture over the period, with annual growth of 2 percent. Global HFC-227ea demand is likely to remain flat, with its proportion of total HFC demand declining slightly over time to less than 5 percent. As such, HFC-227ea MDIs are likely to remain niche products. They are unlikely to expand significantly beyond current products due to expected increasing HFC-227ea prices and uncertainty in the long-term viability of the industrial HFC-227ea business as a result of HFC regulations.

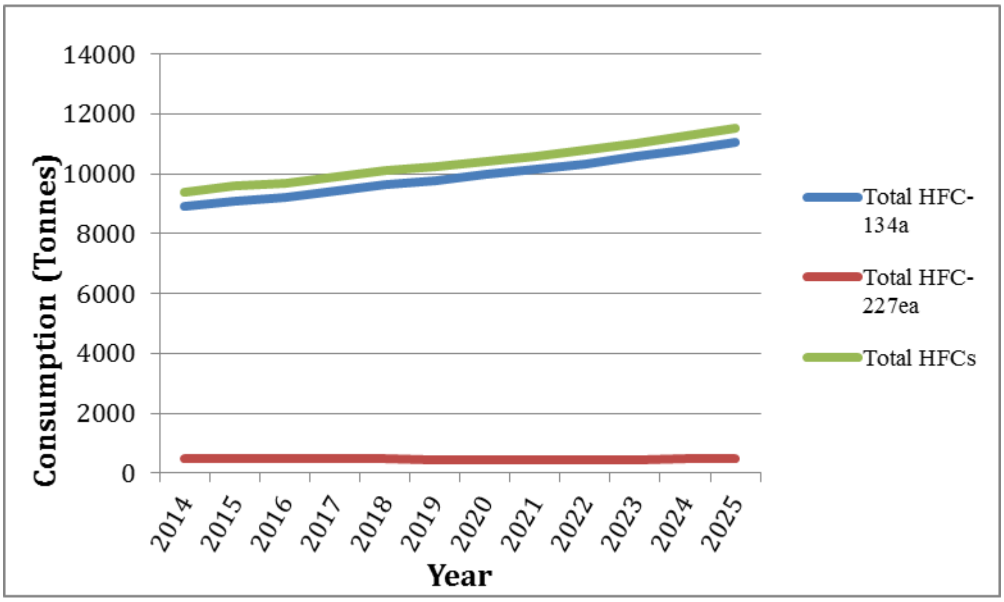

Figure 9-2 Global HFC demand for MDI manufacture, 2014-2025 [19]

Regional demand for HFC-134a in MDI manufacture is variable, with demand in the European Union and the Americas flat or declining, and demand increasing in the Indian sub-continent (India, Bangladesh and Pakistan), Asia Pacific (including China), and the rest of the world (including Russian Federation, Middle East and Cuba). Figure 9-3 shows the various trends. Major growth in HFC-134a MDI manufacture is expected to occur in China, with HFC-134a demand in the Asia Pacific region estimated to increase about 300 percent by 2025. The majority of MDI exports occur from the European Union, China, and India.

per can and per dose. Many companies have also reduced the number of doses in each inhaler (from 200 to 120), which reduces the amount of propellant used per can. Both of these changes will increase the number of inhalers made per tonne of HFCs.

[19] Based on data provided by T.J. Noakes, Mexichem Fluor, United Kingdom, personal communications.

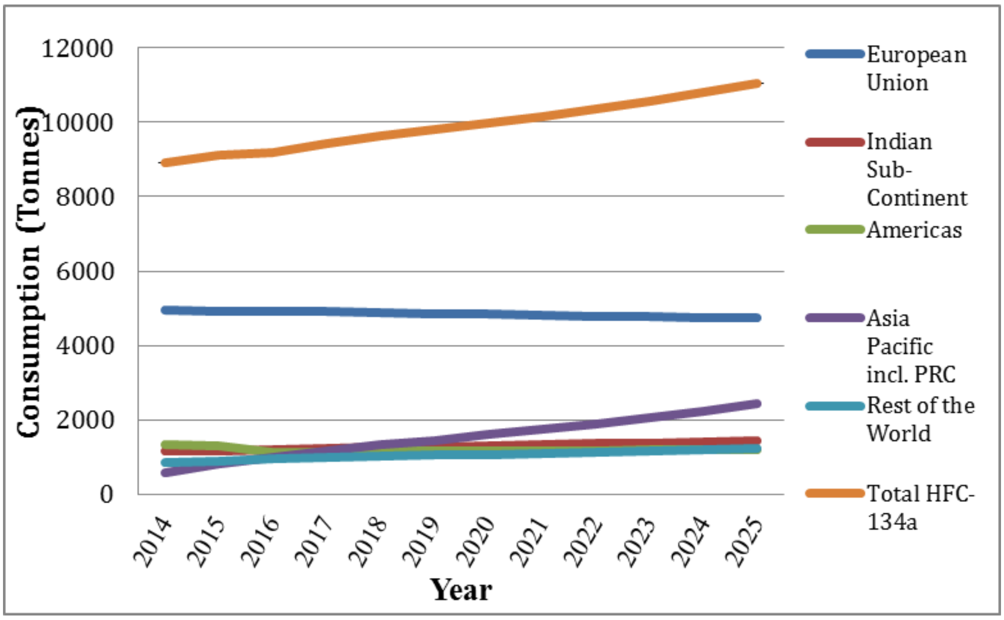

Figure 9-3 Regional HFC-134a demand for MDI manufacture, 2014-2025[20]

9.1.3 Economic costs, implications, and environmental benefits of avoiding high GWP alternatives

HFC emissions from MDIs were estimated previously as 0.02-0.05 percent of annual global greenhouse gas emissions by 2010 in a study by Price *et al*[21]. Under a business as usual model, global HFC demand in MDI manufacture (HFCs -134a and -227ea) has been estimated by industry. For the period 2014 to 2025, the total cumulative HFC consumption in MDI manufacture is estimated as 124,500 tonnes (119,000 tonnes HFC-134a; 5,500 tonnes HFC-227ea), corresponding to direct emissions with a climate impact of approximately 173,000 ktonnes of CO_2 equivalent, which is significantly less than the climate impact of CFC MDIs had they not been replaced. These emissions, and associated environmental impacts, could be avoided under a hypothetical mitigation scenario where the MDI sector was required to phase down its HFC emissions. However, in the short to medium term, this would have adverse health and economic implications for patients, pharmaceutical companies, and countries.

Early in the CFC MDI transition to ODS-free alternatives, healthcare professionals, Price, Valovirta and Fischer[22], observed that measures potentially affecting patient use of HFC MDIs should be carefully considered, especially if measures were imposed while the transition of patients from CFC MDIs was still in progress. They also noted the importance of maintaining a choice of inhaler devices in providing effective treatment. Regulatory authorities appear to be proceeding cautiously with controls for HFCs with regard to MDIs. Recent amendments to the European Union's F-Gas Regulations exclude MDIs from mandated HFC reductions from 1st January 2018 onwards.

DPIs are technically and economically feasible alternatives that are already avoiding the use of some high-GWP HFC MDIs by meeting demand for a significant proportion of inhaled therapy. Nebulisers and other emerging technologies may also be technically and economically feasible alternatives for

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[20] Based on data provided by T.J. Noakes, Mexichem Fluor, United Kingdom, personal communications.

[21] D. Price, E. Valovirta, and J. Fischer, The Importance of preserving choice in inhalation therapy: the CFC transition and beyond, *Journal of Drug Assessment* 2004; 7: 45-61.

[22] D. Price, E. Valovirta, and J. Fischer, The Importance of preserving choice in inhalation therapy: the CFC transition and beyond, *Journal of Drug Assessment* 2004; 7: 45-61.

avoiding the use of some HFC MDIs, both now and in the future. However, HFC MDIs will remain an essential therapy for the foreseeable future. Completely avoiding high-GWP alternatives in this sector is not yet technically or economically feasible because, currently:

- There are economic impediments in switching from HFC MDIs to multi-dose DPIs, especially for salbutamol;
- 10-20 percent of patients cannot avoid using HFC MDIs with available alternatives.

Therefore, the main challenges are the current availability of affordable alternatives to salbutamol HFC MDIs, and treating patients with low inspiratory flow and acute attacks for which, currently, MDIs with a spacer and nebulisers may be the only suitable devices. There are fewer impediments associated with the replacement of HFC MDIs containing preventer medicines such as corticosteroids.

The availability of affordable alternatives to salbutamol HFC MDIs varies from country to country. Companies, especially in Article 5 Parties, are developing single-dose salbutamol DPIs, which are an affordable alternative to HFC MDIs and multi-dose DPIs. For single-dose DPIs, there is a single purchase of an inhaler device with doses purchased on a ‘pay as you go’ basis, e.g. 2 doses per day, or a blister pack of multiple doses that are affordable to patients, despite being more expensive on a cost per dose basis when compared with MDIs. Salbutamol HFC MDIs and multi-dose DPIs, on the other hand, can present a less affordable option to low income patients because they require a more expensive outlay each month or with each purchase. In non-Article 5 Parties, multi-dose salbutamol DPIs are more commonly used than single-dose salbutamol DPIs, with the former generally more expensive than salbutamol HFC MDIs. Despite this, in some markets, multi-dose salbutamol DPIs are used in preference to MDIs e.g. Sweden, where a proactive campaign successfully promoted this technology. Additionally, the profitability of DPIs is lower than MDIs for pharmaceutical companies (which has also been a barrier in the transition from CFC MDIs to HFC MDIs, where profitability of the latter is lower for pharmaceutical companies). Patents also protect DPI technologies, so any company wanting to manufacture DPIs must undertake its own research and development. Consequently, the current economics for patients and pharmaceutical companies are an impediment in switching from HFC MDIs to multi-dose DPIs, especially for salbutamol.

In 2000, the cost effectiveness of a gradual switch from MDIs to DPIs in the European Union was estimated at the time to cost more than €500/tonne of CO_2 equivalent saved, greater than a range of low cost opportunities to reduce greenhouse gas emissions in other sectors, such as energy efficiency measures [23]. An accelerated transition[24] was estimated to be even less cost effective at more than €710/tonne of CO_2 equivalent saved. In about ten years, by about 2025, when patents expire, or even despite patent protection, there is likely to be more competition and more widespread DPI manufacture, such as in Article 5 Parties like China, and more affordable DPIs. These factors are likely to improve the cost effectiveness of DPIs compared with HFC MDIs.

In transitioning patients from MDIs to DPIs, or to other non-MDI devices, there are costs and implications associated with patient re-training, such as physician visits, marketing by pharmaceutical companies, and guidance provided by healthcare agencies and patient advocacy groups. Costs are borne by patients, pharmaceutical companies, government and/or private health insurance. These may not be significant additional costs where there is on-going patient education, rather than with one-off or intermittent advice, regarding the use of inhalers. Patient and physician preferences and resistance

[23] *Study on the Use of HFCs for Metered Dose Inhalers in the European Union*, September 2000, undertaken by Enviros March for the International Pharmaceutical Aerosol Consortium (IPAC).

[24] A gradual transition was assumed to be 8-12 years, and an accelerated transition, 5-8 years. Transition was taken to 80 percent DPI market share, assumed to be the maximum technically feasible at that stage.

to switching medication, when current medication is already effective, may be a potential barrier to change.

Some countries completed their manufacturing transitions from CFC MDIs to CFC-free alternatives before 2010 (including Australia, Canada, Croatia, Cuba, Hungary, Japan, Poland, Ukraine), while since 2010 other countries have completed, or will likely soon complete, their manufacturing transitions before 2015 (including Argentina, Bangladesh, Egypt, European Union, India, Iran, Mexico, United States, Venezuela). China, Pakistan, and Russia are likely to be the last countries to complete their manufacturing transitions in or after 2015.

Development costs for pharmaceutical companies for the transition of MDIs from CFCs to HFCs have been in excess of US$1 billion, with investment still continuing. The return on investments depends on the size of the investment, and the potential within the market to make profit with inhaler sales. The length of time to recover investments will vary for each company and for each product. In general, a favourable return on investment is already likely to have been achieved by large multinational pharmaceutical companies, especially in non-Article 5 Parties. However, smaller companies, especially in Article 5 Parties and in other countries that only recently transitioned, may take longer to achieve a good return on investment. Recovery of investment may also take longer in markets with price controls or other market regulations. A phase-down of HFCs in the MDI sector would have adverse economic impacts for companies where a favourable return on investment had not yet been achieved.

9.2 Sterilants

For the provision of good quality health services, effective sterilization of health care products is required to prevent transmission of infection. Sterilization of medical devices can be performed in industrial settings with large outputs of similar items (such as manufacturers of sterile, single-use syringes) and in hospitals with much smaller outputs, but with a great diversity of items.

There is a range of commercially available sterilization methods including: heat (dry heat or steam), radiations (ionising, ultraviolet, or intense pulsed light radiation), alkylating processes (such as ethylene oxide (EO), formaldehyde) and oxidative processes (including hydrogen peroxide gas, hydrogen peroxide gas plasma, liquid peracetic acid, and ozone).

Sterilization with EO (under controlled gas concentration, temperature and humidity conditions) is used to treat heat and moisture sensitive medical devices, which are packaged in materials that maintain sterility once the product is removed from the sterilization chamber. EO is toxic, mutagenic, carcinogenic, flammable and explosive. EO can be used as a sterilant either alone or diluted with other gases to make non-flammable mixtures. A mixture of 12 per cent by weight EO and 88 per cent chlorofluorocarbon-12 (CFC-12) (12/88) has previously been used widely for this purpose, where CFC-12 acts to make the mixture non-flammable.

On an industrial scale, non-flammable EO mixtures can also be created *in situ* within the sterilizer chamber using nitrogen. Non-flammable EO mixtures can be supplied for industrial or hospital use with carbon dioxide (CO_2) as a diluent.

EO/HCFC blends (10 per cent by weight EO in a mix of HCFC-124 and HCFC-22, or 8.6 per cent by weight EO and 91.4 per cent HCFC-124) were introduced as virtual drop-in replacements for EO/CFC-12 mixtures, as transitional products for sterilization in those countries that employed 12/88 extensively. EO/HCFC blends have been, or are being, phased out in Europe and the United States. EO/HCFC blends may continue to be used in Article 5 Parties, although some may have prohibited their use (e.g. China). Hydrofluorocarbons (HFCs) (10.4 per cent by weight EO in a mix of HFC-125 and HFC-227) were also investigated as further replacement diluents but not widely adopted due to technical reasons and the high GWP of HFCs. EO/HFC-134a (5.6 per cent by weight EO and 94.4 per cent HFC-134a) is supplied by one company for use in hospital sterilisers in Poland.

The EO/CFC sterilization mixture has been successfully phased out in non-Article 5 Parties, and is also likely to have been phased out in Article 5 Parties. Total global use of CFCs for sterilisation is believed to be zero. Estimated global use of HCFCs in sterilization is less than 500-700 metric tonnes, which amounts to less than 25 ODP tonnes worldwide. EO/HCFC use in Article 5 Parties is estimated to be less than 200-400 tonnes.

9.2.1 Alternatives to ODS sterilants and their assessment using criteria

An analysis follows of the technical and economic feasibility of the various alternatives to ODS-consuming sterilants (Table 9-2). The criteria established in Decision XXV/5 are not necessarily relevant to this assessment. In particular, energy efficiency and suitability for regions with high ambient temperature are not priorities in an assessment of the suitability of sterilants, and are not considered further here. A comparison of the carbon footprint of the different sterilisation methods is also not considered further here.

Methods for sterilization of medical devices developed differently in each country due to the respective regulations for fire protection and occupational safety; requirements on process validation; liability considerations; availability of sterilization equipment and materials; and medical practices. No sterilant or sterilization process is compatible with all potential health care products and may vary in the hospital or industrial setting. In general, a number of different sterilisation methods are used by facilities to meet their infection control needs. Hence, the alternatives assessed below are not necessarily interchangeable, and, in the space available, are crudely assessed against each criterion on their own merit, rather than by detailed comparison to EO/CFC or EO/HCFC sterilants, unless otherwise specified. For example, dry heat is included as an alternative despite being only suitable for sterilisation of medical devices able to withstand a temperature greater than 160ºC, whereas EO/CFC and EO/HCFC sterilants are useful for treating heat and moisture sensitive medical devices.

Nevertheless, dry heat is now used for the sterilisation of some medical devices that were previously sterilised using EO/CFC mixture, 12/88, due to greater discrimination in sterilisation practices. The alternatives described below have specific safety features built into the technology to address toxicity, flammability, or other characteristics. Where alternative sterilization technologies are commercialized and meet all of the relevant local/international standards, they may also be considered suitable for safe sterilization applications. More information on alternative sterilants has been reported elsewhere[25].

[25] (1) *2010 Report of the UNEP Medical Technical Options Committee*, 2010 Assessment Report, pp.15-17; (2) US Centers for Disease Control and Prevention, Healthcare Infection Control Practices Advisory Committee, *Guideline for Disinfection and Sterilization in Healthcare Facilities*, 2008, US CDC http://www.cdc.gov/hicpac/Disinfection_Sterilization/13_0Sterilization.html; (3) G. McDonnell, *Antisepsis, Disinfection and sterilization: Types, Action and Resistance*, 2007, ASM press, Washington DC.

