

**MONTREAL PROTOCOL  
ON SUBSTANCES THAT DEplete  
THE OZONE LAYER**



**UNEP**

**REPORT OF THE  
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL**

**JUNE 2016**

**DECISION XXVII/4 TASK FORCE REPORT  
FURTHER INFORMATION ON ALTERNATIVES TO  
OZONE-DEPLETING SUBSTANCES**



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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.

## Preface

This report is a follow up to the March 2016 TEAP XXVII/4 Task Force Report, submitted to the OEWG-37 Meeting of the Parties in Geneva, April 2016.

This June 2016 TEAP XXVII/4 Task Force report is being submitted by the TEAP to the 38th Meeting of the Open-ended Working Group of the Parties to the Montreal Protocol, Vienna, July 2016.

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<b>Table of Contents</b>	<b>Page</b>
<b>PREFACE .....</b>	<b>VII</b>
<b>EXECUTIVE SUMMARY .....</b>	<b>1</b>
ES1. INTRODUCTION	1
ES2. UPDATE ON THE STATUS OF REFRIGERANTS	2
ES3. UPDATE ON R/AC ALTERNATIVE REFRIGERANTS AND TECHNOLOGIES	3
ES4. ALTERNATIVES TO REFRIGERATION SYSTEMS ON FISHING VESSELS	4
ES5. SUITABILITY OF ALTERNATIVES UNDER HIGH AMBIENT TEMPERATURE (HAT) CONDITIONS	5
ES6. BAU AND MITIGATION DEMAND SCENARIOS FOR R/AC	5
<b>1 INTRODUCTION.....</b>	<b>9</b>
1.1 TERMS OF REFERENCE FOR THE XXVII/4 TASK FORCE REPORT	9
1.2 SCOPE AND COVERAGE	9
1.3 COMPOSITION OF THE TASK FORCE AND APPROACH	10
<b>2 UPDATE OF THE STATUS ON REFRIGERANTS .....</b>	<b>13</b>
2.1 INTRODUCTION	13
2.2 REFRIGERANT DATA	13
2.3 REFRIGERANT CLASSIFICATION AND STANDARDS	20
2.4 LIKELIHOOD OF NEW MOLECULES AND NEW RADICALLY DIFFERENT BLENDS	20
2.5 ROAD TO AVAILABILITY OF ALTERNATIVE REFRIGERANTS	21
2.6 ENERGY EFFICIENCY IN RELATION TO REFRIGERANTS	22
2.7 CLIMATE IMPACT RELATED TO REFRIGERANTS	23
2.8 THE GWP CLASSIFICATION ISSUE	24
2.9 ENVIRONMENTALLY SUSTAINABLE AND ENVIRONMENTALLY SOUND	25
2.10 REFERENCES	26
<b>3 UPDATE ON R/AC ALTERNATIVE REFRIGERANTS AND TECHNOLOGIES.....</b>	<b>29</b>
3.1 DOMESTIC APPLIANCES	29
3.2 COMMERCIAL REFRIGERATION	29
3.3 INDUSTRIAL SYSTEMS	30
3.4 TRANSPORT REFRIGERATION	31
3.5 AIR-TO-AIR AIR CONDITIONERS AND HEAT PUMPS	32
3.6 WATER HEATING HEAT PUMPS	32
3.7 CHILLERS	33
3.8 VEHICLE AIR CONDITIONING	35
3.9 NOT-IN-KIND TECHNOLOGIES	35
3.10 DEVELOPMENTS OF CO <sub>2</sub> TECHNOLOGY	37
3.11 STANDARDS IN THE R/AC INDUSTRY	38
3.12 REFERENCES	39
<b>4 ALTERNATIVES TO REFRIGERATION SYSTEMS ON FISHING VESSELS.....</b>	<b>41</b>
4.1 INTRODUCTION	41
4.2 CONSIDERATIONS AND OPTIONS FOR REPLACEMENT AND RETROFIT OF REFRIGERATION SYSTEMS IN FISHING VESSELS	41
<b>5 SUITABILITY OF ALTERNATIVES UNDER HIGH AMBIENT TEMPERATURE (HAT) CONDITIONS.....</b>	<b>45</b>
5.1 INFLUENCE OF HAT CONDITIONS ON R/AC EQUIPMENT DESIGN	45
5.2 RESULTS FROM RESEARCH PROJECTS	46