Alternatives to CFC-containing sterilants	Assessment Criteria					
	Commercially available	Technically proven	Environmentally sound[1]	Economically viable and cost effective	Suitable for safe use	Easily used
Dry Heat[2]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)
Steam[3]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)
Ionising Radiation[4]	◆ (green)	◆ (green)	◆ (yellow)	◆ (green)	◆ (green)	◆ (green)
UV Radiation[5]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (yellow)
Intense Pulsed Light[6]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (yellow)
Formaldehyde[7]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)
100% Ethylene Oxide[8]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)
EO/CO_2[9]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)
EO/HCFC-124/HCFC-22[10]	◆ (green)	◆ (green)	◆ (yellow)	◆ (green)	◆ (green)	◆ (green)
EO/HFC-125/HFC-227ea[11]	◆ (yellow)	◆ (yellow)	◆ (yellow)	◆ (yellow)	◆ (yellow)	◆ (yellow)
EO/HFC-134a[12]	◆ (green)	◆ (green)	◆ (yellow)	◆ (green)	◆ (yellow)	◆ (yellow)
Chlorine Dioxide[13]	◆ (yellow)	◆ (green)	◆ (green)	◆ (yellow)	◆ (yellow)	◆ (yellow)
Hydrogen Peroxide Gas Plasma[14]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)
Hydrogen Peroxide Gas[15]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)
Liquid Peracetic Acid[16]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)
Low Temperature Plasmas[17]	◆ (red)	◆ (yellow)	◆ (green)	◆ (yellow)	◆ (green)	◆ (yellow)
Ozone[18]	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (green)	◆ (yellow)
Peracetic Acid Gas Plasma[19]	◆ (red)	◆ (red)	◆ (green)	◆ (red)	◆ (red)	◆ (red)
Supercritical Carbon Dioxide[20]	◆ (red)	◆ (yellow)	◆ (green)	◆ (red)	◆ (red)	◆ (red)
Nitric oxide/Nitrogen dioxide[21]	◆ (yellow)	◆ (green)	◆ (green)	◆ (yellow)	◆ (yellow)	◆ (green)

Table 9-2 Technical and economic assessment of alternatives to CFC-containing sterilants

Legend: Column 1 lists sterilisation methods, and Columns 2-7 indicate the qualitative assessment of each method according to each criterion, using the following indicators:

◆ Yes or More acceptable; ◆ Not always or Less acceptable; ◆ No or Unacceptable.

1. Environmentally sound: Under this criterion, technologies are compared with characteristics of EO/CFC-12 sterilant but also on their own merits (e.g. considering waste disposal issues, high GWP).
2. Dry Heat: Used only for materials able to withstand temperatures greater than 160°C.
3. Steam: Used only for materials able to withstand temperatures of greater than 115°C, very high moisture levels and changes in pressure.
4. Ionising Radiation: Gamma, accelerated electron, X-ray radiations are widely used in large industrial settings, where more appropriate and economical. Not compatible with all materials. Disposal of spent isotopes required with gamma radiation. Electron beam and X-ray radiation have no radioactive sources requiring disposal.
5. UV Radiation: Widely used for sanitizing (disinfecting) water systems and air. Limited to surface treatment of medical devices. Shadowing needs to be prevented. Specialised industrial applications for sterilization of particular medical devices and small- scale units for non-industrial applications have been commercialised.
6. Intense Pulsed Light: Limited to situations allowing light access to relevant surfaces and volumes, and specific sterilisation applications. Economical for online high throughput processing.
7. Formaldehyde: Used mainly in Europe and parts of South America for materials that are able to withstand temperatures of 80-85°C and high levels of moisture.
8. 100% EO: One of the most commonly used sterilisation methods. Used in large industrial and small hospital settings.
9. EO/CO_2: EO/CO_2 is easily used with the correct equipment. Operating costs are less expensive than EO/HCFC but EO/CO_2 requires high pressure-rated sterilisation equipment. Not a drop-in replacement. Stratification, compatibility and corrosion problems.
10. EO/HCFC-124/HCFC-22 blends: Non-flammable, virtual drop-in replacements for EO/CFC, allowing continued use of expensive EO/CFC steriliser equipment with minor adjustments. Being phased out in non-Article 5 Parties due to HCFC regulations. Honeywell ceased production of EO/HCFC sterilants by the end of 2013[26].
11. EO/HFC-125/HFC-227ea: Developed and tested as a virtual drop-in replacement for EO/CFC. Tests identified technical problems requiring re-engineering or new equipment, and re-validation. Not fully commercialised or widely used. Suppliers in parts of the world (e.g. Asia) continue to explore potential application.
12. EO/HFC-134a: Very limited use worldwide. Only known occurrence is a commercially available single use cartridge available for hospital sterilisers in Poland[27].
13. Chlorine Dioxide: Not widely deployed.
14. Hydrogen Peroxide Gas Plasma: Extensively used worldwide, mostly in the hospital setting.
15. Hydrogen Peroxide Vapour: Used worldwide in the hospital setting, and to a limited extent in industrial settings.
16. Liquid Peracetic Acid: Used for both high-level disinfection and sterilisation. For sterilisation applications, under defined formulation and process conditions, devices are to be used immediately following sterilisation. Easily used with automated equipment.
17. Low Temperature Plasma: Under development for in-line treatment for aseptic processing of pharmaceutical and other applications.
18. Ozone: Uses a humidified process that must be carefully controlled to ensure efficacy. Can adversely affect surface materials.
19. Peracetic Acid Gas Plasma: One process was commercialised but later associated with patient injuries. This process did not receive US FDA approval and a global recall was mandated.
20. Supercritical Carbon Dioxide: Reported activity against vegetative microorganisms but little against bacterial spores. Limited applicability as a sterilising agent.
21. The use of nitric oxide/nitrogen dioxide (under humidified conditions) has been recently described as an alternative sterilisation method for heat sensitive devices.

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[26] http://www.honeywell-sterilants.com/phaseout-info/

[27] http://www.sterylgaz.com.pl/en/main.php?k0=PRODUCTS&k1=GS-1z

9.2.2 Current and future demand for ODS alternatives

The future demands for sterilization technology are likely to increase with increasing demands for healthcare, economic development, aging populations and increases in chronic conditions. Considering the range of sterilization methods in routine application in healthcare and industrial facilities, the use of EO/CFC and EO/HCFC sterilants are no longer required and can be phased out over time. Existing capital equipment using EO/HCFC and/or EO/HFC sterilants could remain in use if a source of gas could be secured for perhaps the next ten years. However, there is no technical or economic reason for EO/HCFC or EO/HFC sterilants to be in used in non-Article 5 Parties beyond 2020.

Methods for sterilization of medical devices have developed differently in each country, meaning that the availability of alternatives varies in different countries. While some of the gaseous technologies, such as EO/HCFC and EO/CO_2, may appear simpler in application, they require automated equipment to reliably and safely produce the required conditions. Consequently they have tended to be used in niche applications, which is likely to continue. Where alternative sterilization technologies are commercialized and meet all of the relevant local/international standards, they may also be considered suitable for safe sterilization applications. Without regulatory approval, alternatives will not see much increased use in a country.

9.2.3 Economic costs, implications, and environmental benefits of avoiding high GWP alternatives

Due to the wide variety of technically and economically feasible alternatives available in sterilisation, and the almost non-existent use of high-GWP alternatives, there will be very few implications for this sector in avoiding high-GWP alternatives to ODS.

10 Annexes with updated information on alternatives previously reported under Decision XXIV/7

10.1 Additional Information on Refrigeration and Air Conditioning

Following is presented additional and detailed data for the refrigerants being considered as alternatives for HCFCs and high GWP HFCs, and also supplementary information for the several refrigeration and air conditioning applications.

The list of refrigerants is included here, as it was in the 2013 TEAP XXIV/7 Task Force report (TEAP, 2013). For most of the refrigerants, the information has not really changed compared to that previous report.

However, there are some changes for a number of the previously undesignated blends, which have now been assigned R-numbers. Furthermore, about ten additional refrigerant blends have been added in light of their inclusion in testing and trials in different refrigeration, air conditioning and heat pump systems. These listed blends do not represent an exhaustive list of all of those proposed by all refrigerant producers. Also, it is reiterated that of these proposed blends that do not yet have a R-number designation, it is possible that the listed composition may change as the development proceeds.

R-717	
Description and discussion of each technology/chemical (including health and safety etc.)	R-717 (ammonia, NH_3) is a single component substance. It has a safety classification of B2 (higher toxicity, lower flammability). It has a zero ODP and zero GWP.
Extent of commercialisation	R-717 has been used for more than 100 years in a variety of different types of refrigerating machines and is widely used today.
Energy efficiency, efficacy	In principle, R-717 has thermo-physical properties which lead to excellent efficiency. The vapour pressure and refrigerating capacity is similar to HCFC-22. However, it has a very high discharge temperature so for lower temperature applications two stage compression is normally needed. The application of ammonia in small to large absorption systems is wide spread, but has to deal with totally different cycle conditions. Efficiency increases are possible using multi stage operations.
Costs, cost effectiveness	The cost of the substance is very low, typically less that $1/kg. Generally systems require the use of steel piping and components and as a result smaller capacity systems can cost much more than HCFC-22 or HFC systems, although as the capacity approaches and exceeds around 400-600 kW, they can become cost-competitive (UNEP 2011, UNEP 2012).
Barriers and restrictions	There are several general barriers. From a practical level these include the lack of suitable components for small capacity systems (although some companies are working on these aspects), due to incompatibility with copper and its alloys. Discharge temperatures are very high and therefore technology options such as additional compression stages and inter-cooling must be adopted in system design. In addition, the use of R-717 requires well-trained and competent and often certified technicians (in handling R-717), which can sometimes be difficult in all regions. Another is the restriction of use (in direct systems) in occupied spaces due to its higher toxicity. Similarly, certain countries have specific national regulations controlling its use. A comprehensive assessment of the barriers to the use of R-717 and other low-GWP refrigerants is provided in a study for UNEP (Colbourne, 2010).

R-744	
Description and discussion of each technology/chemical (including health and safety etc.)	R-744 (carbon dioxide, CO_2) is a single component substance. It has a safety classification of A1 (lower toxicity, non-flammable). It has zero ODP and a GWP of 1.
Extent of commercialisation	R-744 was used from 1900 to 1930 in refrigerating machines and then supplanted by CFCs. Since 1990 its use was revisited and it is currently used in a variety of different types of systems.
Energy efficiency, efficacy	R-744 has thermo-physical properties which lead to reasonably good efficiency for certain levels of temperatures (such as for refrigeration range). The vapour pressure is several times greater than usual refrigerants and the volumetric refrigerating capacity is correspondingly higher below around 25°C. However, with a low critical temperature, the cycle efficiency declines as the temperature before the expansion device increases and other features are needed to achieve similar (to HCFC-22) efficiency values at high ambient conditions. For an ambient temperature of 35°C the efficiency of a basic cycle is about 50-60% of HCFC-12. Compared to a basic cycle, 10 – 20% energy efficiency improvement can be achieved by applying an ejector instead of an ordinary expansion device (Hafner et al., 2012) although using an expander alone can bring the efficiency to within 10% of HCFC-22 (Subiantoro and Ooi, 2013). Other features to help improve efficiency in high ambient conditions include economiser (parallel compression), liquid-suction heat exchange and mechanical subcooling. Also, discharge temperatures are very high and therefore, where the high temperature cannot be utilised, technology options such as additional compression stages and inter-cooling must be adopted in system design.
Costs, cost effectiveness	The cost of the working fluid is very low, typically around $1/kg. However, because of the high pressure, certain types of systems require more robust designs for pressure safety which adds cost, while specific tube dimensions are much smaller compared to current technology which gives the advantage of compact tubing and insulation material. Since CO_2 can result in a relatively greater drop in capacity at higher ambient conditions compressors may have to be designed with higher volumetric displacement to compensate for the reduced capacity at off-design conditions. However, as the capacity approaches a certain value (depending upon the type of application, between 50 – 500 kW), they can become cost-competitive. Similarly the features that are needed to improve efficiency under higher ambient temperature also result in increased cost.
Barriers and restrictions	There are two main technical barriers, being components and system design for high operating pressure and performance degradation at high ambient temperatures, leading to a resultant incremental cost increase. (Although at the present time a portion of the additional costs are influenced by economies of scale.) Also, due to its relatively unusual characteristics, technicians require dedicated training and specific servicing tools. A comprehensive assessment of the barriers to the use of R-744 and other low-GWP refrigerants is provided in a study for UNEP (Colbourne, 2010).

Hydrocarbons (HCs)	
Description and discussion of each technology/chemical (including health and safety etc.)	Hydrocarbons (HCs) include three main pure refrigerants, HC-290 (propane), HC-1270 (propene) and HC-600a (iso-butane) and a number of mixtures; R-433A, R-433B, R-433C, R-436A, R-436B, R-441A and R-443A, some of which also comprise HC-170 (ethane) or HC-600 (butane). All pure substances and the mixtures have safety classification A3 (lower toxicity, higher flammability). They have zero ODP and GWP (direct GWP plus indirect GWP) ranges from 1.8 to 5.5 (WMO, 2010). HCs have excellent thermo physical and transport properties.
Extent of commercialisation	The pure substances have been used commercially for decades, whilst mixtures such as R-436A and R-436B have been used since the phase-out of CFC-12. Most of the other mixtures are not known to be used commercially. Despite their excellent thermo physical and transport properties, large scale production is so far limited in those types of systems which have large charge sizes located within occupied spaces.
Energy efficiency, efficacy	Generally, the efficiency is shown to be good under most conditions. In principle, they have thermo-physical properties which lead to very good efficiency and low discharge temperatures. Performance comparisons for high ambient conditions are sparse, although two recent studies showed performance to be comparable to HCFC-22 (Chen, 2012; Rajadhyaksha et al, 2013).
Costs, cost effectiveness	The cost of the substances is low, typically less that \$1 - \$10/kg. Due to the safety classification, there are often additional costs necessary for handling flammability characteristics in the design of the equipment, although good thermo-physical properties mean that other costs associated with system construction can be reduced. However, the overall cost implication can vary widely depending upon the type of equipment and any standards to which the design needs to comply.
Barriers and restrictions	The main barriers associated with the use of HCs arise from its flammability. In practical terms this means that systems located indoors with moderate to large charge sizes are often restricted. Similarly, safety concerns of component manufactures mean that there are currently gaps in availability of certain types of components including compressors. In addition, technicians must be well-trained and competent in handling HCs if the flammability is to be dealt with safely. Some building safety codes prohibit flammable refrigerants in certain types of buildings. A comprehensive assessment of the barriers to the use of HCs and other low-GWP refrigerants is provided in a report for UNEP (Colbourne, 2010).
HFCs (GWP ≤ 300)	
HFC-1234yf	
Description and discussion of each technology/chemical (including health and safety etc.)	HFC-1234yf is a single component refrigerant with a GWP < 1 (IPCC AR5). It can replace HFC-134a in same systems since the pressure-temperature characteristics are almost identical. It is classed under ISO 817 as an A2L refrigerant (low toxicity, lower flammability).
Extent of commercialisation	This chemical is currently produced at one medium scale production plant. Further commercial scale production is anticipated when there is a sufficient market demand.
Energy efficiency, efficacy	In general this refrigerant produces efficiency levels comparable to HFC-134a although the theoretical COP is a few percent below that of HFC-134a.
Costs, cost effectiveness	As a new molecule that requires a complex production process, this refrigerant has significantly higher cost than HFC-134a.

Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). Due to uncertainties over future adoption, there are currently gaps in availability of certain types of components including compressors. There are also concerns regarding the decomposition products in the event of a release into the environment.
HFC-1234ze(E)	
Description and discussion of each technology/chemical (including health and safety etc.)	HFC-1234ze(E) is a single component refrigerant with a GWP of 1 (IPCC AR5). It can replace HFC-134a in new equipment where its lower volumetric capacity can be addressed in the design of the equipment. This refrigerant is classified under ISO 817 as A2L (low toxicity, lower flammability).
Extent of commercialisation	This chemical is already produced at a commercial scale. It is anticipated that this refrigerant will be available as and when there is a market demand.
Energy efficiency, efficacy	When used in reciprocating or scroll type of compressors, this refrigerant produces efficiency levels comparable to HFC-134a. When used in scroll and reciprocating compressors, the same POE lubricant oil can be used.
Costs, cost effectiveness	As a new molecule, this refrigerant has higher cost than HFC-134a. This is mainly due to its different manufacturing process, which is not quite as complex as for R1234yf, and economies of scale. It is expected that as production increases, the price premium would be reduced although it is likely to remain above current costs of HFC-134a.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). Due to uncertainties over future adoption, there currently are gaps in availability of certain types of components including compressors. There are also concerns regarding the decomposition products in the event of a release into the environment.
HCFC-1233zd(E)	
Description and discussion of each technology/chemical (including health and safety etc.)	HCFC-1233zd(E) is a single component refrigerant with a GWP of 1 (IPCC AR5). This refrigerant has been submitted for designation and classification and is likely to be A1 (low toxicity, non-flammable) under ISO 817.
Extent of commercialisation	This chemical is already produced at a commercial scale for solvents and blowing agent applications. It is anticipated that this refrigerant will be available as and when there is a market demand.
Energy efficiency, efficacy	When used with centrifugal compressors, this refrigerant produces efficiency levels slightly better than HCFC-123, allowing the design of systems with very high energy efficiency.
Costs, cost effectiveness	As a new molecule, this refrigerant has higher cost that HCFC-123. Still this cost would be moderate and will have a reasonable payback period due to its high energy efficiency which lowers the expenses for end users.
Barriers and restrictions	There are concerns regarding the decomposition products in the event of a release into the environment.
R-444A (previously "AC-5")	
Description and discussion of each technology/chemical (including health and safety etc.)	R-444A is a ternary mixture of HFC-32 (12%), HFC-152a (5%) and HFC-1234ze(E) (83%). It has a GWP of 92 and is classified under ISO 817 A2L (low toxicity, lower flammability).
Extent of commercialisation	All the components of R-444A are in commercial production.

Energy efficiency, efficacy	It has been tested in the AHRI "AREP" programme in a range of equipment and has also been independently tested by the developer in small cold-chain equipment, in calorimetry of refrigeration compressors and in a transport refrigeration system. For systems with direct-expansion evaporators, the drop-in tests give energy efficiency, capacity and operating pressures are close to HFC-134a
Costs, cost effectiveness	Being a blend of new molecule HFC-1234ze(E) and existing ones its cost is moderate although the cost of the unsaturated HFC component is currently higher than HFC-134a
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.
"ARM-42a" [HFC-1234yf/HFC-134a/HFC-152a; 82/7/11%]	
Description and discussion of each technology/chemical (including health and safety etc.)	"ARM-42a" is an azeotropic mixture of HFCs (HFC-134a and HFC-152a) with the new unsaturated HFC-1234yf. It has a GWP of 117 (IPCC 4^{th}) and is intended to replace HFC-134a. The components of the mixture are under ISO 817 as A2 or A2L (low toxicity, lower flammability).
Extent of commercialisation	All components are already produced at a commercial scale.
Energy efficiency, efficacy	"ARM-42a" has similar cooling capacity and similar efficiency to HFC-134a. System tests showed slightly lower COP but compressor calorimeter tests higher. With zero glide this refrigerant is particularly suited for chillers or reversible heat pumps. The same POE lubricant oil can be used as with HFC-134a.
Costs, cost effectiveness	The direct cost of this refrigerant is likely to be higher than HFC-134a.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.
R-445A (previously "AC-6")	
Description and discussion of each technology/chemical (including health and safety etc.)	R-445A is a ternary, mixture of R-744 (6%), HFC-134a (9%) and HFC-1234ze(E) (85%). It has a GWP of 130 and is non-flammable at room temperature. It has been found to be flammable above 50°C and is classified under ISO 817 as A2L (low toxicity, lower flammability).
Extent of commercialisation	All the components of R-445A are in commercial production.
Energy efficiency, efficacy	R-445A has predominantly been tested in mobile air conditioning systems where its energy efficiency and capacity have been found close to HFC-134a and HFC-1234yf. Its temperature glide is about twice that of R-407C.
Costs, cost effectiveness	Being a blend of new molecule HFC-1234ze(E) and existing ones its cost is moderate although the cost of the HFO component is currently higher than HFC-134a

Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps and it is not recommended for flooded evaporator technologies.
“ARM-30a” [HFC-1234yf/HFC-32; 71/29%]	
Description and discussion of each technology/chemical (including health and safety etc.)	“ARM-30a” is an azeotropic mixture of HFC-32 and unsaturated HFC-1234yf. It has a GWP of 210 and is intended to replace HFC-134a. The components of the mixture are under ISO 817 as A2L (low toxicity, lower flammability).
Extent of commercialisation	All components are already produced at a commercial scale.
Energy efficiency, efficacy	“ARM-30a” has similar cooling capacity and similar efficiency to HFC-134a. System tests showed lower COP. The same POE lubricant oil can be used as with HFC-134a.
Costs, cost effectiveness	The direct cost of this refrigerant is likely to be higher than HFC-134a.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.
“DR-7” [HFC-32/HFC-152a/HFC-1234yf/HFC-1234ze(E); 40/10/20/30%]	
Description and discussion of each technology/chemical (including health and safety etc.)	“DR-7” is a mixture of HFC-32 and the new unsaturated HFC-1234yf and has a GWP of about 210. It is intended to replace R-404A in medium and low temperature refrigeration equipment without any major modifications as its pressures are similar. The composition of the mixture would be classed as A2L (low toxicity, lower flammability) under ISO 817.
Extent of commercialisation	All components are already produced at a commercial scale, although currently the production of HFC-1234yf vis-a-vis the market demands for it in automotive air conditioning may be an initial barrier to be overcome. It is not known when this refrigerant will be available commercially.
Energy efficiency, efficacy	Compared to R-404A, DR-7 provides almost the same capacity and COP.
Costs, cost effectiveness	The direct cost of this refrigerant will be higher than R-404A. It is miscible with existing POE lubricants.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.

"L-40" [HFC-32/HFC-152a/HFC-1234yf/HFC-1234ze(E); 40/10/20/30%]	
Description and discussion of each technology/chemical (including health and safety etc.)	L-40 is a mixture of HFCs (HFC-32 and HFC-152a) with the new unsaturated HFCs (HFC-1234yf and HFC-1234ze(E)) with a GWP of 290. It is intended to replace R-404A in medium and low temperature refrigeration equipment without any major modifications as its pressures are similar. The composition of the mixture would be classed as A2L (low toxicity, lower flammability) under ISO 817.
Extent of commercialisation	All components are already produced at a commercial scale, although currently the production of HFC-1234yf vis-a-vis the market demands for it in automotive air conditioning may be an initial barrier to be overcome. It is anticipated that this refrigerant will be available during the next 1-2 years.
Energy efficiency, efficacy	When used in the current R-404A system, L-40 is apparently exceeds the capacity of R-404A with an efficiency improvement of around 10%.
Costs, cost effectiveness	The direct cost of this refrigerant will be higher than R-404A. It probably works with existing POE lubricants.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.
R-444B (previously referred to as "L-20")	
Description and discussion of each technology/chemical (including health and safety etc.)	R-444B is a mixture of HFCs (HFC-32 and HFC-152a) with the new unsaturated HFC-1234ze. With a GWP of 295. It replaces HCFC-22 in AC equipment without any major modifications as its pressures are similar. As formulated this mixture will be classified under ISO 817 as A2L (low toxicity, lower flammability).
Extent of commercialisation	All components are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe).
Energy efficiency, efficacy	When use in the current HCFC-22 technologies, R-444B matches the capacity of HCFC-22 with an efficiency ranging from 95% to 97%. Further improvements can produce better efficiencies, especially for cooling only operation in warm climates. The above mentioned good performance in warm climates is mainly due to its relative high critical point (~93°C) compared with other options such as R-410A and HFC-32.
Costs, cost effectiveness	The direct cost of this refrigerant may be similar to current HFCs such as R-407C. It works well with existing POE lubricants. Due to its good efficiency at high ambient temperatures, power consumption would be lower relative to other options.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.

HFCs (300<GWP ≤1000)	
"HPR1D" [R-744/HFC-32/HFC-1234ze(E) 6/60/34%]	
Description and discussion of each technology/chemical (including health and safety etc.)	"HPR1D" is a ternary mixture of R-744, HFC-32 and HFC-1234ze(E) having a GWP of 407 and a temperature glide of about 10 K, intended as an alternative to R-410A. It has low flammability and is expected that it would be classified by ISO as A2L (low toxicity, low flammability)
Extent of commercialisation	All the components are commercially available.
Energy efficiency, efficacy	It has been tested in the AREP program and independently in tests of a heat pump/air conditioner and in compressor calorimetry. Drop-in system tests show capacity and COP to be within about 10% of R-410A. Performance relative to R-410A is improved at higher ambient temperatures.
Costs, cost effectiveness	A proportion of this refrigerant is a new unsaturated HFC molecule whose production cost is currently higher than that of R-410A. This is mainly due to its different manufacturing process and economies of scale. It is expected that as production increases, the price premium would be reduced such that the cost of the blend should be moderate.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.
"ARM-70a" [HFC-32/HFC-134a/HFC-1234yf; 50%/10%/40%]	
Description and discussion of each technology/chemical (including health and safety etc.)	"ARM-70a" is a replacement of R-410A in air conditioning equipments. It has a GWP of about 480 (IPCC 4^{th}). This refrigerant would be classified A2L by ISO 817
Extent of commercialisation	All components are already produced at a commercial scale.
Energy efficiency, efficacy	"ARM-70a" has similar capacity and efficiency than R-404A. Discharge temperatures are slightly higher than R-410A but within the acceptable range of existing compressor technologies
Costs, cost effectiveness	The direct cost of this refrigerant is likely to be slightly higher than R-410A
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.
"DR-5" [HFC-32/HFC-1234yf; 72.5/27.5%]	
Description and discussion of each technology/chemical (including health and safety etc.)	DR-5 is a mixture of HFCs (HFC-32) with the new unsaturated HFC-1234yf and has a GWP of 490. It replaces R-410A in AC equipment. All components of the mixture are classified by ISO 817 as A2L (low toxicity, lower flammability).
Extent of commercialisation	All components are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe).

Energy efficiency, efficacy	The efficiency of L-41 systems is at the same level of R-410A. The capacity is approximately 6% to 10% lower than R-410A still this capacity is easily recovered in new systems. Discharge temperatures are slightly higher than R-410A, still below the limit of existing compressors technologies. Due to its relative higher critical point compared to other refrigerants, DR-5 performs well at high ambient temperatures (warm climates).
Costs, cost effectiveness	The direct cost of this refrigerant would be slightly high as it contains HFC-1234yf which has an expensive manufacturing cost. It works well with existing POE lubricants. Due to its good efficiency at high ambient temperatures, power consumption would be lower relative to R-410A.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.
R-447A (previously referred to as "L-41")	
Description and discussion of each technology/chemical (including health and safety etc.)	R-447A is a mixture of HFCs; HFC-32, the new unsaturated HFC-1234ze and a small amount of HFC-125. It replaces R-410A in AC equipment. This mixture is classified as A2L (low toxicity, lower flammability). It has a GWP of 572.
Extent of commercialisation	All components are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe). Some countries or regions may take longer than others due to building codes restrictions and lack of regulatory drivers.
Energy efficiency, efficacy	The efficiency of R-447A systems is at the same level of R-410A. The capacity is approximately 6% to 10% lower than R-410A. Discharge temperatures are slightly higher than R-410A, still below the limit of existing compressors technologies. Due to its relative higher critical point compared to other refrigerants, R-447A performs well at high ambient temperatures (warm climates).
Costs, cost effectiveness	The direct cost of this refrigerant is similar to R-410A. It works well with existing POE lubricants. Power consumption increases its effectiveness at high ambient temperatures relative to R-410A.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.
R-450A (previously referred to as "N-13")	
Description and discussion of each technology/chemical (including health and safety etc.)	R-450A is a binary mixture of HFC-134a and HFC-1234ze(E) which as formulated is non-flammable. It has a GWP of 547 therefore reduces substantially the direct environmental impact. It replaces HFC-134a in new equipment where its lower volumetric capacity can be addressed in the design of the equipment. This refrigerant would be classified by ISO 817 A1 (low toxicity, non-flammability).

Extent of commercialisation	These chemicals are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe).
Energy efficiency, efficacy	When used in reciprocating or scroll compressors, this refrigerant produces efficiency levels comparable to HFC-134a, although the capacity is lower. When used in scroll and reciprocating compressors, the same POE lubricant oil can be used.
Costs, cost effectiveness	Being a blend of new molecules HFC-1234ze(E) and existing ones (HFC-134a), its cost is moderate and not significant different from existing blends available in the market.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below). System components including compressors are not currently widely available. As with other zeotropic blends, temperature glide issues may influence the design of equipment and be an issue for certain applications such as reversible heat pumps.
"AC-5X" [HFC-32/HFC-134a/HFC-1234ze(E); 7/40/53%]	
Description and discussion of each technology/chemical (including health and safety etc.)	"AC-5X" is a ternary mixture of HFC-32, HFC-134a and HFC-1234ze(E) which is formulated as non-flammable. It has a GWP of 620 and is considered as an alternative to HFC-134a. As formulated it is anticipated it would be classified by A1 in ISO 817 (low toxicity, non-flammable)
Extent of commercialisation	All components are already produced at a commercial scale.
Energy efficiency, efficacy	In drop-in tests and calorimetry studies it has shown a close match to HFC-134a
Costs, cost effectiveness	The bulk of this refrigerant is a new HFO molecule and consequently has higher cost than HFC-134a. This is mainly due to its different manufacturing process and economies of scale. It is expected that as production increases, the price premium would be reduced such that the cost of the blend should be moderate.
Barriers and restrictions	The barriers are not different from conventional non-flammable HFC blends, typically that temperature glide issues may influence the design of equipment.
"XP-10" [HFC-134a/HFC-1234yf; 44/56%]	
Description and discussion of each technology/chemical (including health and safety etc.)	XP-10 is a binary mixture of HFC-134a and HFC-1234yf, which as formulated is non-flammable. It has a GWP of 630 therefore reduces substantially the direct environmental impact. It replaces HFC-134a in new equipment, producing similar capacity and efficiency. As formulated, this refrigerant would be classified by ISO 817 A1 (low toxicity, non-flammable).
Extent of commercialisation	These chemicals are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years in Asia (China, Japan, Korea), followed by other regions (Middle East, Europe).
Energy efficiency, efficacy	When used in reciprocating or scroll compressors, this refrigerant produces efficiency levels comparable to HFC-134a. When used in scroll and reciprocating compressors, the same POE lubricant oil can be used. Due to its high critical temperature, it will perform very well in warm climates.
Costs, cost effectiveness	Being a blend of a high manufacturing cost molecule (HFC-1234yf) and HFC-134a, its cost is expected to be high.

Barriers and restrictions	Its high cost would be the main barrier for widespread adoption by the market. Otherwise, the barriers are not different from conventional non-flammable HFC blends, typically that temperature glide issues may influence the design of equipment.
HFC-32	
Description and discussion of each technology/chemical (including health and safety etc.)	HFC-32 is a single component refrigerant that was originally used as a component of R-410A, which is 50% HFC-32 and 50% HFC-125, and other blends. HFC-125 was used to reduce the flammability of HFC-32 and high discharge temperature. It has a GWP of 716. Pressure and capacity are around 1.5 times higher than HCFC-22 and equivalent to R-410A. It is classed as A2L (low toxicity, lower flammability) under ISO 817.
Extent of commercialisation	HFC-32 is one of components of R-410A and R-407C, so fairly large production capacity is already available, Cylinders are made available in the market.
Energy efficiency, efficacy	The efficiency of HFC-32 systems or higher than R-410A and the theoretical COP is a few per cent better than R-410A at typical air conditioning conditions. The capacity is approximately slightly higher (~ 5%) but it can be easily accommodated with slight adjustment of the compressor displacement in new systems. Its system charge is lower than for R-410A. It has better heat transfer properties and transport properties than R-410A due to lower molar mass. Discharge temperatures are higher than R-410A. Higher polarity of refrigerant makes necessary the use of new lubricant oils. Some mitigation device or controls may be necessary for handling the discharge temperature of the compressor especially at high ambient temperatures.
Costs, cost effectiveness	The direct cost of this refrigerant is lower than that of R-410A as it is a not patented substance, simple molecular structure and lower fluorine necessity in molecule. The new lubricant oils and mitigation devices for high discharge temperature may add some cost. The better heat transfer and lower pressure drops in the pipes reduces the use of copper and aluminium resulting in more compact units which in general means lower cost units.
Barriers and restrictions	The main barriers are related to the safe use of lower flammability refrigerants (see explanation below).
HFCs (1000 < GWP ≤ 3000)	
R-448A (previously referred to as "N-40")	
Description and discussion of each technology/chemical (including health and safety etc.)	R-448A is a mixture of saturated HFCs (HFC-32, HFC-125 and HFC-134a) with unsaturated HFC-1234yf and HFC-1234ze, which as formulated is non-flammable. It has a GWP of 1270 and is therefore similar to pure HFC-134a. It replaces R-404A in existing and new refrigeration equipment. This refrigerant would be classified by ISO 817 A1 (low toxicity, non-flammable).
Extent of commercialisation	The component chemicals are already produced at a commercial scale. It is anticipated that this refrigerant will be available during the next 1-2 years.
Energy efficiency, efficacy	This refrigerant has a capacity similar to R-404A and a greater efficiency (up to +8%). The same POE lubricant oil can be used as with R-404A.
Costs, cost effectiveness	Being a blend, which includes HFC-1234yf and HFC-1234ze(E), its cost is likely to be higher than conventional HFC mixtures.

Barriers and restrictions	The barriers are not different from conventional non-flammable HFC blends, typically that temperature glide issues may influence the design of equipment.
"LTR-4X" [HFC-32/HFC-125/HFC-134a/HFC-1234ze(E); 28%/25%/16%/31%]	
Description and discussion of each technology/chemical (including health and safety etc.)	LTR-4X is a zeotropic mixture of HFC-32, HFC-125, HFC-134a and HFC-1234ze(E) which has a GWP of 1295 and is formulated as non-flammable. It replaces R-404A or R-407A/F in refrigeration equipment. It is anticipated that this refrigerant will be classified under ISO 817 as A1 (low toxicity, non-flammable)
Extent of commercialisation	All the components are in commercial production
Energy efficiency, efficacy	Performance in DX systems is close to that of R-407A and R-404A with compressor discharge temperatures similar to R-407A.
Costs, cost effectiveness	A proportion of this refrigerant is a new unsaturated HFC molecule and consequently has higher cost than R-404A. This is mainly due to its different manufacturing process and economies of scale. It is expected that as production increases, the price premium would be reduced such that the cost of the blend should be moderate.
Barriers and restrictions	The barriers are not different from conventional non-flammable HFC blends, typically that temperature glide issues may influence the design of equipment.
R-449A (previously listed as "DR-33")	
Description and discussion of each technology/chemical (including health and safety etc.)	R-449A is a mixture of saturated HFCs (HFC-32, HFC-125 and HFC-134a) and unsaturated HFC-1234yf, which as formulated is non-flammable. It has a GWP of 1410 and is therefore similar to pure HFC-134a. It replaces R-404A in new refrigeration equipment. This refrigerant would be classified by ISO 817 A1 (low toxicity, non-flammable).
Extent of commercialisation	The component chemicals are already produced at a commercial scale.
Energy efficiency, efficacy	This refrigerant has a capacity marginally higher than R-404A and a slightly greater efficiency. The same POE lubricant oil can be used as with R-404A.
Costs, cost effectiveness	Being a blend, which includes HFC-1234yf, its cost is likely to be higher than conventional HFC mixtures.
Barriers and restrictions	The barriers are not different from conventional non-flammable HFC blends, typically that temperature glide issues may influence the design of equipment.
HFC-134a	
Description and discussion of each technology/chemical (including health and safety etc.)	HFC-134a is a pure substance with a GWP of 1370. It is used in a variety of equipment including heat pumps and chillers. It is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy	Energy efficiency is good, provided that pipes and heat exchangers are suitably sized.
Costs, cost effectiveness	The cost of the substance is greater than HCFC-22 but less than HFC blends.
Barriers and restrictions	There are no significant barriers to its use.