5.2.1	<i>PRAHA project</i> .....	47
5.2.2	<i>ORNL Project</i> .....	49
5.2.3	<i>AREP Project</i> .....	51
5.2.4	<i>General remarks on the three research projects</i> .....	54
5.3	FURTHER CONSIDERATIONS	55
5.4	REFERENCES	56
<b>6</b>	<b>BAU AND MIT SCENARIOS FOR ARTICLE 5 AND NON-ARTICLE 5 PARTIES FOR 1990-2050: REFRIGERATION AND AIR CONDITIONING</b> .....	<b>59</b>
6.1	EXPANSION OF SCENARIOS	59
6.2	METHOD USED FOR CALCULATION	60
6.3	HFC PRODUCTION AND DEMAND (CONSUMPTION) DATA	62
6.4	NON-ARTICLE 5 SCENARIOS UP TO 2050	64
6.4.1	<i>BAU scenario</i> .....	64
6.4.2	<i>MIT-3 scenario</i> .....	67
6.4.3	<i>MIT-5 scenario</i> .....	69
6.5	ARTICLE 5 SCENARIOS UP TO 2050	71
6.5.1	<i>BAU scenario</i> .....	71
6.5.2	<i>MIT-3 scenario</i> .....	74
6.5.3	<i>Impact of manufacturing conversion periods in the MIT-3 scenario</i> .....	76
6.5.4	<i>MIT-4 scenario</i> .....	78
6.5.5	<i>Impact of manufacturing conversion periods in the MIT-4 scenario</i> .....	80
6.5.6	<i>MIT-5 scenario</i> .....	81
6.5.7	<i>Impact of manufacturing conversion periods in the MIT-5 scenario</i> .....	82
6.6	REFRIGERANT DEMAND AND MITIGATION BENEFIT NUMBERS	83
6.7	REFERENCES	91
<b>7</b>	<b>LIST OF ACRONYMS AND ABBREVIATIONS</b> .....	<b>93</b>
	<b>ANNEX 1 - SUMMARY OF INFORMAL DISCUSSION ON THE TEAP DECISION XXVII/4 TASK FORCE REPORT FOR OEWG-37</b> .....	<b>95</b>
	<b>ANNEX 2 - BACKGROUND INFORMATION ABOUT REFRIGERATION IN THE FISHING INDUSTRY</b> .....	<b>97</b>
A2.1	THE FISHING INDUSTRY	97
A2.1.1	<i>Pacific fishing vessels</i> .....	97
A2.1.2	<i>The EU fishery fleet</i> .....	100
A2.2	REFRIGERATION WITHIN THE FISHING INDUSTRY	101
A2.2.1	<i>Refrigeration on board</i> .....	101
A2.2.2	<i>Ice plants and Refrigerated Sea Water (RSW)</i> .....	102
A2.2.3	<i>Freezer trawlers</i> .....	102
A2.2.4	<i>Ultra-low temperature freezing</i> .....	103
A2.3	REFRIGERANTS CURRENTLY USED	104
A2.3.1	<i>Refrigerants used on board</i> .....	104
A2.3.2	<i>Refrigerants used on land operations</i> .....	104
A2.3.3	<i>Refrigerant leakage</i> .....	104
A2.3.4	<i>High ambient temperatures (HAT)</i> .....	105
A2.4	LOW-GWP ALTERNATIVES TO ODS REFRIGERANTS	105
A2.4.1	<i>Alternatives to HCFC-22</i> .....	105
A2.4.2	<i>Option 1 – Non-halocarbon refrigerants (R-717 and R-744)</i> .....	107
A2.4.3	<i>Option 2 – Refrigerant replacement with plant adjustments</i> .....	109
A2.4.4	<i>Option 3 – Refrigerant drop-in</i> .....	110
A2.4.5	<i>Option 4 – Maintaining HCFC-22</i> .....	111
A2.4.6	<i>Ultra-low temperature solutions</i> .....	111
A2.4.7	<i>Land based equipment</i> .....	113
A2.4.8	<i>Not-In-Kind technologies</i> .....	113
A2.5	REFERENCES	114
	<b>ANNEX 3 - EU (F-GAS, MAC DIRECTIVE), USA (EPA SNAP PROGRAM) AND JAPAN REGULATORY PROHIBITIONS (CH. 6)</b> .....	<b>116</b>
	<b>ANNEX 4 - UPDATED TABLES FOR TOTAL, NEW MANUFACTURING, AND SERVICING DEMAND</b> .....	<b>123</b>

## **Executive summary**

### **ES1. Introduction**

- Decision XXVII/4 requested TEAP to provide an update of information on alternatives to ozone-depleting substances listed in the September 2015 Update XXVI/9 Task Force report and considering the specific parameters outlined in the current Decision.
- Given that Parties are holding two Open-ended Working Group (OEWG) meetings this year, TEAP has taken the approach to provide two reports responding to Decision XXVII/4. TEAP provided its first March 2016 report to OEWG-37 focused on the refrigeration and air conditioning (R/AC) sector, and included updates on alternatives, results of testing on alternatives under high ambient temperature (HAT) conditions, discussion of other parameters outlined in the decision, and an extension of the mitigation scenarios to 2050.
- After TEAP presented its first report to OEWG-37 and offered clarifications on the information, TEAP received comments from Parties during the plenary discussion of the report as well as during an informal discussion meeting with TEAP, Thursday 7 April. The summary of the informal discussion meeting is provided in Annex 1. The comments have been taken into consideration by the TEAP Decision XXVII/4 Task Force within the timeline remaining to the Task Force to complete its second report for submission to OEWG-38.
- TEAP's approach with its second report under Decision XXVII/4 is to provide Parties with a single reference document as much as possible for OEWG-38. This second report, therefore, contains much of the same information as in the first report with a focus on the R/AC sector and updates and additions are indicated at the beginning of each chapter or section, as appropriate.
- In particular, TEAP's second report under Decision XXVII/4 for OEWG-38 provides the following:
  - In Chapter 2, further elaboration is provided on the use of the term "environmentally sound" in response to comments;
  - In response to comments related to further updates and information on refrigerants and not-kind-technologies, this second report includes a new chapter (Chapter 3) providing updates on refrigerant alternatives and technologies;
  - In response to comments related to safety of the new alternatives, this second report elaborates on the technical perspective related to safe use of the refrigerants in the chapter on refrigeration (Chapter 3);
  - A new chapter (Chapter 4) responds to the decision request to provide new and updated information as this is available related to the availability of alternatives for replacement and retrofit of refrigeration systems in fishing vessels, including in small island countries. Related to this chapter, Annex 2 provides additional background information on refrigeration systems in the fishing industry (with particular consideration on the Pacific Islands region);
  - Based on comments related to a more balanced discussion (both positive and negative) of the results of the testing programs for refrigerants under HAT conditions, a revised chapter (Chapter 5) covering these studies is included in this report including summary tables of each of the testing programs;
  - Comments related to scenarios included further information related to HFC production, the magnitude of present banks of HFCs, a business-as-usual

(BAU) scenario without and with regulations (see also Annex 3), whether scenarios could be presented on a regional basis, clarification of the estimated growth rates used compared to refrigerant demand growth, consideration of the impacts for a longer manufacturing conversion of 18 years. This issue is addressed in the revised chapter of this second report (Chapter 6) concerning Article 5 mitigation scenarios. Related to this chapter, Annex 4 of this report contains updated tables for total, new manufacturing, and servicing demand.

- Given the short timeline between OEWG-37 and the development of the second Task Force report to OEWG-38, this second report again focused on the R/AC sector. To the extent that updates and new information on alternatives are available to the Task Force, the other sectors (foams, fire suppression, metered dose inhalers (MDIs), other medical and non-medical aerosols, and solvents) will be covered in the Task Force's update report to MOP-28. The following sections provide the technical summaries of the report's main chapters. The summaries of the chapters from the first report remain essentially the same as in that report with any update or additional information indicated in bold upfront.

## **ES2. Update on the status of refrigerants**

- **Based on comments from Parties on TEAP's first report to OEWG-37, this chapter includes the following updates and new information:**
  - **A further elaboration on the use of the term "environmentally sound".**
- Chapter 2 lists 80 fluids which have either been proposed or are being tested in industry programmes, or are pending publication, or have been published in ISO 817 and ASHRAE 34 refrigerant standards since the 2014 RTOC Assessment Report. The majority of these are new mixtures, but traditional fluids and two new molecules are also included. Chapter 2 includes discussions on how refrigerants are classified in refrigerant standards and increased safety risks of some of low-GWP refrigerants that need to be addressed.
- There are alternative refrigerants available today with negligible ODP and lower GWP, however, for some applications it can be challenging to achieve the same lifetime cost level of conventional systems while keeping the same performance and size. The search for new alternative fluids may yield more economical solutions, but the prospects of discovering new, radically different fluids are minimal.
- Market dynamics are critical in the rate of adoption of new refrigerants. There is a limit to the number of different refrigerants that a market (customers, sales channels, service companies) can manage. Hence, companies will be selective about where they launch a product, avoiding areas which are saturated, and promoting sales where they see the greatest market potential.
- It is difficult to assign energy efficiency to a refrigerant, because energy efficiency of refrigeration systems is an additional variable to the refrigerant choice also related to system configuration and component efficiencies. One approach when assessing the energy efficiency related to a refrigerant is to start with a specific refrigerant and use a system architecture suitable for this refrigerant, while comparing to a reference system for the refrigerant to be replaced. Other approaches screen alternative refrigerants suitable for a given system architecture. The common methods can be divided into theoretical and semi-theoretical cycle simulations, detailed equipment simulation models, and laboratory tests of the equipment. In practice, the achievable energy efficiency is limited by the cost of the system, as the success in the market depends on a cost-performance trade-off.

- The difficulties in assessing the total warming impact related to refrigerants is discussed, including the difficulty of defining “low global warming potential”, and assessing the energy efficiency related to the use of a refrigerant.
- Total climate impact related to refrigerants consists of direct and indirect contributions. The direct contribution is a function of a refrigerant’s GWP, charge amount, emissions due to leakage from equipment and those associated with the service and disposal of the equipment. The definition of the qualifiers “high”, “medium” and “low” in relation to GWP is a qualitative, non-technical choice related to what is acceptable in specific applications. The indirect contribution accounts for the CO<sub>2</sub>-equivalent emissions generated during the production of energy consumed by the refrigeration, air-conditioning, and heat pump equipment. These emissions are affected by equipment's operating characteristics and the emission factor of the local electricity production. Operating characteristics include operating conditions, operating profile, system capacity, system hardware, among others, which makes a comparison difficult in many instances. The indirect contribution is the dominant contributor in very low to no leakage or “tight systems”.

### **ES3. Update on R/AC alternative refrigerants and technologies**

- **Based on comments from Parties on TEAP’s first report to OEWG-37, this new chapter provides updates on refrigerant alternatives and technologies, including discussion of Not-In-Kind-technologies and the status of CO<sub>2</sub> technologies, and also discusses standards within the R/AC sector; also included is an elaboration on the technical perspective related to safe use of the alternative refrigerants as covered in relevant standards.**
- HC-600a and HFC-134a continue to be the primary refrigerant options for production of new domestic refrigeration appliances. It is projected that, by 2020, about 75% of new refrigerator production will use HC-600a, most of the rest will use HFC-134a, and a small share may apply unsaturated HFC refrigerants such as HFO-1234yf.
- In supermarkets, blends such as R-448A, R-449-A, R-449B, R-450A, and R-513A are now beginning to grow in use, starting with Europe and the United States. The same holds true for condensing units and self-contained equipment. In the self-contained equipment category, early trials with HFO-1234yf and HFO-1234ze have started. The use of R-407A and R-407F continues to grow further in many parts of the world.
- Refrigerants such as R-744 are increasingly being used in supermarket systems worldwide – both in cascaded systems (R-744 for low temperature cascaded with a second refrigerant such as HFC-134a or similar and R-717 in limited cases) and in transcritical systems. Transcritical systems are being researched extensively to reduce their energy penalty at high ambient conditions through the use of component and system technologies such as ejector, adiabatic condensing, sub-cooling and parallel compression.
- In industrial refrigeration the major trend, which also is a major challenge, is the focus on refrigerant charge reduction. The market for heat pumps is increasing rapidly. Industrial heat pumps use heat that is considered waste in other parts of production processes.
- In transport refrigeration, R-452A has been introduced during 2015 as a customer option on new truck and trailer refrigeration units. R-404A remains widely available. Activities are ongoing to assess R-744 and other non-flammable (class A1) lower GWP solutions such as R-448A and R-449A. R-513A, R-513B, and R-456A are

being considered as future drop-in solutions for HFC-134a. Flammable (A3) and lower flammable (A2L) refrigerant research is continuing, aiming at producing publicly available and technically sound references to support code and standard activities.

- For air-to-air air conditioners and heat pumps, the most substantial recent developments are related to the increased rate of substitution of HCFC-22 and the greater consideration of use of medium and low GWP alternatives. Some manufacturers are adopting HCs and there is also uptake of HFC-32.
- For space heating and water heating heat pumps, legislation on minimum energy efficiency has entered into force in Europe, Japan and the USA, and has decreased the number of air to water heat pumps that can be placed on the market.
- In chillers, after years of research and screening tests, an array of choices is emerging and some commercialisation has begun. Emerging refrigerants are: HCFO-1233zd, HFC-32, R-452B, R-513A, R-514A, HFO-1234yf and HFO-1234ze(E).
- In mobile air conditioners (MACs), the penetration of HFO-1234yf for new vehicles has continued and has spread to many additional models, primarily in non-Article 5 countries, but is still far from complete. In addition, development of R-744 MACs has continued and commercialisation appears imminent. Other alternatives - including hydrocarbons, HFC-152a and additional HFC/HFO blends R-444A and R-445A - have not received much additional consideration and appear unlikely to be chosen for new vehicles in the near future.
- Vapour compression technology has been the primary technology for all R/AC applications in the last 100 years. Technologies that do not employ vapour compression technology are called Not-In-Kind technologies (NIK), of which, during past years, several have been under development. Some studies have classified the development status of those technologies as: (1) most promising (membrane heat pump, thermo-elastic); (2) very promising (evaporative liquid desiccant A/C, magneto-caloric, Vuilleumier heat pump); (3) moderately promising (evaporative cooling, thermo-electric, ground-coupled solid desiccant A/C, absorption heat pump, duplex-Stirling heat pump, thermo-acoustic, adsorption heat pump, thermo-tunneling); and (4) least promising (stand-alone solid desiccant A/C, stand-alone liquid desiccant A/C, ejector heat pump, Brayton heat pump).