R-407C	
Description and discussion of each technology/chemical (including health and safety etc.)	R-407C is a mixture refrigerant comprising HFC-134a, HFC-125 and HFC-32 with a GWP of 1700. It has been used widely in air conditioning, chiller and heat pump systems, especially to help the transition from HCFC-22. It is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy	The efficiency is acceptable, although heat exchangers need to be designed suitably to take account of the temperature glide.
Costs, cost effectiveness	The cost of the refrigerant is approximately two to three times greater than HCFC-22.
Barriers and restrictions	The barriers are not different from conventional non-flammable HFC blends, typically that temperature glide issues may influence the design of equipment.
R-407F	
Description and discussion of each technology/chemical (including health and safety etc.)	R-407F is a mixture of the same components of R-407C but in slightly different proportions. Its GWP is 1820. It is typically used recently for centralised commercial refrigeration systems. It is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy	The efficiency is acceptable and better than of the R-404A it is normally used to replace. However, heat exchangers need to be designed suitably to take account of the temperature glide.
Costs, cost effectiveness	The cost of the refrigerant is approximately two to three times greater than HCFC-22.
Barriers and restrictions	The barriers are not different from conventional non-flammable HFC blends, typically that temperature glide issues may influence the design of equipment.
R-407A	
Description and discussion of each technology/chemical (including health and safety etc.)	R-407A is a mixture of the same components of R-407C but in slightly different proportions. Its GWP is 2100. It is typically used recently for centralised commercial refrigeration systems. It is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy	The efficiency is acceptable and better than of the R-404A it is normally used to replace. However, heat exchangers need to be designed suitably to take account of the temperature glide.
Costs, cost effectiveness	The cost of the refrigerant is approximately two to three times greater than HCFC-22.
Barriers and restrictions	The barriers are not different from conventional non-flammable HFC blends, typically that temperature glide issues may influence the design of equipment.
R-410A	
Description and discussion of each technology/chemical (including health and safety etc.)	R-410A is a mixture refrigerant comprising HFC-125 and HFC-32 with a GWP of 2100. It is used widely in air conditioning, chiller and heat pump systems. The safety is classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally.
Energy efficiency, efficacy	Generally the efficiency is equivalent to HCFC-12 or better, especially at lower temperatures. This efficiency however deteriorates at higher ambient temperatures.
Costs, cost effectiveness	The cost of the refrigerant is approximately two to three times greater than HCFC-22.

Barriers and restrictions	A slight barrier to its use it the operating pressures being higher than that of HCFC-22, although this is more perceived than practical. For countries which experience high ambient temperatures capacity and efficiency can degrade more rapidly than with HCFC-22.
HFCs (GWP > 3000)	
R-404A and R-507	
Description and discussion of each technology/chemical (including health and safety etc.)	R-404A is a mixture refrigerant comprising HFC-134a, HFC-125 and HFC-143a with a GWP of 3700. It has been used widely in commercial refrigeration systems. R-507 has a similar GWP and operates similarly to R-404A. Both are classed as an A1 refrigerant (lower toxicity, non-flammable).
Extent of commercialisation	It is well commercialised globally. R-404A is more widely commercialised than R-507.
Energy efficiency, efficacy	The efficiency is acceptable. A major advantage of R-404A and R-507 is the low discharge temperature, which makes it possible to have a high temperature lift in a single stage system.
Costs, cost effectiveness	The cost of the refrigerant is approximately two to four times greater than HCFC-22.
Barriers and restrictions	There are no significant barriers to its use, although it is now becoming considered less desirable within several regions due to its comparatively high GWP.

Barriers to flammable refrigerants

For the safe use of higher (A3 under ISO 817) and lower flammability (A2 under ISO 817) and lower flammability refrigerants with low flame speed (A2L under ISO 817), standards such as ISO-5149 IEC 60335-2-24, IEC-60335-2-40 and IEC 60335-2-89 provide relevant safety requirements. For A2L refrigerants, some of these standards are under revision to accommodate requirements specifically for this new safety class. In practical terms the requirements means that systems located indoors with large charge sizes can be limited. In addition, technicians must be well-trained and competent in handling flammable refrigerants if the flammability is to be dealt with safely. In some countries building safety codes may prohibit the use flammable refrigerants in certain types of buildings.

10.1.1 Domestic Refrigeration

Domestic refrigeration sub-sector comprises appliances that are broadly used domestically, such as refrigerators, freezers and combined refrigerator/freezer products. Beverage dispensing machines are similar products and are commonly included in domestic refrigeration, but represent a small fraction of total units.

Approximately 100 million domestic refrigerators and freezers are produced annually, and it is estimated that this quantity is equally divided between non-Article 5 and Article 5 countries. A typical product includes a factory-assembled, hermetically sealed, vapour-compression refrigeration system employing a 50 to 250 watt induction motor, containing 50 to 250 grams of refrigerant. Commercially available alternative technology to vapour-compression refrigeration is employed in specific products, such as absorption cycles for small fridges in hotels and so. The age distribution of the global installed products is extremely broad with median age estimates ranging from 9 to 19 years at retirement, being higher values typical for Article 5 countries. Long product life and high volume annual production combine for an estimated 1500 to 1800 million unit global installed inventory.

The main refrigerants used are hydrocarbon HC-600a (isobutane) and HFC-134a. More than 50% of current new production (globally) employs HC-600a, the remainder uses HFC-134a. HC-600a continues to be the main alternative to HFC-134a. Concerns in connection with the high flammability no longer exist for the low charges applied. No new alternative has matured to become energy-efficient and cost-competitive. Considering costs, HC-600a itself is less expensive than HFC-134a,. but production cost for refrigerators can be higher due to the requirements for safety systems.

Initial developments to assess HFC-134a replacement with HFC-1234yf have begun, but is not being pursued as a high priority. HFC-1234yf has demonstrated the potential for comparable efficiency to HFC-134a. The lower flammability makes its application easier in countries with strong reservations about HC-600a.

10.1.2 Commercial Refrigeration

Commercial refrigeration is characterised by storing and displaying food and beverages at two main levels of temperature: medium level (around 0°C) for chilled food and low level (around -18°C) for frozen food. The refrigerating capacities of equipment vary from some hundreds of Watts to 1.5 MW depending on the three types of equipment: stand-alone equipment, condensing units, and supermarket systems. Refrigerant choices depend on the refrigerant charge, the level of temperature, the energy efficiency, as well as on regional regulations.

Stand-alone equipment

Stand-alone equipment also called “plug-in” consists of systems where all refrigeration components are integrated; for smallest types, the refrigeration circuit is entirely brazed or welded.

Large global food companies have committed to not use HFCs in their new systems.

The energy efficiency of the vending machine and bottle cooler with carbon dioxide cassettes is similar to HFC-134a machines with energy penalty that increases when the ambient temperature is higher than 25°C; the higher the ambient temperature the higher the energy penalty. The cost is slightly higher compared to HCFC or HFC equipment. The high technological level of expertise required forms a barrier for the application.

Where it concerns low GWP HFCs, tests have been performed under the auspices of AHRI “Low GWP AREP program during the year 2013. 34 reports are available; most of the tests have been performed as drop-in tests without any optimization of the refrigeration system in order to adapt it to the thermodynamic properties of the new refrigerants. Report #8 compares the main energy performances of HFC-1234yf, HFC-1234ze, and two blends, as it can be seen in Table 10-1. Both the relative capacity and the COP are lower compared to HFC-134a in this application, but the differences are relatively small. Simple adaptations such as compressor swept volume and heat-exchanger sizing can suffice to meet the original performances.

Refrigerant	Relative capacity compared to HFC-134a	Relative COP compared to HFC-134a
HFC-134a	1	1
HFC-1234yf	0.91	0.89
HFC-1234ze(E)	0.92	0.94
XP-10	0.92	0.90
N-13	0.95	0.94

Table 10-1 HFC-134a replacement candidates for commercial bottle coolers (AHRI Report #8)

Condensing units

Refrigeration capacities of condensing units range typically from 1 kW to 20 kW. Condensing units are composed of one (or two) compressor(s), one condenser, and one receiver; they are located external to the sales area. Condensing units are typically installed in specialty shops such as bakeries, butcher shops, and convenience stores. In most Article 5 countries there is an extensive use of condensing units, not only in small shops but also in supermarkets where up to 20 condensing units operate in parallel.

R-717 is never used in condensing units because of cost and safety issues.

R-744 based condensing units are available in Northern Europe, but the market penetration is low. R-744 systems 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; cost is the main barrier for these R-744 systems.

Several indirect condensing units with HC-290 or HC-1270 operate in Europe with typical refrigerant charges varying from 1 to 20 kg. The energy efficiency is good. The indirect system energy penalty is limited if the secondary loop is well designed, with larger heat-exchanger areas. Costs for these HC-based systems are typically 5 to 15% higher compared to HFC systems. For smaller capacities, direct HC condensing units are being used.

Table 10-2 presents candidates to replace R-404A in condensing units, according to the AHRI study above mentioned

Commercial name	Volumetric capacity referred to R-404A at -29°C	COP relative to COP R-404A
R-404A	1	1
ARM-30a	0.81	0.89
DR-7	1.02	1.07
L-40	0.83	0.86

Table 10-2 Candidates to the replacement of R-404A. (AHRI report #9)

Centralised systems

Centralised systems are the preferred option in supermarkets. They operate with racks of compressors installed in a machinery room. Two main design options are used, i.e., direct and indirect systems.

Direct systems are the most widespread. The refrigerant circulates from the machinery room to the sales area, where it evaporates in display-case heat exchangers, and then returns in the vapour phase to the suction headers of the compressor racks. The supermarket cold rooms are cooled similarly. R-404A and HCFC-22 are the most used refrigerants for those centralized systems. The refrigerant options table listed several candidates that are being promoted as replacements for R-404A in the large direct expansion supermarket systems.

Among the new technical options in use since about 10 years, CO_2 cascade systems are found in two main architectures. This option has taken a significant uptake in Europe with about 1,600 stores equipped, the installed base being around 20,000 supermarkets with sales area ranging from 400 m^2 to more than 15,000 m^2.

The preferred option for large European commercial companies is HFC-134a at the medium-temperature level (-10 to -15°C) cascading with R-744 direct system for the low temperature (-35 to -38°C), since this is a global option, applicable in all climates.

For cold climates, CO_2 is used at both temperature levels and when the outdoor temperature is higher than 25°C, the CO_2 high-temperature system will operate at high pressure, around 9 to 10 MPa in transcritical operation, which is significantly less energy efficient compared to usual operation in refrigerant condensing mode. The additional cost is again limited to 10 to 15%. The lower energy efficiency for high ambient temperatures constitutes a barrier. In summary, R-744 clearly is an important option for centralised systems in future commercial refrigeration, especially in cascade systems with another refrigerant at the medium temperature level or in trans-critical systems.

10.1.3 Transport Refrigeration

Technical requirements for transport refrigeration systems are extremely complex. The equipment has to operate over a wide range of ambient temperatures and weather conditions (wind, solar radiation, rain, sea water spray, etc.). The equipment has to be able to carry any one of a wide range of cargos with different temperature needs and often even different temperatures simultaneously in different compartments. At the same time acceleration and vibration has to be accommodated.

Refrigerant charges vary from less than 1 kg (refrigerated vans) to more than several kg (trucks, trailers and reefer containers) to 3,000 kg on board large fishing vessels (Schwarz et al., 2011). Leakage rates are estimated at 20% for trucks/trailers, 30% for vans and up to 40% for fishing vessels (Schwarz et al., 2011). All intermodal containers use hermetic or semi-hermetic systems, which have an estimated leakage rate below 5%.

In 2012, three manufacturers of transport refrigeration equipment exhibited concepts of trailer or vans refrigeration units with R-744 at a trade show (Thermoking, 2012; Konvekta, 2012; Carrier, 2011). Although these systems feature several advantages, a detailed comparison with today’s standard equipment, and development leading to market introduction, is yet to be seen. The challenges include reduced energy efficiency under high ambient temperatures, larger physical space requirements, possible higher failure rates associated with circuit complexity, and higher price, at least initially.

The use of hydrocarbons (mainly HC-290) in truck refrigeration units has been tested with a small number of vehicles in the UK, Australia and Germany. If not for flammability concerns, they would be the preferred choice because they can provide lower energy consumption in the order of 20% or more. Recently, a refrigerated truck with propene (HC-1270) was developed by a German company and is now in field tests for a supermarket chain in Germany. The system was reported to be superior to R-404A and comparable to R-410A (Burke, 2011). For a broader market introduction, manufacturers and customers require specific legal rules and standards for hydrocarbons to ensure safety in mobile applications.

Cryogenic or open loop systems, which evaporate liquid CO_2 or N_2 charged to an insulated container aboard the truck, are alternatives to the vapour compression cycle for recurring distribution routes. The systems have advantages of being quiet and reliable. They offer a constant capacity that is independent of the engine (vehicle) speed. On the other hand, systems that discharge CO_2 or N_2 to the cargo box (not all do) bear a risk of asphyxiation if not equipped by gas sensors. They require energy for the liquefaction of the cryogenic liquid, which can make the systems expensive to operate and may result in higher overall greenhouse gas emissions, depending on the energy source used for liquefying CO_2 or N_2.

One Japanese manufacturer has developed a system using ice slurry charged trucks for delivery of chilled goods in large cities with air pollution restrictions. The ice slurry is produced in a stationary refrigeration system and special compartments on board the trucks are charged with ice slurry prior to loading chilled food. Ice slurry can due to its heat of fusion keep truck and food cool for 8 to 10 hours

10.1.4 Large size (industrial) refrigeration

Large size refrigeration systems, often also called industrial refrigeration systems, are characterised by heat extraction rates in the range several 100 kW to 10 MW, typically at evaporating temperatures from –50 °C to +20 °C. About 75% of all large size refrigeration capacity is installed in the food industry, the rest in industrial processes and leisure applications (Schwarz et al., 2011). Over 90% of the large industrial refrigeration installations use R-717 whereas the market share of R-717 is only

5% (India and China) to 25% (Europe and Russia) for smaller industrial refrigeration systems (RTOC, 2010).

Industrial R-717 systems are in general 15% more energy efficient than their HFC-counterparts and 40% of the European industrial refrigeration systems use R-717 (Schwarz et al., 2011). While industrial refrigeration systems using R-717 are very tight due to the pungent smell of R-717, HFC systems in the EU show leakage rates of 8-10% at present (Schwarz et al., 2011).

Applying improvement levers such as reduced condensing temperature, increased evaporation temperature, variable speed compressors and multistage systems, the energy consumption of R-717 plants can be drastically reduced (Gerwen, van, 2011). A replacement of a 3.2 MW HCFC-22 refrigeration system by one using R-717 resulted in 40% reduction of energy consumption (McNeill, 2011). As the new plant utilises heat recovery and water heating by means of an additional heat pump, the total annual cost savings are more than £1.4 million, resulting in a payback time of 2.7 years (McNeill, 2011).

Hydrocarbons are not widely used, other than in situations where safety measures are already required, e.g. in a petrochemical plant or for compact chillers. 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 ammonia systems (RTOC, 2010).

R-744 is used with excellent efficiency in systems as the low temperature stage to a cascaded upper R-717 system especially in the food industry where the refrigerant has to evaporate in freezing equipment in the factory. According to van Gerwen (2011) “the use of R-744 as a refrigerant in the low pressure stage of a cascade refrigeration system, with ammonia in the high stage, could be an opportunity for further improvement”. In colder climates R-744 is energy efficient as the sole refrigerant.

Air can be used with good energy efficiency in low temperature applications, namely below -60 °C. At least one manufacturer is offering such systems (Machida, 2011).

Carbon dioxide can be used in some cases as an alternative to glycol or brine solutions as the heat transfer fluid of indirect R-717 or hydrocarbon systems, offering significant reductions in volume flow rate which gives operating cost reductions of up to 20% (Maratou, 2013) and can also result in installation cost reductions (Rhiemeier, 2009).

10.1.5 Water heating heat pumps

Within the category of water heating heat pumps we have the heat pump water heaters, the space heating heat pumps and combined space and hot water heat pumps.. The required warm water temperature affects the selection of refrigerant. 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 for the purpose to reduce the life-time cost and/or to reduce the impact to the environment. To compete with fossil fuel water heating systems the cost and energy efficiency is most important and has its impact on the selection of the refrigerant.

Most heat pumps commercialised today make use of non-ODS refrigerants. Refrigerants used or R-410A, HFC-134a, R-407C, HC-290, HC-600a, R-717, R-744. The majority of new equipment use R-410A. In some Article 5 countries HCFC-22 is being used as it has favourable thermodynamic properties and high efficiency. To replace HCFC-22 by a non-ODS there are no technical barriers. The technical and process changes related to pressure, lubrication and contamination control are well known. Replacements are commercially available, technically proven and energy efficient. All replacements have a similar or lower environmental impact. R-410A has a slightly higher GWP but the required charge is less than HCFC-22. The issue in high ambient is of less or no importance for water heating heat pumps. The main parameters to select the alternatives and the main issue to switch over from HCFC-22 are the cost effectiveness, economic impact, safe use and easiness of use. Replacements such as HFC-32 and other low-GWP HFC blends are under way to become commercial available.