#### **ES4. Alternatives to refrigeration systems on fishing vessels**

- **This new chapter responds to the decision request to provide new and updated information, as this is available, related to the availability of alternatives for replacement and retrofit of refrigeration systems in fishing vessels, including in small island countries.**
- 70% of the global fishing fleet continues to use HCFC-22 as its main refrigerant. Therefore the main challenge for the industry is to find a feasible transition from HCFC-22 to low-GWP alternatives. Considering that 70% of the global fishing fleet is based in Asia/Pacific, this challenge becomes even more important for Asia/Pacific countries and specifically for the Pacific Island region, whose economy is heavily dependent on their fishing industry. For this reason, particular attention was paid to the situation in this region.
- Based on several parameters (age of vessels, availability of alternatives, technical and economic feasibility of conversions, meeting regulatory requirements of product importer), the transition from HCFC-22 to low-GWP alternatives can be implemented following four different options:

Option 1 – Non-halocarbon refrigerants (i.e., R-717 and R-744);

Option 2 - Refrigerant replacement with plant adjustments;

Option 3 – Refrigerant drop-in; and

Option 4 - Maintaining HCFC-22 systems.

#### **ES5. Suitability of alternatives under high ambient temperature (HAT) conditions**

- **Based on comments from Parties on TEAP’s first report to OEWG-37, this revised chapter provides a more balanced discussion (both positive and negative) of the results as well as additional information on the three testing programs for refrigerants under HAT conditions and includes the following changes and additions:**
  - **Further discussion of the methods for considering the impact of the ambient temperatures on the design of R/AC equipment; and**
  - **Further information on the reports published for the three projects that tested alternative refrigerants at temperatures above 35°C including tabulated summaries of each of the three projects.**
- Chapter 5 updates information on three research projects (where more projects will currently be ongoing) testing alternative refrigerants at HAT conditions and on the design of products using alternatives in new and retrofit applications.
- Results from the three projects, PRAHA, AREP-II, and ORNL, indicate a way forward in the search for efficient low-GWP alternatives for high ambient temperature conditions especially when coupled with a full system redesign. The scope of the research for ORNL and that for the reports from AREP-II analysed here mostly covered soft-optimized testing (i.e., adjusted expansion device or adjusted charge amount). While the PRAHA project included a change of compressors, suppliers did not custom-design those compressors for the particular applications.
- Further improvements are likely through optimizing heat exchangers circuitry for heat transfer properties and proper compressor sizing and selection.
- Full redesign of systems, including new components, will likely be needed to realise systems, using new alternative refrigerants to match or exceed the performance of existing systems in both capacity as well as energy efficiency. When selecting new refrigerants it is important to consider further increases on the current energy efficiency requirements.
- While the commercialization process of refrigerants can take up to ten years, the commercialization of products using these alternatives will take further time.
- In HAT conditions, the cooling load of a conditioned space can be up to three times that for moderate climates. Therefore larger capacity refrigeration systems may be needed, which implies a larger refrigerant charge. Due to the requirements for charge limitation according to certain safety standards, the possible product portfolio suitable for HAT conditions is more limited than for average climate conditions when using the same safety standards.
- Although risk assessment work on flammable refrigerants is an on-going research in some countries, there is a need for a comprehensive risk assessment for A2L and A3 alternatives at installation, servicing and decommissioning at HAT conditions.

#### **ES6. BAU and mitigation demand scenarios for R/AC**

- **This chapter contains the same scenarios as the TEAP Decision XXVII/4 Task Force Report (March 2016). Based on comments received by TEAP on its report**

to OEWG-37, this revised chapter also contains the following changes and additions:

- **Consideration of existing regulations as well pending regulations in non-Article 5 Parties and the impact of the latter;**
  - **Comparison of the demand in non-Article 5 Parties between a BAU scenario with regulations considered (up to 2050) and without regulations considered (up to 2030);**
  - **A revised table on growth percentages for the various R/AC subsectors, for both the new manufacturing and the total demand (correcting certain percentages of decreasing HCFC demand that were included in the growth percentages in the March 2016 version of the XXVII/4 TF report);**
  - **Additional information on the production of various HFCs, not only the currently most important ones for the R/AC sector, and a comparison with the global calculated demand for the R/AC sector;**
  - **Addition of an 18-year manufacturing conversion period for the Article 5 MIT-3 scenario and its impact on total demand; and**
  - **Related to this chapter, Annex 4 of this report contains updated tables for total, new manufacturing, and servicing demand.**
- The revised scenarios in this report include an extension of the timescale used from the year 2030 to 2050 and a consideration of the BAU scenario for non-Article 5 countries that includes the EU F-gas regulation as well as the US HFC regulations for specific sectors and sub-sectors. The mitigation scenarios remain the same as in the September 2015 XXVI/9 report as follows:
    - MIT-3: conversion of new manufacturing by 2020 (completed in non-Article 5 Parties; starting in Article 5 Parties)
    - MIT-4: same as MIT-3 with delayed conversion of stationary AC to 2025
    - MIT-5: conversion of new manufacturing by 2025 (completed in non-Article 5 Parties; starting in Article 5 Parties)
  - These scenarios (in principle for the R/AC sector only) were cross-checked against current estimated HFC production data that became available in May 2015 (June and September XXVI/9 Task Force report) and shortly thereafter. Most recent estimates made for the 2015 global production of the four main HFCs<sup>1</sup> are presented in the table below (some revisions were made in this June report); it shows a combined total for the four main HFCs of about 510 ktonnes.

<b>Chemical</b>	<b>Best estimate for global HFC production in year 2015 (ktonnes)</b>
HFC-32	94
HFC-125	130
HFC-134a	258
HFC-143a	28

- The global calculated bottom-up demand for the R/AC sectors in 2015 amounts to 473 ktonnes (of which 220 ktonnes in non-Article 5, 273 ktonnes in Article 5 Parties). Compared to the total of 510 ktonnes it would imply that the demand from other sectors than R/AC would amount to about 37 ktonnes (this would mainly, but not only, concern HFC-134a, used as a foam blowing agent and used in medical and technical aerosols, as well as some minor use of the other HFCs in other sectors).

<sup>1</sup> These are the four main HFCs currently used in the R/AC (including MACs) sector; HFC-134a is also used as a foam blowing agent, in MDIs and technical aerosols.

- Over the period 2015-2050, the revised BAU scenario shows
  - 250% growth in the demand in tonnes and in tonnes CO<sub>2</sub>-eq. in non-Article 5 Parties;
  - 700% growth in tonnes and a 800% growth in tonnes CO<sub>2</sub>-eq. in Article 5 Parties;
  - The increase in total demand for the four main HFCs currently used in R/AC is due primarily to the growth in demand in the stationary AC sub-sector and secondly, to the growth in demand in the commercial refrigeration sub-sector. As mentioned, total global R/AC demand is in the order of 510 ktonnes for the year 2015 for the four main HFCs.
- *Delaying the start of conversion:* MIT-3 assumes that conversion in all sub-sectors starts in 2020, MIT-5 assumes that conversion starts in 2025. In terms of overall climate impact, the *total* integrated HFC demand for the R/AC sector in Article 5 Parties over the period 2020-2030 was previously estimated in the different scenarios as follows (assuming a 6 years transition):
  - BAU: 16,000 Mt CO<sub>2</sub> eq.
  - MIT-3: 6,500 Mt CO<sub>2</sub> eq.; a 60% reduction to BAU (2020-2030)
  - MIT-4: 9,800 Mt CO<sub>2</sub> eq.; a 40% reduction to BAU (2020-2030)
  - MIT-5: 12,000 Mt CO<sub>2</sub> eq.; a 30% reduction to BAU (2020-2030)
- With the scenarios extended to 2050 in this report, the BAU demand for the extended period 2020-2050 increases almost five-fold. In this context, although the differences in reduction between the various mitigation scenarios MIT-3, -4 and -5 remain large, they become proportionately less compared to BAU. Consideration of the intermediate period 2020-2040 may provide a more realistic estimate of the savings that can be realised via the various MIT scenarios in Article 5 Parties. The *total* integrated HFC demand for the R/AC sector in Article 5 Parties over 2020-2040 is as follows (assuming a 6 years transition):
  - BAU: 42,300 Mt CO<sub>2</sub>-eq.
  - MIT-3: 10,600 Mt CO<sub>2</sub>-eq.; a 75% reduction to BAU (2020-2040)
  - MIT-4: 15,600 Mt CO<sub>2</sub>-eq.; a 63% reduction to BAU (2020-2040)
  - MIT-5: 18,800 Mt CO<sub>2</sub>-eq.; a 56% reduction to BAU (2020-2040)
- The MIT-3 and MIT-5 scenarios are given for all Parties, but predominantly reflect demand in Article 5 Parties:
  - MIT-3 substantially reduces the high-GWP HFC demand compared to BAU since it addresses all manufacturing conversions in all R/AC sub-sectors as of 2020. As the R/AC manufacturing with high-GWP refrigerants is phased out, the servicing demand becomes dominant. The stationary AC sub-sector is the principal source of the HFC demand.
  - MIT-5 delays manufacturing conversion of all sub-sectors, including the rapidly expanding stationary AC sector from 2020 until 2025, so that HFC demand initially rises, but then falls as of the year 2025. Servicing rises substantially as a consequence, and persists for much longer than in MIT-3. MIT-5 shows the impact of persisting servicing needs as a result.
  - *Conversion period:* the longer the conversion period in mitigation scenarios, the greater the climate impacts (see MIT-3 or MIT-5 from 6 to 12 years) and the resulting overall costs in particular because of continuing servicing needs. An 18 years conversion period has been studied for the MIT-3 scenario (costs have not been further addressed compared to what was available in the XXVI/9 TF report). Whereas the 6 and 12 years conversion periods result in a demand decrease starting after 2020-2024, the 18 years conversion period yields a 10% increase in

demand first, until the year 2030, then starts to decrease and reaches the 2020 demand value again in the year 2037. For the 18 years conversion period there is still some high GWP servicing demand after 2050. The demand for the period 2020-2050 for a 6 years conversion period is about 15,800 Mt CO<sub>2</sub>-eq., increases to 20,500 Mt CO<sub>2</sub>-eq. for a 12 years, and to 27,000 Mt CO<sub>2</sub>-eq. for an 18 years conversion period. The latter implies a 70% increase in demand compared to demand for a 6 years conversion period.

- For demand in Article 5 Parties, the following is also of importance:
  - Peak values determined for the refrigerant demand increase with later start of conversion. The peak value for MIT-3 in 2020 is about 820 Mt CO<sub>2</sub>-eq. The peak value for MIT-4 in the year 2023, with conversion of stationary AC starting in 2025, is 25% higher (at 1025 Mt CO<sub>2</sub>-eq.), whereas the peak value for demand for MIT-5 in the year 2025 is 62% higher than the one for MIT-3 (at 1330 Mt CO<sub>2</sub>-eq.).
  - For MIT-3, the average decline over a period of 10 years after the peak year is 5.3% per year (from 820 down to 390 Mt CO<sub>2</sub>-eq. in 2030), for MIT-4 it is 4.5% per year (from 1025 down to 570 Mt CO<sub>2</sub>-eq. in 2033) and for MIT-5 it is 5.5% per year (from 1330 down to 605 Mt CO<sub>2</sub>-eq. in 2035).
  - For each separate Article 5 Party the peak (freeze) values will still be in the same years for the various MIT scenarios considered, however, annual reduction percentages achievable thereafter may be significantly different per country.