HFC-134a and HFC blends R-407C, R-417A and R-410A are commercial available solutions, which have the highest grade of safety and easiness to use. R410A is most cost effective for small and medium size systems, while for large systems HFC-134a is most efficient. R-407C and R-417A are, from a design point of view, the easiest alternatives for HCFC-22 but cannot compete with the other HFC-solutions. As R-417A has a quite higher GWP than HCFC-22 it is difficult to propose this solution as environmentally sound.

10.1.6 Air Conditioning

Small self-contained (window, portable, through-the-wall, packaged terminal)

Small Self-Contained (SSC) air conditioners are small capacity air conditioners in which all of the refrigeration system components are contained within a single package. These products have cooling capacities typically ranging from 1.0 kW to 10 kW. This category of products includes window mounted, through-the wall, portable and packaged terminal ACs. Small self-contained ACs are designed to heat or cool single spaces, such as bedrooms, small shops, restaurants and offices.

As discussed in TEAP (2013), R-717 has not and is unlikely to be used in SSC AC systems.

Information regarding the use of R-744 in this type of equipment was provided in TEAP (2013), where only niche type products are available (i.e., ECUs). Estimated costs are likely to be around double that of the baseline products and therefore not considered economically viable in most cases. This is particularly the case for high ambient climates. In fact, the low critical temperature of R-744 that leads to poor performance at high ambient temperatures is what makes it difficult to apply in SSC ACs when good performance at temperatures above 30 ^{o}C are necessary.

Mini-split (non-ducted)

Residential and light commercial air-conditioning is often done with non-ducted split air conditioners. Non-ducted split ACs are widely applied in commercial buildings, schools, apartments and free-standing residences. 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 designs. In cool and cold climates reversible ACs (heat pumps) are gaining market acceptance in some regions and are dominant in others, where they are used primarily for heating but also provide cooling during summer operation.

R-444B is feasible to use in split ACs, for example, to replace HCFC-22 or R-407C, trialling is ongoing and efficiency is comparable (TEAP, 2013). The cost implications should be comparable to that of HCFC-22 and R-407C although probably greater due to the refrigerant cost but nevertheless economically viable. It is not unsuitable for use in high density urban areas and it is otherwise easy to use except the need to training of the service sector in the handling of flammable refrigerants.

The use of single component unsaturated HFCs, such as HFC-1234yf and especially HFC-1234ze(E), have not been seriously considered for single split ACs because their volumetric capacity is much lower than HCFC-22, which implies much bulkier systems and – along with high anticipated refrigerant price – implies a considerable increase in product cost (TEAP, 2013).

Multi-split, split (ducted) and ducted split commercial and non-split air conditioners

This section deals with the alternatives for each of these three sub-categories together as the alternatives and implications are almost the same.

A second type of non-ducted products are multi-split; essentially the same as a single split (as described in 3.6.2) but a single condensing unit may feed two or more indoor units (sometimes, up to 50). Whilst dual indoor unit models may be used for residential applications, this category of split systems is more often used in commercial buildings. As with single splits, multi-splits also offer reversible (heating) options. Variable Refrigerant Flow (VRF) systems are a sub-category of the multi-split non-ducted 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. VRF systems have capacities ranging from 10 kW to over 130 kW.

Ducted, split residential ACs are typically used 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), placed 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. Capacities range from 5 kW to 17.5 kW.

Ducted commercial ACs and heat pumps are manufactured in two forms: split system units which are matched with an indoor air handler/heat exchanger assembly and single packaged units which contain an integral fan and heat exchanger assembly which is connected by means of ducting to the air distribution system of the commercial structure. The majority of ducted commercial packaged ACs and heat pumps are mounted on the roof or outside on the ground of offices, shops, restaurants or institutional facilities. 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. Commercial ducted systems are offered in a wide range of capacities from around 10 kW to over 100 kW.

R-744 is seldom suitable for these systems. For systems which involve lengthy piping (such as multi-split) the cost implications can be significant whereas for packaged systems (such as non-split ducted) the cost implications are less severe. Nevertheless, there is no reason why R-744 systems would be unsuitable for densely populated areas. In these types of systems R-744 has use challenges for the above mentioned reasons and possible requirements for additional servicing skills.

Although feasible in a small proportion of situations, HCs are not used in multi-split and some types of ducted systems due to charge size limitations in occupied spaces (TEAP, 2013). Although they have been applied in a number of development models of split and non-split ducted systems, typically where additional safety measures are applied to reduce the amount of “leakable” charge, extensive application is challenging. Nevertheless, estimated costs are unlikely to be prohibitive, both HC-290 and HC-1270 perform well at high ambients and they are not unsuitable for densely populated areas. However, due to charge amount limitations, they are not easily applicable and require expert consideration as to suitability of cases.

As highlighted in TEAP (2013), the use of single component unsaturated HFCs, such as HFC-1234yf and especially HFC-1234ze(E), have not been seriously considered for multi-split and ducted ACs because their volumetric capacity is low , implying bulkier systems and – along with high anticipated refrigerant price –a considerable increase in product cost. Some exceptions may exist for niche situations in systems intended for regions with very high ambient temperatures.

10.1.7 Chillers

Comfort air conditioning in large commercial buildings and building complexes (including hotels, offices, hospitals, universities, and other central systems) is provided by chillers in most cases. They cool water or other heat transfer fluid (such as a water-antifreeze mixture) that is pumped through heat exchangers in air handlers or fan-coil units for cooling and dehumidifying the air. Chillers also are used for process cooling in commercial and industrial facilities such as data processing and communication centres, electronics fabrication, precision machining, and moulding. District cooling is another application that provides air conditioning to multiple buildings through a large chilled water distribution system, as opposed to air conditioning each building with separate systems. Chiller operation is driven by cooling requirements but provision for heat recovery may be included. The principal components of a vapour-compression chiller are one or more compressors driven by electric motors (or less commonly, engines or turbines using open drive compressors), a liquid cooler (evaporator), a condenser, a refrigerant, a lubrication system, a refrigerant expansion and flow control device, a power handling device (commonly a starter or variable speed electronic drive), and a control and protection unit.

The complete chiller usually is factory assembled and tested; no connection between refrigerant-containing parts is required on site by the installer except for very large chillers which may be shipped as multiple assemblies. Installation is accomplished by connection to water, power, and control systems. Vapour-compression chillers are identified by the type of compressor they employ; centrifugal or positive displacement compressors. Chillers can be further divided according to their condenser heat exchanger type, the most common being water-cooled or air-cooled and less common are evaporatively-cooled condensers and dry coolers.

Positive displacement chillers

Positive displacement chillers include those with reciprocating piston, screw, and scroll compressors. Smaller capacity models tends to be air cooled, which accounts for the majority of chillers, but as the capacity increases above around 350 kW water-cooled models become more frequent. Capacities can exceed several MWs.

R-407C, R-410A and HFC-134a are widely used in positive displacement chillers and can be considered as the baseline options.

R-717 is used fairly widely in reciprocating and screw chillers for refrigeration and air conditioning, is well proven for a variety of applications and provides excellent efficiency (TEAP, 2013). The cost effectiveness becomes favourable as the cooling capacity approaches 200 kW and up to about 6 MW, relative to HCFC-22, thus they tend to be economically viable above a certain capacity. In terms of regions with high ambient temperatures, R-717 chillers can and are used, although the very high discharge temperatures need to be accommodated for through inter-stage and oil cooling. Whether these chillers can be suitable for use in densely populated urban areas depends upon national regulations; some countries have no limits whereas others have limits in the order of several hundreds of kilograms (although this often exceeds the required charge anyway). In principle, R-717 is easily used in chillers, provided the measures identified previously are achieved and that the service sector is suitably trained.

R-744 is now used in reciprocating chillers by many different manufacturers, with good efficiency whilst operating at ambient temperatures not exceeding the critical temperature (around 30 C), thus inferring a preference for water-cooled machines in hotter climates (TEAP, 2013). Due to construction material requirements, R-744 chillers become economically viable at capacities of several hundred kW. There is no reason for it to be unsuitable in densely populated urban environments. Provided engineers are capable of extending their refrigeration knowledge to understand the concepts of transcritical operation and that technicians have received the necessary training, this option is easily used.

Both HC-290 and HC-1270 are produced by a number of manufacturers in Europe and other regions and range from 40 kW to over 1 MW with high energy efficiency (TEAP, 2013). Generally the cost implications of applying HCs in chillers are negligible and can therefore be considered economically viable. There are no reasons why HC-290 and HC-1270 would not be suitable for use in densely populated areas. In principle they are easy to use provided engineers have the capability of considering flammability aspects and that the service sector is appropriately trained to handle flammable refrigerants.

HFC-1234ze(E) is suitable for chillers and has been trialled in systems in Europe, with good efficiency (TEAP, 2013). In principle the price of the equipment should not be affected significantly by design although the price of the refrigerant may have an impact on economic viability. Due to its high critical temperature, it will perform well in warm climates. There is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle flammable refrigerants.

HFC-1234yf is also considered suitable for chillers and has also been trialled, providing comparable efficiency to HFC-134a. In principle the price of the equipment should not be affected significantly by design although the price of the refrigerant may have an impact on economic viability. Due to its high critical temperature, it is likely to perform well in warm climates. There is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle flammable refrigerants.

It is feasible to use HFC-32 in positive displacement chillers with equivalent energy efficiency to the baseline options (TEAP, 2013). Some manufacturers are developing models. It is likely that the cost of equipment will not be affected significantly and thus likely to be economically viable. There is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle flammable refrigerants.

The blends R-444B, R-446A, R-447A and DR-5 could be used as replacements for HCFC-22, R-407C or R-410A in positive displacement chillers that employ reciprocating or scroll compressor technologies. It is not known whether any manufacturers are developing equipment with these alternative refrigerants. Depending upon the price of the refrigerant, the cost of equipment should not be affected significantly and are likely to be economically viable. There is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle flammable refrigerants.

A number of the new mixtures have been tested in chillers. HPR1D compared against R-410A showed a drop in COP and capacity of about 8%, ARM-70 gives a 7% improvement in COP and 11% lower capacity and ARM-32a shows 6% higher COP but a 26% drop in capacity (Schultz and Kujak, 2012). In another evaluation (Schultz and Kujak, 2013a), ARM-32a gives a 6% higher capacity than HCFC-22 but 11% lower COP, whilst LTR4X and LTR6A provide the same capacity but 10% and 19% lower COP, respectively. When compared with R134a in a water cooled chiller, ARM-42a has a marginally lower COP and capacity (Schultz and Kujak, 2013b), but capacity ranges from -1 – +6% and COP from -7 – -3% compared to R134a in an air cooled chiller (Kulankara and McQuade, 2013).

R-450A is also feasible for use in positive displacement chillers and can be used in existing HFC-134a technologies with minor modifications (TEAP, 2013), whilst maintaining adequate efficiency. Due to its high critical temperature, it will perform very well in warm climates. The cost of equipment should be economically viable. There is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle flammable refrigerants.

Similarly, XP-10 is feasible for use in HFC-134a type chillers with only minor modifications, with comparable efficiency (TEAP, 2013). It is not known whether any manufacturers are developing equipment with this refrigerant. There is no reason why it would not be suitable for use in densely populated urban areas and it would in principle be easily used.

Centrifugal chillers

These are chillers, which employ centrifugal compressors with one, two, and three compression stages. They are generally used for air conditioning applications in very large buildings and for district cooling. Centrifugal compressors most commonly are used in water cooled systems, especially those with capacities exceeding 1 MW. Air cooled centrifugal chillers are less common. These chillers operate by using the momentum of a molecule to increase pressure. A simplified description would be that, the lighter the molecule, the higher the chiller speed has to be. Natural substances, lacking the relatively heavy halogens in their structure, thus tend to require a more complex rotor (higher speed, diameter, more stages) than halogenated substances. Consequently, their use so far has been limited.

HFC-134a is used widely in various capacities of centrifugal chillers and is considered to be the baseline refrigerant.

It is not practical to use R-410A and HFC-32 in centrifugal chillers. The thermal conductivity is basically better than HFC-134a, but due to high internal leak flow and high pressure difference with smaller molar mass, the compressor efficiency is not as high as one with HFC-134a or other low pressure refrigerants such as HFC-1234ze(E). In addition, boiling volume is not as high as HFC-134a and HFC-1234ze, so use of R-410A and HFC-32 will result in a larger evaporator. Consequently, the use of high pressure HFCs is very limited and negligible in general centrifugal chillers.

R-717 is seldom used in centrifugal chillers and R-744 is not used in such machines (TEAP, 2013).

HCs are used to a limited extent in centrifugal chillers typically within certain petro-chemical industries (TEAP, 2013), but are not considered further here.

R-718 (water) chillers are in use in several installations in Europe and are now commercially available in Japan in capacities of up to 350 kW using a special axial type compressor. Larger capacities are likely to be available within the next two years. Current products have high energy efficiency. The cost at large-scale production and thus the economic viability is not clear to date. In principle R-718 chillers should perform well under high ambient temperatures and there is no reason for them to be unsuitable in high density urban areas. There are no known limitations and should be easy to apply.

HFC-1234yf is considered suitable for centrifugal chillers and is likely to give comparable efficiency to HFC-134a. In principle the price of the equipment should not be affected significantly by design although the price of the refrigerant may have a significant impact on economic viability. Due to its high critical temperature, it is likely to perform well in warm climates. There is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle flammable refrigerants.

HFC-1234ze(E) is suitable for chillers and has been trialled in systems in various regions, and is expected to offer an efficiency improvement over HFC-134a (TEAP, 2013). Systems should be economically viable provided that the price of the refrigerant is not too high. Due to its high critical temperature, it will perform well in warm climates. There is no reason why it would not be suitable for use in densely populated urban areas and it would be easily used provided the service sector is appropriately trained to handle flammable refrigerants.

HCFC-1233zd(E) is considered as a key alternative in low pressure centrifugal chillers, and should produce efficiency levels slightly better than HCFC-123, both at moderate and high ambient temperatures. It is being trialled in chillers by some manufacturers. Given that this refrigerant has a higher cost than HCFC-123 the cost of chillers would be greater but likely to be economically viable. There is no reason why it would not be suitable for use in high density urban areas and why it would not be easy to apply.

10.1.8 Mobile Air Conditioning

Cars and truck cabins used the same refrigerant CFC-12 from the 1950's to 1992; it was then replaced by HFC-134a, which is still in use everywhere, even with the European ban that should have begun in 2011 for "new model" cars. Dependent on the country, the preferred option is to keep going with HFC-134a or to shift to HFC-1234yf. The uptake of HFC-134a replacement refrigerants did not occur as expected, neither for HFC-1234yf nor for CO_2 (R-744), considered a second option, part of the reason was the allowance of the EU considering new model approvals as "old model" type ones.

For city or long haul buses and also train cabins, choices have always been somewhat more open. They were CFC-12 and HCFC-22, followed later by HFC-134a and R-407C. In Germany, over 50 buses are operated on R-744. The alternative air cycle (Brayton-Joule) technology has been installed on 67 ICE trains with 536 air cycle systems and on several test trains worldwide. One trend is the combination of the MAC with a heat pump function for energy saving heating in colder seasons with already 15 buses in Europe

Cars

The car industry has organised its global production (being more than 60 million vehicles in 2012) with a high level of specialisation. Air-conditioning systems are supplied by tier 1 suppliers that manufacture the complete AC system: heating, cooling and ventilation, as well as the control system. The car companies are interested in a strong competition among their suppliers and the consequence is that the best refrigerant should be a single, unique, and global one. From the carmaker point of view, the refrigerant has to be a commodity in terms of availability and costs. History shows that HFC-134a has been the only refrigerant chosen by all car companies to replace CFC-12, and until recently the expectation was that there will again be a single refrigerant world-wide.

As previously stated, R-744 equipment has seen a number of developments from 2000 to 2010 and several manufacturers reportedly reached "implementation readiness". Tier 1 suppliers as well as car makers have developed several technical options with R-744: internal heat exchangers, external control compressors, micro-channel gas coolers, and evaporators dedicated to R-744. New hoses with ultra-low permeation have also been developed. The interest in and development of R-744 in this sub-sector declined significantly around 2009-2010, as car manufacturers and suppliers concentrated their efforts on HFC-1234yf. In 2013 there has been a renewed interest in R-744 MACs, with several German OEMs announcing their intention to develop such systems (see e.g. www.R744.com, 2013) and some of which stating their preference to stay with HFC-134a until R-744 will have been commercialised. However, to date no global OEM has installed R-744 for automotive air-conditioning,

A number of tests have been performed in hot and cold climates. R-744 has been demonstrated to be similar in efficiency as best in class HFC-134a systems for some experimental fleet vehicles, except when the vehicle is idling and also under high temperature conditions (above 35°C)

The main barriers for R-744 systems have been issues such as costs, reliability and servicing aspects. Even for a series of at least 150,000 R-744 AC systems per year, costs would at least double compared to the baseline, according to Tier 1 suppliers (in the year 2010). The CO_2 option not being a global one, requires two AC systems (one for R-744, another one for HFC-134a) to be mounted on the same assembly line. Two other barrier issues were related to reliability and servicing:

- the shaft of the open-type compressor was a highly potential leak-prone component, this could be technically solved."
- R-744 servicing requires special training and also specific equipment making it necessary to develop a new world-wide servicing network for global car companies.