# 1 Introduction

## 1.1 Terms of Reference for the XXVII/4 Task Force report

Decision XXVII/4 of the Twenty-seventh Meeting of the Parties requested the Technology and Economic Assessment Panel (TEAP) to prepare a draft report for consideration by the Open-ended Working Group (OEWG) at its thirty-seventh meeting, and thereafter an updated report to be submitted to the Twenty Eighth Meeting of the Parties in 2016. In their discussions prior to adoption of this decision, Parties considered a focus primarily on areas where updates to the September 2015 report of the task force of the TEAP addressing the issues of decision XXVI/9, including with regard to information on the availability of alternatives and to extending the mitigation scenarios from the previous report to 2050.

In Decision XXVII/1, paragraph 1, Parties agreed to “work within the Montreal Protocol to an HFC amendment in 2016 by first resolving challenges by generating solutions in the contact group on the feasibility and ways of managing HFCs during Montreal Protocol meetings.” Further, in paragraph 4 of that decision, Parties agreed to “hold in 2016 a series of Open-ended Working Group meetings and other meetings, including an extraordinary meeting of the parties.” Subsequently, in 2016, Parties will hold the thirty-seventh and thirty-eighth OEWG meetings on 4-8 April and 18-21 July, respectively, along with the third Extraordinary Meeting of the Parties 22-23 July. A resumed OEWG-37 meeting has since been planned for 15-16 July. TEAP is providing its response to Decision XXVII/4 in three parts: a first report submitted to OEWG-37 primarily focused on the R/AC sector; this second report now submitted to OEWG-38 addresses comments received at OEWG-37 with the focus remaining on the R/AC sector. Updates related to the other sectors including medical aerosols, non-medical or technical aerosols, and solvents, where updated information is available to the TEAP, as well as responding to comments on the second report from Parties at OEWG-38, as appropriate, will be submitted to the Twenty-eighth Meeting of the Parties (MOP-28). The approach taken by TEAP is further discussed below.

## 1.2 Scope and coverage

The text of Decision XXVII/4 (“Response to the report by the Technology and Economic Assessment Panel on information on alternatives to ozone-depleting substances”), as it relates to this report is as follows:

### **Decision XXVII/4: Response to the report by the Technology and Economic Assessment Panel on information on alternatives to ozone-depleting substances**

*Noting with appreciation* the September 2015 report of the task force of the Technology and Economic Assessment Panel addressing the issues listed in subparagraphs 1 (a)–(c) of decision XXVI/9,

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-seventh meeting, and thereafter an updated report to be submitted to the Twenty-Eighth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer in 2016, that would:

(a) Update, where necessary, and provide new information on alternatives to ozone-depleting substances, including not-in-kind alternatives, based on the guidance and assessment criteria provided in subparagraph 1 (a) of decision XXVI/9, and taking into account the most recent findings on the suitability of alternatives under high-ambient temperatures, highlighting in particular:

(i) the availability and market penetration of these alternatives in different regions;

- (ii) the availability of alternatives for replacement and retrofit of refrigeration systems in fishing vessels, including in small island countries;
- (iii) new substances in development that could be used as alternatives to ODS and that could become available in the near-future;
- (iv) the energy efficiency associated with the use of these alternatives;
- (v) The total warming impact and total costs associated with these alternatives and the systems where they are used;

(b) Update and extend to 2050 all the scenarios in the Decision XXVI/9 report.

### 1.3 Composition of the Task Force and approach

The TEAP established a Task Force to prepare the reports responding to Decision XXVII/4. The updated composition of the Task Force is as follows:

#### Co-chairs

- ❑ Lambert Kuijpers (The Netherlands, Senior Expert member TEAP, RTOC)
- ❑ Bella Maranion (USA, co-chair TEAP)
- ❑ Roberto Peixoto (Brazil, co-chair RTOC)

#### Members:

- ❑ Radim Cermak (CZ, member RTOC)
- ❑ Denis Clodic (France, outside expert)
- ❑ Daniel Colbourne (UK, member RTOC)
- ❑ Martin Dieryckx (Belgium, member RTOC)
- ❑ Piotr Domanski (USA, outside expert (NIST))
- ❑ Dave Godwin (USA, member RTOC)
- ❑ Bassam Elassaad (Lebanon, member RTOC)
- ❑ Armin Hafner (Norway, outside expert)
- ❑ Samir Hamed (Jordan, member RTOC)
- ❑ D. Mohin Lal (India, member RTOC)
- ❑ Richard Lawton (UK, member RTOC)
- ❑ Simon Lee (UK, member FTOC)
- ❑ Tingxun Li (PR China, member RTOC)
- ❑ Richard Lord (USA, outside expert)
- ❑ Carloandrea Malvicino (Italy, member RTOC)
- ❑ Petter Nekså (Norway, member RTOC)
- ❑ Keiichi Ohnishi (Japan, co-chair MCTOC)
- ❑ Alaa A. Olama (Egypt, member RTOC)
- ❑ Alexander C. Pachai (Denmark, member RTOC)
- ❑ Xueqin Pan (France, outside expert)
- ❑ Fabio Polonara (Italy, co-chair RTOC)
- ❑ Rajan Rajendran (USA, member RTOC)
- ❑ Helen Tope (Australia, co-chair MCTOC)
- ❑ Dan Verdonik (USA, co-chair HTOC)
- ❑ Samuel Yana-Motta (Peru, member RTOC)
- ❑ Asbjørn Vonsild (Denmark, member RTOC)
- ❑ Jianjun Zhang (PR China, co-chair MCTOC)
- ❑ Shiqiu Zhang (PR China, Senior Expert member TEAP)

The structure of the TEAP XXVII/4 Task Force Report was considered by the Task Force and also by TEAP prior to the final formulation of this second report. The factors considered include:

- The relatively short period between the delivery of the final XXVI/9 Report (September 2015) and the preparation of the first report to OEWG-37 and second XXVII/4 Report to be submitted for OEWG-38.
- The similarity of the criteria set out within Decision XXVII/4 and Decision XXVI/9.
- The importance of avoiding too much repetition and bringing focus on updated information from the previous report.
- 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 fire protection, solvents and medical uses) do not have reliable data from which relevant mitigation scenarios can be derived or for which mitigation scenarios were not derived.