For electric cars or hybrid cars, electric driven high voltage hermetic compressors can be used. They are currently being developed for cars. Hermetic compressors have no shaft seal and are consequently tighter, which would enhance the R-744 MAC systems reliability. Nevertheless, the cost issue for this type of system needs to be solved. R744 is very efficient in the heat pump mode down to low temperatures as minus 20°C.

Hydrocarbons are efficient refrigerants and, like other refrigerants, have to be chosen according to their condensing and evaporating pressures. Safety concerns are a clear and strong barrier against the use of HCs in cars. During the competition between R-744 and HFC-152a, HFC-152a received a very strong opposition from the German car-makers that are vehemently against any use of flammable refrigerants in cars.

The sales of HC blends for car AC systems for the aftermarket will continue in some countries, but this does not constitute a global trend and will not receive the support of any carmaker. In conclusion, HCs are not at present a global option for car AC systems.

Because of the flammability issue, two low-GWP non-flammable blends “Blend H” and “DP-1” have been proposed by chemical manufacturers in 2003. Blend-H failed for reason of decomposition issues and because the fire extinguishing component is an ODS and classified as mutagenic. Additionally, as of 2011, other blends have been proposed, in particular AC-5 and AC-6, which are currently being evaluated by an SAE International Cooperative Research Program.

HFC-1234yf , even if slightly flammable, is seen as the global solution for the car industry medium-sized manufacturing plant has started operation and is supplying some models built primarily in Europe, Japan, and the United States. However, if HFC-1234yf is to be a global solution for the entire industry, additional production capacity will be needed. HFC-1234yf is now being implemented in several models, especially in Europe, where the regulation requires refrigerants with a GWP < 150 for new model cars since 2011, although enforcement of the requirement was delayed until 2013 while chemical production capacity was being installed. The change from HFC-134a to HFC-1234yf seems to be one of the likely options because the car industry favours global options for AC systems. The preference of companies outside Germany would be to change to HFC-1234yf. It can be mentioned that HFC-1234yf is currently available to some extent and the first cars using this refrigerant are therefore in production now.

Its thermodynamic properties are very close to those of HFC-134a and so the adaptation is easy requiring on mechanically driven systems only minor changes to prevent any risk related to its very low flammability while the impact on electrically driven system is under investigation to evaluate the risk related with high voltages.

German car manufacturers in 2012 raised again the issue of HFC-1234yf flammability and postponed its introduction in their assembly lines, until a separate safety assessment would have been conducted. Since then, two separate studies have been completed. Another Cooperative Research Program by the SAE confirmed previous conclusions that HFC-1234yf could be used safely for automotive air conditioning. Germany's Federal Motor Transport Authority KBA concluded that HFC-1234yf was inherently more dangerous than HFC-134a under severe conditions, whereas in the cases studied by KBA there was insufficient evidence for an immediate action under the European product safety law. The KBA strongly recommended further investigations of the HFC-1234yf use and confirmed the car producers' responsibility for the safety of their products."

Many tests have been performed on HFC-1234yf and some adaptations on the suction line diameter and on the heat-exchanger tuning have been done in order to match HFC-134a energy performances. Developments have been made and no significant differences are measured compared to the best in class HFC-134a systems. The cost of the chemical is announced to be up to 10 times more than that of HFC-134a, but it is known that, in the chemical industries, prices could vary from 1 to 10 depending on the sales volume. One OEM implementing this refrigerant stated that the total cost of the system, including the chemical and other components, was $75 more than an HFC-134a system.

The mass-production of HFC-1234yf has been delayed up to the beginning of 2014 based on current information. Due to the slow uptake of HFC-1234yf, even in Europe, HFC-134a is currently charged in most new AC systems. HFC-134a AC systems are the bench mark technology for all alternatives. The cost is also the reference for mass produced AC systems with a strong competition among Tier 1 suppliers. Obviously the only barrier is its GWP. It is likely that HFC-134a will be replaced under different schedules in the various world regions.

Public transport

AC systems of both trains and buses are similar and are produced in small series of some hundreds per year. The cooling capacities vary from 10 to 35 kW depending on the size of the bus or the train car. Due to the small market of this application, technologies in use are coming from stationary air-conditioning industry for heat exchangers. For buses, compressors are open-type compressors driven by the engine as for the car AC system. For trains, compressors are electrically-driven hermetic compressors. The refrigerant choice could therefore be different for those applications.

Carbon dioxide has been developed in Germany since 1996 by one company and the total fleet is about 50 city buses. In moderate climates, R-744 performs well and lessons learned from several years of experiences do not show significant troubleshooting. Another German manufacturer proposes and sells R-744 based AC systems for trains. Different test bench and field tests were done with R-744 based AC systems. The energy efficiency under German climate conditions appears to be in the same range as for the reference refrigerant HFC-134a. For high ambient conditions, the energy efficiency is lower at equal design efforts. The main barrier is related to costs, design habits and also the required sophisticated designs for hot climates. R-744 systems as developed for refrigerated transport by companies also manufacturing the “usual” HFC based AC systems for buses and trains, may trigger the change to R-744 systems for buses and trains.

In conclusion, AC systems for buses and trains are a niche application. New developments with R-744 will be a consequence of developments in larger market application and regulatory constraints.

HCs are not applicable in trains and buses due to safety issues for public transportation.

The HFC-1234yf development for car AC systems will have direct consequences for bus and train AC systems currently operated on HFC-134a. The shift can be done, based on first lessons learned in the car industry. For train AC systems, the use of R-407C or the use of new blends containing the chemicals HFC-1234yf or HFC-1234ze(E) could be proposed in the near future.

As mentioned for car AC systems, the energy efficiency can be as good as the reference line with HFC-134a, based on simple adaptations taking into account thermodynamic properties of HFC-1234yf. The refrigerant cost, although greater than the usual price, is not a strong barrier, because its cost represents less than 1% of the total cost of those AC systems. The current barrier is related to the fact that no current regulation constraints exist. The change from HFC-134a to HFC-1234yf is a relatively easy option, as well as the possible shift from R-407C to new low GWP blends.

Air systems based on the reverse Brayton–Joule cycle with air compressors and turbines are standard systems for aircraft Air Conditioning systems. Air Cycle AC systems have become standard in aerospace application, because of the low complexity of the system architecture leading to high reliability and operational robustness and the ability of the air cycle system to overcome the high differential pressure between the ambient and the cabin. The difference between airplanes and trains is the outdoor temperatures (-50°C for airplanes). The efficiency of air cycle systems is lower compared to vapour compression systems at the peak performance point. For high ambient temperatures, the cooling capacity is decreasing rapidly. For moderate climates, air systems are possible. Advantages of air cycle AC systems are the absence of a refrigerant and the lower life cycle cost due to the high reliability and robustness of the system architecture. The German Railway (Deutsche Bahn) considers air cycle systems more advantageous based on the successful operation of air cycle systems in the 3rd generation of ICE trains.

Currently, the two dominant refrigerants are HFC-134a and R-407C in developed countries and HFC-134a and HCFC-22 in developing countries. R-407C is often chosen for train cars, due to the inherent compactness of the AC system to be integrated in the roof of the train car. Barriers are based on the GWP of those refrigerants, even if those applications could be exempted of using low-GWP refrigerants for another couple of years in Europe. Within the next 10 years, R-407C is expected to be replaced by all the different alternatives previously mentioned.

While the current HFCs could be used for a long period in train and bus niche applications, the shift from these high-GWP refrigerants to alternatives will be related to the overall developments in stationary AC systems.

10.2 Foams

10.2.1 Polyurethane appliances

In the strictest sense, this sector covers both domestic and commercial appliances, although the major trends characterised in this section of the chapter will be related to the larger, and more homogeneous, domestic sector. However, the statistical information presented graphically will cover both groups of appliances.

(a) Commercially available alternatives to Ozone Depleting Substances

The Task Force Report in response to Decision XXIII/9 provided a full list of HCFC replacement options and offered a summary of the pros and cons of each option, as well as some additional commentary on critical aspects for decision-making in the appliance sector. Decision XXIV/7 has requested that the commercially available options and the alternatives under development (emerging options) be treated separately. Therefore, the Decision XXIV/7 Report tables have been reconstituted and updated accordingly.

HCFC REPLACEMENT OPTIONS FOR APPLIANCES (DOMESTIC & COMMERCIAL), TRUCKS & REEFERS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Domestic refrigerators/freezers			
Cyclopentane & cyclo/iso blends	*Low GWP*	*Highly flammable*	*High incremental capital costs but most enterprises in sub-sector are large*
	Low operating costs		*Global industry standard*
	Good foam properties		
Saturated HFCs (HFC-245fa)	*Non-flammable*	*High GWP*	*Low incremental capital costs*
	High operating costs		*Improved insulation (cf. HC)*
	Good foam properties		*Well proven technology*
Commercial refrigerators/freezers plus vending equipment			
Cyclopentane & cyclo/iso blends	*Low GWP*	*Highly flammable*	*High incremental capital cost, may be uneconomic for SMEs*
	Low operating costs		*Well proven technology*
	Good foam properties		
HFC-245fa, HFC-365mfc/227ea	*Non-flammable*	*High GWP*	*Low incremental capital cost*
	Good foam properties	*High operating costs*	*Improved insulation (cf. HC)*
O_2 (water)	*Low GWP*	*Moderate foam properties – high thermal conductivity & high foam density*	*Low incremental capital cost*
	Non-flammable	*High operating costs*	*Improved formulations (second generation) claim no need for density increase vs HFC co-blown*
Methyl Formate	*Low GWP*	*Moderate foam properties -high thermal conductivity & high foam density-*	*Moderate incremental capital cost (corrosion protection recommended)*
	Flammable although blends with polyols may not be flammable	*High operating costs*	
Refrigerated trucks & reefers			
Cyclopentane & cyclo/iso blends	*Low GWP*	*Highly flammable*	*High incremental capital cost, may be uneconomic for SMEs*
	Low operating costs		
	Good foam properties		
HFC-245fa, HFC-365mfc /227ea	*Non-flammable*	*High GWP*	*Low incremental capital cost*
	Good foam properties	*High operating costs*	*Improved insulation (cf. HC)*
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity & high foam density-*	*Low incremental capital cost*
	Non-flammable	*High operating costs*	*Not used in reefers*

The assessment of these alternatives against the criteria of commercial availability, technical proof of performance, environmental soundness (encompassing efficacy, health, safety and environmental characteristics), cost effectiveness (capital and operating) and processing versatility in challenging ambient conditions is, in itself, a challenging objective. Typically, performance against such criteria can only be judged fully on a case-by-case basis and assessments made at a higher level will only be indicative. With this in mind, the following table seeks to give such an indicative assessment based on a nominal ranking of seven categories from '+++' (the best) to '---' (the worst):

	c-pentane	i-pentane	HFC-245fa	HFC365mfc/227ea	CO_2(water)	Methyl Formate
Proof of performance	+++	+++	+++	++	+	+
Flammability	---	---	++	+(+)	+++	--
Other Health & Safety	0	0	+	+	-	0
Global Warming	+++	+++	--	---	++	++
Other Environmental	-	-	0	0	++	-
Cost Effectiveness (C)	--	---	++	++	++	0
Cost Effectiveness (O)	++	+++	--	--	+	+
Process Versatility	++	++	++	+	0	0

As has been noted in previous reports, the mix of performance properties (technical, economic and environmental) does not lead unambiguously to one single selection. Indeed, the proliferation of blends across the whole of the foam sector and nowhere more so than the appliance sector is an indication of the reality that there is no single best solution. Often a key factor is the size of the manufacturing plant, since the economies of scale have a considerable bearing on the relative importance of capital and operational costs. Cost also is a major factor in the consideration of the major emerging technologies.

(b) Emerging Alternatives

As noted in the 2012 Task Force Report in response to Decision XXIII/9, the major emerging technologies in the appliance sector are based mostly around liquid unsaturated HCFCs/HFCs. These are all fairly similar in their properties and all seem to suggest a stepwise improvement in thermal performance over other low-GWP alternatives. The following table provides an overview of the 'pros' and 'cons' of these technologies.

HCFC REPLACEMENT OPTIONS FOR APPLIANCES (DOMESTIC & COMMERCIAL), TRUCKS & REEFERS			
SECTOR/OPTION	*PROS*	*CONS*	*COMMENTS*
Domestic refrigerators/freezers			
Unsaturated HFC/HCFCs (HFOs)	*Low GWP*	*High operating costs*	*Successful commercial trials; first expected commercialization in 2013*
	Non-flammable		*Promising energy efficiency performance: equal or better than saturated HFCs*
			Low incremental capital cost
Commercial refrigerators/freezers plus vending equipment			
Liquid Unsaturated HFC/HCFCs (HFOs)	*Low GWP*	*High operating costs*	*First expected commercialization in 2013*
	Non-flammable		*Promising energy efficiency performance: equal or better than saturated HFCs*
			Low incremental capital cost
Refrigerated trucks & reefers			
Liquid Unsaturated HFC/HCFCs (HFOs)	*Low GWP*	*High operating costs*	*First expected commercialisation in 2013*
	Non-flammable		*Promising energy efficiency performance: equal or better than saturated HFCs*
			Low incremental capital cost

The range of unsaturated HCFCs/HFCs has been reduced from the selection provided in the Decision XXIV/7 Report. The disclosure of the molecule behind Arkema's code name AFA-L1 has now occurred and revealed it as they same molecule being developed and commercialised by Honeywell. However, the following table provides an analysis of these new molecules against the criteria considered for the commercially available alternatives based on limited experience in appliance sector trials.

	HFO-1234ze(E)	*HFO-1336mzzm(Z)*	*HFO-1233zd(E)*
	Gaseous	*liquid*	*liquid*
Proof of performance	+	++	++
Flammability	++	+++	+++
Other Health & Safety	+	+	+
Global Warming	+++	+++	+++
Other Environmental	+	+	+
Cost Effectiveness (C)	++	++	++
Cost Effectiveness (O)	--	--	--
Process Versatility	+	+	+

(c) Barriers and restrictions

As noted above, the commercialisation time-line and global availability of the various unsaturated HCFCs/HFCs will have a considerable bearing on their widespread adoption under the HCFC Phase-out Management Plans currently being enacted. Two of the three potential manufacturers are committing to timelines of 2015 or better, but the supply/demand curves for these alternatives are still not fully understood.

One factor in the adoption of these new technologies is the potential use of blends of unsaturated HFCs/HCFCs with hydrocarbons to achieve intermediate thermal performance benefits at affordable cost. If the compromises made are too great, then the benefits will be too marginal to justify transition from existing hydrocarbon solutions where they are already in place, and to prefer unsaturated HCFC/HFC solutions over hydrocarbon where they are not. However, with the cost of these new compounds not completely established at this point, it is not clear whether solutions maximising the thermal performance benefits will be affordable.

For those still using HCFC-141b, one strategy being considered in the case of some manufacturers is to make an intermediate transition to a high-GWP (lower investment) technology option such as saturated HFCs on the written understanding that a further transition to a low-GWP option will follow within a specified period. The choice would be left open until such time as optimum technology approaches have been established.

For transitions directly from HCFC-141b to hydrocarbons, there are potential strategies to reduce the investment costs for smaller enterprises. These include the potential for using pre-blended mixes containing cyclo-pentane. However, this approach is not expected to impact the domestic appliance sector too greatly, since economies of scale would generally support a more comprehensive conversion strategy. However, in the case of some manufacturers of commercial appliances (e.g. vending machines), there may be more relevance. Further information is covered under Section 3.4. (c).

10.2.2 Polyurethane Boardstock

This is one of the largest markets for rigid polyurethane foams in non-Article 5 Parties, but has only recently started to grow significantly in Article 5 Parties as requirements for building energy efficiency have increased. The historical analysis therefore focuses primarily on the non-Article 5 experiences.

(a) Commercially available alternatives to Ozone Depleting Substances

Again, drawing from the evaluations conducted for Decision XXIV/7 with relevant updates where necessary, the following table illustrates the commercially available options for the polyurethane boardstock sector.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	*PROS*	*CONS*	*COMMENTS*
Boardstock – continuously produced			
Cyclopentane & n-Pentane	*Low GWP*	*Highly flammable*	*High incremental capital costs but most enterprises in sub-sector are large*
	Low operating costs		*Industry standard*
	Good foam properties		
HFC-245fa, HFC-365mfc/277ea	*Non-flammable*	*High GWP*	*Low incremental capital cost*
	Good foam properties	*High operating costs*	
			Improved insulation (cf. HC)

In general, saturated HFCs have shown little uptake in most PU Boardstock markets because the hydrocarbon-based products have been shown to be fit-for-purpose at a more competitive cost. Since new capacity in the industry can accommodate hydrocarbon process safety issues at the design stage, the high incremental capital costs associated with later transitions can be mitigated to some extent.

As building energy standards increase, there could be increasing pressure for better thermal efficiency, especially where space is limited and product thickness is constrained. There has therefore been some interest in possible blends of hydrocarbons with saturated HFCs. Indeed, it is suspected that some manufacturers may have adopted this strategy commercially, although it is difficult to track because no further plant modifications would normally be necessary. Such trends may also be short-lived, since there is increasing market pressure (e.g. through LEED and other environmental building schemes) to avoid the use of saturated HFCs.

According to the chosen criteria, the relative performance of alternative technology solutions in this sector can be summarised as follows:

	c-pentane	***n-pentane***	***i-pentane***	***HFC-245fa***	***HFC365mfc/227ea***
Proof of performance	+++	+++	+++	++	++
Flammability	---	---	---	++	+(+)
Other Health & Safety	0	0	0	+	+
Global Warming	+++	+++	+++	--	---
Other Environmental	-	-	-	0	0
Cost Effectiveness (C)	--	--	--	++	++
Cost Effectiveness (O)	++	+++	+++	--	--
Process Versatility	++	++	++	++	+

The slight environmental concerns reflected for hydrocarbon options relate to some emerging concerns about local VOC regulations. In some regions there are exemptions for thermal insulation manufacturing plants, but this approach is not universal.