Given the two OEWG meetings, TEAP has taken an approach of providing a response to Decision XXVII/4 as follows:

- For OEWG-37, TEAP provided a first Task Force report focused on R/AC only addressing the relevant paragraphs under paragraph 1(a) of the decision including updates on alternatives, research studies on alternatives under high ambient temperature conditions, and extension of mitigation scenarios to 2050.
- For OEWG-38, TEAP is now providing a second Task Force report that incorporates updates to the R/AC sector information only based on discussions at OEWG-37, and responds to other parts of the decision, including information on alternatives to refrigeration systems on fishing vessels.
- For MOP-28, TEAP will provide a Task Force update report, as appropriate, following discussions during OEWG-38. This will also include update chapters on foam alternatives (and scenarios), fire protection and medical and technical aerosols, to the extent new information is available.

The chapter layout of this June XXVII/4 Task Force report is as follows:

*Executive Summary*

*Chapter 1 - Introduction*

*Chapter 2 - Update on the status of refrigerants*

*Chapter 3 - Update on R/AC alternative refrigerants and technologies*

*Chapter 4 - Alternatives to refrigeration systems on fishing vessels*

*Chapter 5 - Suitability of alternatives under high ambient temperature (HAT) conditions*

*Chapter 6 - BAU and MIT scenarios for A5/non-A5 countries for 1990-2050: R/AC*

*Annex 1 - Summary of informal discussion on the TEAP Decision XXVII/4 Task Force Report for OEWG-37*

*Annex 2 - Background information about refrigeration in the fishing industry*

*Annex 3 - EU (F-gas, MAC Directive), USA (EPA SNAP Program) AND Japan regulatory prohibition*

*Annex 4 - Updated tables for total, new, manufacturing, and servicing demand*



## 2 Update of the status on refrigerants

This chapter essentially contains the same information as the March 2016 version of the XXVII/4 Task Force report, apart from the addition of a subchapter on the definition of “environmentally acceptable” and “environmentally sound” (see 2.9). No new refrigerants or blends have been added to the tables.

### 2.1 Introduction

This chapter in the first report provided updated information on alternatives in the refrigeration and air conditioning sectors since the TEAP Task Force Decision XXVI/9 report, September 2015 (UNEP, 2015) and as requested in Decision XXVII/4. It included:

- A presentation of 80 fluids that have been proposed for testing or are being tested in industry programmes, are pending publication, or have been published in ISO 817 and ASHRAE 34 refrigerant standards since the 2014 RTOC Assessment Report. The majority of these are new mixtures, but traditional fluids and two new refrigerants based on a new molecule are also included.
- A description of how refrigerants are classified in the refrigerant standards, while also noting that with the introduction and potential widespread adaptation of refrigerants which are flammable, have higher toxicity and/or operate at notably higher pressures than the conventional ODS refrigerants or alternative non-flammable HFC refrigerants, as well as increased safety risks of some of low-GWP refrigerants that need to be addressed.
- A discussion of the process of making refrigerants available to the market, including the market mechanisms that decides where a refrigerant will be available.
- A discussion on the methods of assessing the energy efficiency related to the use of a refrigerant.
- A discussion on the discovery of new refrigerants is included. There are alternative refrigerants available today with negligible ODP and lower GWP, but for some applications it can be challenging to reach the same lifetime cost level of the systems while keeping the same performance or to keep the equipment within a reasonable size. The search for new alternative fluids may yield more economical system designs, but the prospects of discovering new, radically different fluids are minimal.
- A discussion of the total warming impact related to refrigerants is discussed, including the difficulty of defining low global warming potential, which plays an essential role in the total warming impact calculation.

### 2.2 Refrigerant data

A total of 80 fluids, new and “old”, are under investigation as alternatives to ODS refrigerants or higher GWP refrigerants (see (UNEP, 2014) for comparison). The fluids have been proposed for testing, are being tested in industry programmes or are pending publication or have been published in ISO 817 (ISO 817:2014) or ASHRAE 34 (ASHRAE 34:2013) since the 2014 RTOC Assessment report (UNEP, 2014).

Of the 80 fluids, 11 are pure substances, of which 10 have been published in ISO 817 or ASHRAE 34, while of the 69 mixtures, 55 have publicly known compositions, but only 17 have been published in the ISO 817 or ASHRAE 34 standards, and of these, 11 were included in the RTOC report (UNEP, 2014).

It is expected that, testing, development and commercialization will decrease the number of viable candidates and that market experience will likely further narrow down the number of viable lower GWP candidates in the future.

For ease of reference, the names of the four largest test programs are provided below.

- AHRI Low-GWP Alternative Refrigerants Evaluation Program (AREP). This project is divided into two phases: Phase I (AREP-I), which is finished, and phase II (AREP-II), which is still ongoing;
- “Promoting low-GWP Refrigerants for Air-Conditioning Sectors in High-Ambient Temperature Countries” (PRAHA);
- “Egyptian Project for Refrigerant Alternatives” (EGYPRA);
- the Oak Ridge National Laboratory (ORNL) “High-Ambient-Temperature Evaluation Program for Low-Global Warming Potential (Low-GWP) Refrigerants”, Phase I (and a new Phase II).

The results of the above programs’ testing of alternatives at high ambient temperature (HAT) conditions are further discussed in Chapter 5. In addition to the programs listed above, several independent or industry-led test campaigns for specific refrigerants are being performed for various applications and climate conditions. Results will be published when available.

The fluids participating in the four programmes named above and the refrigerants proposed under ASHRAE (ASHRAE, 2015), are presented in Table 2-3 for pure fluids and in Table 2-4 for blends with publicly known compositions. For ease of reference, key properties for selected commonly used refrigerants are given in Table 2-5 and Table 2-6.

The fluids which composition is not yet public are (with the safety class in brackets):

- ARC-1 (A1) and LPR1A (A2L) for replacing HCFC-123;
- BRB36 (A1) for replacing HFC-134a;
- ARM-32c (A1), D542HT (A1), DR-91 (A1), and N-20b (A1) for replacing HCFC-22, R-407C;
- ARM-20b (A2L) for replacing HCFC-22, R-404A, R-407C;
- ARM-32b (A1), D42Yb (A1), D42Yz (A1), and ARM-25a (A2) for replacing R-404A;
- ARM-71a (A2L) and HPR2A (A2L) for replacing R-410A.