(b) Emerging alternatives

The market pressure on saturated HFCs outlined in the previous section opens up the possibility for hydrocarbon blends with unsaturated fluorocarbons (both HCFCs and HFCs). The uncertainty of cost makes this option even less clear cut for PU Boardstock than it is for domestic appliances.

Nonetheless, there continues to be sufficient interest in the option to justify its inclusion in this section as an emerging technology – albeit as a blend with hydrocarbons.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	PROS	CONS	COMMENTS
Boardstock – continuously produced			
Liquid Unsaturated HFC/HCFCs (HFOs)	*Low GWP*	*High operating costs*	*First expected commercialization in late 2013*
	Non-flammable		*Trials in progress, particularly with blends*
			Low incremental capital cost

The overall assessment of the criteria for unsaturated HCFCs/HFCs is very similar to that shown for PU appliances.

	HFO-1234ze(E)	HFO-1336mzzm(Z)	HFO-1233zd(E)
	Gaseous	*Liquid*	*liquid*
Proof of performance	+	++	++
Flammability	++	+++	+++
Other Health & Safety	+	+	+
Global Warming	+++	+++	+++
Other Environmental	+	+	+
Cost Effectiveness (C)	++	++	++
Cost Effectiveness (O)	--	--	--
Process Versatility	+	+	+

The only potential difference is that the use of a gaseous option being used in the PU Appliances sector is less likely than for PU Boardstock. Nevertheless, it has been retained for completeness.

(c) Barriers and restrictions

In practice, the quantity of PU Boardstock foam still using HCFCs is very limited and this fact alone testifies to the lack of barriers to appropriate transition. As noted earlier, much of the new capacity in the sector has been installed since the ozone issue emerged and the necessary requirements for hydrocarbon have typically been designed in.

The only likely transition pressure now emerging relates to the on-going goal of improved thermal efficiency. The major barrier to the adoption of blends of saturated HFCs with hydrocarbons is market pressure, while the potential barrier to the wider use of unsaturated HFCFs/HFCs is one of cost and, in the short term, availability.

10.2.3 Polyurethane Panels

In the context of this analysis, the primary panels being referred to are steel-faced and either continuously or discontinuously produced. The market for such panels has developed very differently in various regions of the world, with the early adoption being mostly in Europe. However, the prefabricated approach to building that these panels allow is becoming increasingly widespread globally and manufacturing capacity has continued to grow to meet the need.

(a) Commercially available alternatives to Ozone Depleting Substances

The following table illustrates the main commercially available alternatives in the panel sector.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Steel-faced panels – continuously produced			
Cyclopentane & n-Pentane	*Low GWP*	*Highly flammable*	*High incremental capital costs but most enterprises in sub-sector are large*
	Low operating costs		*Industry standard*
	Good foam properties		
HFC-245fa, HFC-365mfc/277ea	*Non-flammable*	*High GWP*	*Low incremental capital cost*
	Good foam properties	*High operating costs*	
			Improved insulation (cf. HC)
Steel-faced panels – discontinuously produced			
Cyclopentane & n-Pentane	*Low GWP*	*Highly flammable*	*High incremental capital cost, may be uneconomic for SMEs*
	Low operating costs		
	Good foam properties		
HFC-245fa, HFC-365mfc/277ea, HFC-134a	*Non-flammable*	*High GWP*	*Low incremental capital cost*
	Good foam properties	*High operating costs*	*Improved insulation (cf. HC)*
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity-*	*Low incremental capital cost*
	Non-flammable		
Methyl Formate/Methylal	*Low GWP*	*Moderate foam properties - high thermal conductivity-*	*Moderate incremental capital cost (corrosion protection recommended)*
	Flammable although blends with polyols may not be flammable		

As noted earlier, the pressure for improved thermal performance in the architectural (cladding) panel is less pronounced than it is for other building insulation types because of the structural requirements which are associated with that application. However, the same cannot be said for refrigerated transport where additional benefits in thermal performance can improve the load-carrying capacity of a vehicle. Therefore, there is on-going interest in saturated HFCs as legitimate alternatives, or at least components of blends for that application.

In the discontinuous sector, there are other potential technologies based around CO_2 (water) and HCOs such as methyl formate or methylal. These reduce the perceived risks associated with the use of hydrocarbons on discontinuous plants but do result in some compromises in foam properties including higher density and potentially poorer thermal performance. Nonetheless, they do offer low-GWP solutions in markets, which may not be too sensitive to thermal performance issues.
These are all important considerations in the Article 5 context where the need to phase-out HCFCs requires the widest range of alternatives, especially for small and mixed use discontinuous panel facilities. The strengths and weaknesses of these alternatives are once again shown in the following table – this time relating to the panel sector.

	c-pentane	i-pentane n-pentane	HFC-245fa	HFC365mfc/227ea	CO_2(water)	Methyl Formate
Proof of performance	+	++	++	++	++	+
Flammability	---	---	++	+(+)	+++	--
Other Health & Safety	0	0	+	+	-	0
Global Warming	+++	+++	--	---	++	++
Other Environmental	-	-	0	0	++	-
Cost Effectiveness (C)	--	---	++	++	++	0
Cost Effectiveness (O)	++	+++	--	--	+	+
Process Versatility	++	++	+	++	+	+

(b) Emerging alternatives

Again, the major emerging alternatives are unsaturated HCFCs/HFCs. In view of the relative abundance of commercially available alternatives, these blowing agents are likely to be focused on niche markets in the panel sector.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Steel-faced panels – continuously produced			
Liquid Unsaturated HFC/HCFCs (HFOs	*Low GWP*	*High operating costs*	*First expected commercialization in 2013*
	Non-flammable		*Trials in progress*
			Low incremental capital cost
Steel-faced panels – discontinuously produced			
Liquid Unsaturated HFC/HCFCs (HFOs	*Low GWP*	*High operating costs*	*First expected commercialization in 2013*
	Non-flammable		*Trials in progress*
			Low incremental capital cost

In principle, unsaturated HCFCs/HFCs offer opportunities for improving thermal performance while retaining a low-GWP blowing agent. For reasons stated in respect of other foam sectors, the cost of these blowing agents is still uncertain and could prevent reliance on them in isolation. That said, the added value of a panel is certainly greater than that of Boardstock, so the ability to adsorb cost could be greater in this sector. Nevertheless, the most likely approach will be the adoption of blends with hydrocarbons provided that an incremental improvement in thermal performance can be achieved. This will be particularly important for the thermally sensitive applications such as refrigerated transport. The proof of performance is at a lower level in this sector than elsewhere and this is reflected in the following table:

	HFO-1234ze(E)	HFO-1336mzzm(Z)	HFO-1233zd(E)
	gaseous	*liquid*	*liquid*
Proof of performance	0	+	+
Flammability	++	+++	+++
Other Health & Safety	+	+	+
Global Warming	+++	+++	+++
Other Environmental	+	+	+
Cost Effectiveness (C)	++	++	++
Cost Effectiveness (O)	--	--	--
Process Versatility	+	+	+

(c) Barriers and restrictions

The major barriers to the substitution of alternatives in the panel sector are not primarily related to the technologies available but to the wide range of enterprises involved (both in size and location) and the broad spectrum of applications served. Versatility is a key necessity for any technology in the discontinuous sector, but no single solution has emerged as being as versatile as the ozone depleting substances replaced. This may act as a deterrent to early phase-out of the remaining HCFC use in Article 5 enterprises where local requirements need to be matched.

10.2.4 Polyurethane Spray

Polyurethane spray foam has been used for many years as an efficient means of insulating structures which would be difficult to insulate in other ways, because of shape or location An example would be that of an insulated road tanker. Another would be the insulation of large flat roofs, which may not be as flat as might be presumed! More recently, however, polyurethane spray foams have emerged as a vital component of renovation strategies for existing buildings. Again, the efficiency and versatility of application, as well as the relative durability and thermal efficiency are all characteristics, which have contributed to the rapid growth of PU spray foam in both developed and developing regions.

(a) Commercially available alternatives to Ozone Depleting Substances

The commercially available technologies have been largely referenced already in the narrative, but can be summarised as follows:

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Spray foam			
Cyclopentane & n-Pentane	*Low GWP*	*Highly flammable*	*Unsafe to use in this application*
HFC-245fa, HFC-365mfc/277ea	*Non-flammable*	*High GWP*	*Industry standard*
	Good foam properties	*High operating costs but improved by using mixed HFC/ CO_2 (water)*	
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity & high density-*	*Extra thickness leading to a cost penalty*
	Non-flammable		
Methyl Formate	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*Safety concerns when used for this application*

It is important to note that the impacts of the saturated HFCs have been reduced by co-blowing with major drivers has been to reduce cost. As will be seen later in this sub-section this may be an important approach for the future.

HCOs (most notably methyl formate) have also been used for some PU spray work. The potential of supplying the system to site as blended polyol is believed to contribute to the management of risk, but it is still unclear whether the hazards seen with hydrocarbons in confined spaces have been avoided using the slightly less flammable methyl formate. Work continues in this area, although some systems are already being used commercially. The performance of these ODS alternatives against the criteria for this report can be summarised as follows:

	HFC-245fa	*HFC365mfc/227ea*	*Super-critical CO_2*	*CO_2(water)*	*Methyl Formate*
Proof of performance	+++	+++	++	++	+
Flammability	++	+(+)	++	+++	--
Other Health & Safety	+	+	+	-	0
Global Warming	--	---	++	++	++
Other Environmental	0	0	+	++	-
Cost Effectiveness (C)	++	++	0	++	0
Cost Effectiveness (O)	--	--	+	++	++
Process Versatility	++	++	+	+	+

(b) Emerging alternatives

Alongside the appliance sector, the PU spray foam sector is attracting the most interest for potential adoption of the unsaturated HCFCs/HFCs. The rapid growth rate for the sector overall, the absence of serious low-GWP contenders and the fact that relatively high emission rates make the climate impact more immediate all align to encourage the manufacturers to focus on this application.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Spray foam			
Liquid Unsaturated HFC/HCFCs (HFOs	*Low GWP*	*High operating costs but improved by using mixed HFC/ CO_2 (water)*	*First expected commercialization from 2013*
	Non-flammable		*Trials in progress*
			Low incremental capital cost

The cost of the alternatives remains the key question but this consideration is slightly diffused by the fact that the CO_2 (water) technology developed around HFC-245fa and HC-365mfc/227ea looks transferable to the unsaturated blowing agents as well. Manufacturers are in the process of field trials and the development of fairly sophisticated life cycle assessments to ensure that they have assessed the environmental impacts correctly. The co-blowing solution does not detract significantly from the overall thermal performance of the foam and the introduction of a low-GWP solution of this type would clear the way for widespread use of PU spray foam in a wide variety of refurbishment applications over the next 30-50 years as global attention focuses increasingly on building energy efficiency in existing stock. However, there are emerging concerns about the potential stability of the gaseous unsaturated blowing agents in low-pressure, pre-blended formulations. This is the subject of intense further development work, but no immediate solution has so far been forthcoming. The following table has been updated accordingly.

	HFO-1234ze(E)	***HFO-1336mzzm(Z)***	***HFO-1233zd(E)***
	gaseous	*liquid*	*Liquid*
Proof of performance	0	+	+
Flammability	++	+++	+++
Other Health & Safety	+	+	+
Global Warming	+++	+++	+++
Other Environmental	+	+	+
Cost Effectiveness (C)	++	++	++
Cost Effectiveness (O)	--	--	--
Process Versatility	+	+	+

(c) Barriers and restrictions

Since the future of the sector rests largely on the emerging technologies, the main barriers relate to the stability, economics and availability of the unsaturated blowing agents. Much of the PU spray foam activity in China remains reliant on HCFC-141b and there is reluctance to make a transition to a sub-optimal solution when an emerging technology could out-perform it within 5 years. Various strategies are being considered including a two-step option via saturated HFCs. However, there is a need to gain commitment to the second conversion at the outset.

10.2.5 Polyurethane In-situ/Block

One of the enduring advantages of polyurethane chemistry in general, and polyurethane foams in particular, is their ability to meet a broad range of applications. Since these applications can be diverse, ranging from cavity filling (e.g. buoyancy on leisure boats) to the fabrication of complex shapes required for pipe and flange insulation, the in-situ and block processes provide a resource to meet these needs. Self-evidently, these applications are also difficult to track in any organised way since they vary so much. Nevertheless, it is possible to track the manufacturing facilities that provide these products and services.

(a) Commercially available alternatives to Ozone Depleting Substances

The commercially available alternatives to HCFCs in the in-situ and block sectors are summarised in the following table:

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Insulated pipes (pipe-in-pipe for district central heating systems)and other in-situ systems			
Cyclopentane	*Low GWP*	*Highly flammable*	*High incremental capital cost*
	Low operating costs		*Industry standard*
	Good foam properties		
HFC-245fa, HFC-365mfc/277ea	*Non-flammable*	*High GWP*	
	Good foam properties	*High operating costs*	
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity-*	
	Non flammable		
Block foams for various applications including panels, pipe insulation section, etc			
Cyclopentane & n-Pentane	*Low GWP*	*Highly flammable*	*High conversion costs, may be uneconomic for SMEs*
	Low operating costs		*Well proven technology*
	Good foam properties		
HFC-245fa, HFC-365mfc/277ea	*Non-flammable*	*High GWP*	*Low conversion costs*
	Good foam properties	*High operating costs but improved by using mixed HFC/ CO_2 (water)*	
CO_2 (water)	*Low GWP*	*Moderate foam properties -high thermal conductivity & poor ageing-*	*Extra thickness leading to a cost penalty*
	Non flammable		

As with other thermal insulation sectors, saturated HFCs are used in block foams with a CO_2 (water) co-blowing agent to limit climate impact and also to optimise the cost/performance relationship. It has generally been found that levels of saturated HFC can be lowered in these formulations to around 50-60% of the blowing agent mix without having a detrimental effect on thermal performance. The blowing agent criteria for block and in-situ foams are shown below. In some instances, more than one rating is providing reflecting the fact that there is a disparate set of processes represented in this category.

	c-pentane	n-pentane	HFC-245fa	HFC365mfc/227ea	CO_2(water)
Proof of performance	+/++	+/++	++	++	++
Flammability	---	---	++	+(+)	+++
Other Health & Safety	0	0	+	+	-
Global Warming	+++	+++	--	---	++
Other Environmental	-	-	0	0	++
Cost Effectiveness (C)	--	---	++	++	++
Cost Effectiveness (O)	++	+++	--	--	+
Process Versatility	++	++	++	++/+++	+/++

(b) Emerging alternatives

In this instance, the Task Force has chosen to categorise methyl formate and methylal in the emerging alternative category. This reflects the fact that some of the applications across the sector have yet to be trialled using this HCO blowing agent. There are expected to be some limitations based on densities achievable and risks of corrosion with some equipment, but the availability of a relatively low cost, low-GWP solution with lower flammability than the pentanes may still prove of relevance for the sector going forward.

HCFC REPLACEMENT OPTIONS FOR PU FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Block foams for various applications including panels, pipe insulation section, etc			
HCO (Methyl Formate/Methylal)	*Low GWP*	*Higher density required*	*Density increase necessary through role of MF as a solvent*
Liquid Unsaturated HFC/HCFCs (HFOs	*Low GWP*	*High operating costs*	*Trials in progress*
	Non-flammable		

The option of liquid unsaturated HCFCs/HFCs in this sector is legitimate, but there is some concern that price and geographic availability may be significant limiting factors. Again, co-blowing with CO_2 (water) may prove helpful for cost reasons, but uptake is expected to be more limited than in other sectors of the foam industry. The following table shows an assessment against the report criteria:

	Methyl Formate	HFO-1336mzzm(Z)	HFO-1233zd(E)
		Liquid	*liquid*
Proof of performance	0/+	++	++
Flammability	--	+++	+++
Other Health & Safety	+	+	+
Global Warming	+++	+++	+++
Other Environmental	+	+	+
Cost Effectiveness (C)	++	++	++
Cost Effectiveness (O)	--	--	--
Process Versatility	+	++	++

(c) Barriers and restrictions

One of the major barriers to transition in this sector is the size and location of the enterprises involved. The provision of sophisticated low-GWP alternatives does not extend easily to these more diffuse networks and the effectiveness of transitions relies massively on the competence and commitment of the systems houses supplying the small and micro-enterprises. Efforts are needed to raise the profile of these operations with blowing agent technology providers and their supply networks.

10.2.6 *Polyurethane Integral Skin*

Integral skin foams are the one group of foams, which are not primarily used for thermal insulation purposes. They sub-divide into two types – 'rigid integral skin' (typically items such as steering wheels in automobiles) and 'flexible integral skin' (typically covering items such as shoe soles and some packaging foams). As the name suggests, the primary feature of integral skin products is their ability to encapsulate a relatively low density core (for weight saving purposes) with an integrated skin which is made from the same material and in the same process. As a polymer, polyurethane is particularly versatile in forming a resilient skin when moulded and this provides a level of utility which is rarely seen in other product types.

(a) Commercially available alternatives to Ozone Depleting Substances

The following table lists the commercially available options as of today:

HCFC REPLACEMENT OPTIONS FOR INTEGRAL SKIN PU FOAMS FOR TRANSPORT & FURNITURE APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Integral skin foams			
CO_2 (water)	*Low GWP*	*Poor skin quality*	*Suitable skin may require* in-mould-coating – *added expense*
	Low conversion costs		*Well proven in application if skin acceptable*
n-Pentane	*Low GWP*	*Highly flammable*	*High conversion costs, may be uneconomic for SMEs*
	Low operating costs		*Low operating costs*
	Good skin quality		*Well proven in application*
Shoe-soles			
CO_2 (water)	*Low GWP*		*Well proven in application with polyester polyol technology*
	Low conversion costs		
	Skin quality suitable for sports shoe mid-soles		
HFC-134a or HFC-245fa	*Used to give required skin in town shoes*	*High GWP/Cost*	

The specific ranking of these blowing agent options is shown in the table below.

	n-pentane	***HFC-134a***	***HFC-245fa***	***CO_2(water)***
Proof of performance	++	++	+	++
Flammability	---	+++	++	+++
Other Health & Safety	0	+	+	-
Global Warming	+++	---	---	++
Other Environmental	-	0	0	++
Cost Effectiveness (C)	---	++	++	++
Cost Effectiveness (O)	+++	--	--	+
Process Versatility	++	++	++	0

(b) Emerging alternatives

The area of most interest with respect to emerging technologies is the potential use of oxygenated hydrocarbons (HCOs). Both methyl formate and methylal are being considered for these applications and the early indications are that they could be significant future alternatives in the sector. Although both a flammable, the level of flammability is less than that associated with pure hydrocarbons. There is also the potential that systems houses may be able to formulate blended systems in such a way as to avoid flammability issues in the workplace. One area of concern for methyl formate is the potential corrosion of moulds, but at the levels of addition, this may not be a problem in practice. The other issue relating to both HCOs the high solvency power of the blowing agents which could lead to some softening of the skins. The following table summarises the issues:

HCFC REPLACEMENT OPTIONS FOR INTEGRAL SKIN PU FOAMS FOR TRANSPORT & FURNITURE APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Integral skin foams			
Methyl formate	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*Moderate conversion costs*
	Good skin quality	*Moderate operating costs*	*Newly proven in application*
Methylal	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*High conversion costs, may be uneconomic for SMEs*
	Good skin quality	*Moderate operating costs*	*No industrial experience*
Shoe-soles			
Methyl formate	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*Moderate conversion costs*
	Good skin quality	*Moderate operating costs*	*Newly proven in application*
Methylal	*Low GWP*	*Flammable although blends with polyols may not be flammable*	*High conversion costs, may be uneconomic for SMEs*
	Good skin quality	*Moderate operating costs*	*No industrial experience*

Again, the specific performance ranking of the blowing agents is shown in the table below:

	Methylal	***Methyl Formate***
Proof of performance	+	++
Flammability	--	--
Other Health & Safety	0	0
Global Warming	++	++
Other Environmental	-	-
Cost Effectiveness (C)	+	0
Cost Effectiveness (O)	++	++
Process Versatility	+(+)	+(+)

It is noteworthy to mention that unsaturated HFCs/HCFCs are not seen as a realistic emerging technology in this sector because of the cost implications and the lack of any significant performance enhancement.

(c) Barriers and restrictions

There are no fundamental barriers to the introduction of the emerging technologies, although pilot projects on the pre-blending of HCOs in polyols will be necessary. There have been some concerns in the past about the implications of the limited supplier base and access to intellectual property, although these have been largely addressed. However, the biggest challenge to the replacement of any remaining use of ozone depleting substances will be the roll-out of these technologies on a sufficiently widespread basis.

If the widespread introduction of HCOs can be successful, there is likely to be the gradual replacement of both saturated HFCs (HFC-134a and HFC-245fa) and CO_2(water) blown technologies. The replacement of saturated HFCs, will certain deliver some additional climate benefits.

10.2.7 Extruded Polystyrene (XPS)

Extruded polystyrene board is unique amongst the foam sectors considered in this report in that it is blown exclusively with gaseous blowing agents. This is a consequence of the extrusion process. Extruded polystyrene (XPS) should not be confused with expanded polystyrene (EPS – also sometimes called 'bead foam') which uses pre-expanded beads of polystyrene containing pentane. EPS has never used ozone depleting substances and is seldom addressed in UNEP Reports for the Montreal Protocol. XPS is used primarily as a building insulation and often competes with PU Boardstock. Its particular competitive advantage is in relation to its moisture resistance, which makes it especially useful for under-floor insulation applications. There is another form of XPS known as 'Sheet' which is typically used for non-insulating applications such as leisure products (e.g. surf boards) and packaging materials. XPS sheet exited from CFC use early in the history of the Montreal Protocol and has used hydrocarbons almost exclusively ever since.

(a) Commercially available alternatives to Ozone Depleting Substances

The following table illustrates the commercially available alternatives in the extruded polystyrene sector:

HCFC REPLACEMENT OPTIONS FOR XPS FOAM			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Extruded Polystyrene Foams			
Butane	*Low GWP*	Highly flammable	
	Low operating costs		
HFC-134a/HFC-152a	*Non-flammable*	*High GWP*	
	Good foam properties, especially thermal performance	*Medium/high operating costs*	
CO_2 /Ethanol/DME	*Low GWP, low unit cost*	*Small operation window*	*Difficult to process especially for more than 50mm thickness board*
	Non-flammable	*Flammable co-blowing agent*	*Need ethanol and DME as co-blowing agent*

As described earlier in this section, these three alternatives describe the primary options available in each of the three main non-Article 5 regions of the world. It should be noted that blends of saturated HFCs (HFC-134a/HFC-152a) are substantially used in North America and, to a lesser extent, in Europe, primarily by smaller producers who do not have the access to CO_2 technology. Where they are used in Japan, they serve markets that cannot accept the flammability of hydrocarbon solutions. The assessment of these blowing agents via the criteria of this report is shown in the following table:

	butane	*HFC-134a/ HFC-152a*	*CO_2 with ethanol or DME*
Proof of performance	++	+++	++
Flammability	---	+++	++
Other Health & Safety	0	+	+
Global Warming	+++	---	+++
Other Environmental	-	0	0
Cost Effectiveness (C)	--	++	---
Cost Effectiveness (O)	+++	--	++
Process Versatility	++	++	+

(b) Emerging alternatives

(c) HCFC REPLACEMENT OPTIONS FOR XPS FOAM			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Extruded Polystyrene Foams			
Gaseous unsaturated HFCs (HFOs)	*Low GWP*	*High unit cost*	*Semi-commercial availability – under evaluation*

For all the reasons expressed in this section, there is considerable interest in the potential of unsaturated gaseous HCFCs/HFCs as either blowing agents or co-blowing agents with HCOs such as ethanol or dimethyl ether (DME). The technological solution has the potential of becoming a relative standard in the industry, but the key deciding factor in that respect will be the cost. This aspect is reflected in the criteria assessment below:

	HFO-1234ze(E)
	Gaseous
Proof of performance	+
Flammability	++
Other Health & Safety	+
Global Warming	+++
Other Environmental	+
Cost Effectiveness (C)	++
Cost Effectiveness (O)	--
Process Versatility	++

(c) Barriers and restrictions

For the HCFC consuming market in China and elsewhere, the challenge is to decide whether there is a transitional option that moves to a low-GWP alternative before the availability of unsaturated HFCs such as HFO-1234ze (E) is secured. It is clear that hydrocarbons would have been an obvious option and that would have been a high priority for a number of producers in China operating under the HCFC Phase-out Management Plan there. However, in recent years, there have been a series of fires (mostly in the construction phase of major building projects) which have caused a reaction against organic insulation materials in general and XPS in particular. One of the underlying problems has been the inconsistency in use of flame retardants within XPS formulations, with recycled feedstock not being properly characterised in some instances. The XPS industry is making a strong case that properly formulated XPS board can be used safely throughout its lifecycle, but these developments have created a further barrier to the introduction of hydrocarbons as blowing agents at this sensitive time.

The introduction of unsaturated HFCs will certainly avoid such a controversy, but the availability of such technology in Article 5 Parties is uncertain – particularly when the technology is yet to be commercially adopted elsewhere. There is also the unanswered question concerning the impact on cost. A temporary switch to saturated HFC blends could ensure that the Montreal Protocol objectives are met, but this will do little to benefit the climate when over 1 billion tonnes of CO_2-eq could be avoided by a more benign solution.

10.2.8 Phenolic Foam

Phenolic foams are manufactured by a number of different processes, many of which shadow those already discussed for polyurethane foams. The largest markets for the product are as phenolic boardstock (manufactured by continuous lamination) and block foams, used primarily for fabricating pipe work insulation. Although the product made an entry into the North American market in the early 1980s, the particular technology was dogged with problems. As a result, there is little use of phenolic foam in that region today. However, successful phenolic boardstock technologies emerged in both Europe and Japan, with sales of the product continuing to grow, not only because of overall increases in the demand for thermal insulation, but also because of gains in market share. Phenolic foam's main competitive advantage rests in its intrinsic fire and smoke properties. However, since it is made by an emulsion process, it also offers smaller cells which result in improved thermal performance. More recently, the product has begun to emerge on the Chinese market - in part as a response to concerns over recent fires.

The use of phenolic foam as pipework insulation also stems from the intrinsic fire and smoke properties of the product and the growth of the product's use has been particularly strong in regions where internal fire regulations are strict or where the high rise nature of construction requires additional fire precautions.

(a) Commercially available alternatives to Ozone Depleting Substances

The following table sets out the commercially available alternatives for the phenolic foam sector:

HCFC REPLACEMENT OPTIONS FOR PF FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Continuous processes (including flexibly-faced lamination and pipe section manufacture)			
n- pentane/iso-pentane	*Low GWP*	*Highly flammable*	*High incremental capital cost*
	Low operating costs		*Industry standard*
	Good foam properties		
HFC-365mfc/277ea	*Non-flammable*	*High GWP*	
	Good foam properties	*High operating costs*	
2-chloropropane	*Low GWP*	*Negligible ODP*	
	Non flammable		
Block foams for various applications including panels, pipe insulation section, etc			
HFC-365mfc/277ea	*Non-flammable*	*High GWP*	*Low conversion costs*
	Good foam properties	*High operating costs but improved by using mixed HFC/ CO_2 (water)*	

The lack of low-GWP alternatives for discontinuous block foams signals the need for further work in this area. However, the ranking of these options against the report criteria can be summarised as follows:

	n-pentane i-pentane	*2-chloropropane*	*HFC-365/227ea*
Proof of performance	+++	+++	+
Flammability	---	0	++
Other Health & Safety	0	0	+
Global Warming	+++	+++	---
Other Environmental	-	0	0
Cost Effectiveness (C)	---	-	++
Cost Effectiveness (O)	+++	+	--
Process Versatility	++	+	++

(b) Emerging alternatives

As with other sectors, there is considerable focus on the potential of unsaturated HFCs/HCFCs.

HCFC REPLACEMENT OPTIONS FOR PF FOAM FOR BUILDING/ CONSTRUCTION APPLICATIONS			
SECTOR/OPTION	***PROS***	***CONS***	***COMMENTS***
Continuous processes (including flexibly-faced lamination and pipe section manufacture)			
Unsaturated HFC/HCFC liquids	*Non-flammable*	*Low conversion costs*	*Limited trials at this stage*
	Good foam properties	*High operating costs*	
Block foams for various applications including panels, pipe insulation section, etc			
Unsaturated HFC/HCFC liquids	*Non-flammable*	*Low conversion costs*	*Limited trials at this stage*
	Good foam properties	*High operating costs*	

One drawback for the adoption of this technology in phenolic foam is that there is no CO_2(water) co-blowing to offset some of the cost. Another option might be to use unsaturated HFCs/HCFCs as components of blends with hydrocarbons or other blowing agents. However, care will need to be taken with discontinuous block foams to avoid process flammability issues. The following table summarises the current status of these emerging options with respect to phenolic foam.

	HFO-1336mzzm(Z)	*HFO-1233zd(E)*
	liquid	*liquid*
Proof of performance	0	-
Flammability	+++	+++
Other Health & Safety	+	+
Global Warming	+++	+++
Other Environmental	+	+
Cost Effectiveness (C)	++	++
Cost Effectiveness (O)	--	--
Process Versatility	+(+)	+(+)

(c) Barriers and restrictions

The main technical barriers to the transition to unsaturated HFCs/HCFCs have already been set out in the previous section and need to be addressed in a first stage assessment. However, even if the technical hurdles are overcome, the investment case may not be compelling for the transition out of saturated HFCs in the discontinuous block foam sector in view of the small quantities consumed. It may require market pressure on the continued use of saturated HFCs or evidence of significant thermal performance improvements to provide additional support for the next transition step.

10.3 Summary of alternatives for high ambient temperature on Refrigeration and Air Conditioning applications

In this report, alternatives to ozone-depleting substances have been assessed in various sectors and subsectors, considering several aspects and its appropriateness for use in regions with high ambient temperature. Below this information is summarized for the main RAC applications

Air conditioners

Multi-split, Split (ducted) and Ducted split commercial and non-split air conditioners

- The use of R-744 is not suitable for high temperature climates due to the inability or excessive cost necessary to achieve desired efficiencies.

- HFC-32 is likely to be suitable for regions with high ambient temperatures in most types of multi-split and ducted ACs (TEAP, 2013), although necessary consideration is needed to provide suitable training for the service sector to handle the lower flammability aspects.

- In principle, the mixtures R-446A, R-447A, R-444B, DR-5, ARM-71 and ARM-32c are suitable for regions with high ambient temperatures. Necessary consideration is needed to provide suitable training for the service sector to handle the flammability aspects.

- In Multi-split, Split (ducted) and Ducted split commercial and non-split air conditioners, both HC-290 and HC-1270 perform well at high ambient. However, due to charge amount limitations, they are not easily applicable and require expert consideration as to suitability of cases.

- As highlighted in TEAP (2013), the use of single component unsaturated HFCs, such as HFC-1234yf and especially HFC-1234ze(E), have not been seriously considered for multi-split and ducted ACs because their volumetric capacity is low , implying bulkier systems and – along with high anticipated refrigerant price –a considerable increase in product cost. Some exceptions may exist for niche situations in systems intended for regions with very high ambient temperatures.

Chillers

Positive displacement chillers

- R-717 chillers can and are used in regions with high ambient temperatures, although the very high discharge temperatures need to be accommodated for through inter-stage and oil cooling.

- Due to the low critical temperature, the use of R-744 presents several technical barriers, mainly being components and system design for high operating pressure and performance degradation at high ambient temperatures, leading to a resultant incremental cost increase. For an ambient temperature of 35°C the efficiency of a basic cycle is about 50-60% of HCFC-22.

- Due to its good efficiency at high ambient temperatures, systems with R-444B would have power consumption lower relatively to other options. The direct cost of this refrigerant may be similar to current HFCs such as R-407C. It works well with existing POE lubricants.

- Due to its relative higher critical point compared to other refrigerants, DR-5 performs well at high ambient temperatures (warm climates). The direct cost of this refrigerant would be slightly high as it contains HFC-1234yf which has an expensive manufacturing cost. It works well with existing POE lubricants. Due to its good efficiency at high ambient temperatures, power consumption would be lower relative to R-410A.

- Due to its relative higher critical point compared to other refrigerants, R-447A performs well at high ambient temperatures (warm climates). The direct cost of this refrigerant is similar to R-410A. It works well with existing POE lubricants. Power consumption increases its effectiveness at high ambient temperatures relative to R-410A.

- The use of HFC-32 imply that some mitigation device or controls may be necessary for handling the discharge temperature of the compressor especially at high ambient temperatures.

Centrifugal chillers

R-718 (water) chillers are in use in several installations in Europe and are now commercially available in Japan in capacities of up to 350 kW using a special axial type compressor. In principle R-718 chillers should perform well under high ambient temperatures. There are no known limitations and should be easy to apply.

- HCFC-1233zd (E) is considered as a key alternative in low pressure centrifugal chillers, and should produce efficiency levels slightly better than HCFC-123, both at moderate and high ambient temperatures.

11 List of acronyms and abbreviations

ABC	Dry Chemical Powder
AIHA	American Industrial Hygiene Association
ASTM	American Society for Testing and Materials
BTP	Bromotrifluoropropene
CEFIC	European Chemical Industry Council
CEN	European Committee for Standardisation
CFC	Chlorofluorocarbon
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CTOC	Chemicals Technical Options Committee
EC	European Commission
EPA	US Environmental Protection Agency
EU	European Union
FIC	Fluoroiodocarbon
FK	Fluoroketone
FTOC	Foams Technical Options Committee
GWP	Global Warming Potential
HARC	Halon Alternatives Research Corporation
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HCO	Oxygenated hydrocarbon
HFC	Hydrofluorocarbon
HFE	Hydrofluoroether
HFO	Hydrofluoroolefin
HTOC	Halons Technical Options Committee
IIR	International Institute for Refrigeration
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LCCP	Life Cycle Climate Performance
VCLCG	Liquefied Compressed Gas
NFPA	National Fire Protection Association
NOAEL	No Observed Adverse Effect Level
n-PB	n-Propyl Bromide
ODP	Ozone Depletion Potential
ODS	Ozone Depleting Substance
OEL	Occupational Exposure Limit
PFC	Perfluorocarbon
RAC	Refrigeration and Air Conditioning (also R/AC)
RTOC	Refrigeration, AC and Heat Pumps Technical Options Committee
SNAP	Significant New Alternatives Policy
STOC	Solvents, Coatings and Adhesives Technical Options Committee
TEAP	Technology and Economic Assessment Panel
TEWI	Total Equivalent Warming Impact
TLV	Threshold Limit Value
UL	Underwriters Laboratories Inc.
UNEP	United Nations Environment Programme
VOC	Volatile Organic Compound

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