Table 2-3: Pure substances proposed under various test programs and in ASHRAE 34

Refrigerant Designation	Proposed to replace (from AREP phase I)	Safety Class	High ambient programmes for HCFC-22 and R-410A alternatives participation in AREP program					Chemical Formula	Chemical Name	Molecular Weight	Boiling Point (°C)	ATEL/ODL (kg/m <sup>3</sup> )	LFL (kg/m <sup>3</sup> )	GWP 100 Year (IPCC5)	GWP 100 Year (RIOC)
			AREP Phase 1	AREP Phase 2	PRAH	EGYPT	US DOE								
HFC-32	R-404A, R-410A <sup>x</sup>	A2L	X	X	X	X	X	CH <sub>2</sub> F <sub>2</sub>	Difluoromethane (methylene fluoride)	52,0	-52	0,30	0,307	677	704
HC-290	HCFC-22, R-404A, R-407C	A3	X		X	X	X	CH <sub>3</sub> CH <sub>2</sub> CH <sub>3</sub>	propane	44,1	-42	0,09	0,038		5
HC-600a	HFC-134a	A3	X					CH(CH <sub>3</sub> ) <sub>2</sub> -CH <sub>3</sub>	2-methylpropane (isobutane)	58,1	-12	0,059	0,043		~20
R-717	HCFC-22, R-407C	B2L	X					NH <sub>3</sub>	ammonia	17,0	-33	0,000 22	0,116		
R-744	R-404A, R-410A	A1	X					CO <sub>2</sub>	carbon dioxide	44,0	-78 <sup>o</sup>	0,072	NF	1	1
HCFO-1233zd(E)	HCFC-123	A1		X				CF <sub>3</sub> CH=CHCl	trans-1-chloro-3,3,3-trifluoro-1-propene	130,5	18,1	0	NF	1	1
HFO-1234yf	HFC-134a	A2L	X	X				CF <sub>3</sub> CF=CH <sub>2</sub>	2,3,3,3-tetrafluoro-1-propene	114,0	-29,4	0,47	0,289	<1	<1
HFO-1234ze(E)	HFC-134a	A2L	X	X				CF <sub>3</sub> CH=CHF	trans-1,3,3,3-tetrafluoro-1-propene	114,0	-19,0	0,28	0,303	<1	<1
HC-1270	HCFC-22, R-407C	A3	X					CH <sub>3</sub> CH=CH <sub>2</sub>	propene (propylene)	42,1	-48	0,001 7	0,046		1,8
HFO-1336mzz (Z)	HCFC-123	A1						CF <sub>3</sub> CH=CH-CF <sub>3</sub>	cis-1,1,1,4,4,4-hexafluoro-2-butene	164,1	33,4	0	NF	2	2
HCC-1130(E)**	HCFC-123	B2						CHCl=CHCl	trans-dichloroethene	96,9	47,7			<1	<1

Notes:

Fluids given with a green background are fluids which were not previously mentioned in the XXVI/9 Task Force report.

<sup>x</sup> HFC-32 was proposed to replace R-404A and R-410A in phase I of the AREP program, but is only proposed to replace R-410A in phase II of same and later projects.

<sup>o</sup> For R-744 the sublimation temperature is given instead of boiling point. Triple point is -56,6 °C at 5,2 bar.

\*\*HCC-1130(E) is pending official ASHRAE 34 approval, submitted January 2016.

**Table 2-4: Blend refrigerants proposed under various test programs or in ASHRAE 34**

Refrigerant Designation	Refrigerant development name	Proposed to replace (from AREP phase I)	Safety Class	Participation in AREP alternatives program			Composition	Molecular Weight	Bubble point/dew or Normal boiling point (°C)	GWP 100 Year (IPCC5)	GWP 100 Year (RTOC)
				Phase 1	Phase 2	Phase 3					
				High ambient programmes for HCFC-22 and R-410A							
				US DoE							
				EGYPTA							
				PRAHA							
R-514A**	XP30	HCFC-123	B1				R-1336mzz(Z)/1130 (E) (74,7/25,3)	139,6		1,7	1,7
—	ARM-41a	HFC-134a	A1	X			R-134a/1234yf/32 (63/31/6)	99,5		860	900
R-513A	XP10	HFC-134a	A1	X	X		R-1234yf/134a (56/44)	108,4	-29,2	570	600
—	N-13a	HFC-134a	A1	X			R-134a/1234ze(E)/1234yf (42/40/18)	108,7		550	570
R-450A	N-13b	HFC-134a	A1	X	X		R-1234ze(E)/134a (58/42)	108,7	-23,4/ -22,8	550	570
R-515A**	HDR-115	HFC-134a	A1				R-1234ze(E)/227ea (88/12)	118,7	-19,2	400	380
R-513B*		HFC-134a	A1				R-1234yf/134a (58,5/41,5)	108,7	-29,9	540	560
—	D-4Y	HFC-134a	A1	X	X		R-1234yf/134a (60/40)	108,9		520	540
—	AC5X	HFC-134a	A1	X	X		R-1234ze(E)/134a/32 (53/40/7)	100,9		570	590
—	ARM-42a	HFC-134a	A2L	X	X		R-1234yf/152a/134a (82/11/7)	104,8		110	110
R-444A	AC5	HFC-134a	A2L	X	X		R-1234ze(E)/32/152a (83/12/5)	96,7	-34,3/ -24,3	89	93
R-445A	AC6	HFC-134a	A2L				R-744/134a/1234ze(E) (6/9/85)	103,1	-50,3/ -23,5	120	120
—	R290/R600a	HFC-134a	A3	X			R-600a/290 (60/40)	51,6			14
R-456A**		HFC-134a	A1				R-32/134a/1234ze(E) (6/45/49)	101,4	-31,1/ -25,7	630	650
R-407G		HFC-134a	A1				R-32/125/134a (2,5/2,5/95,0)	100,0	-29,1/ -27,2	1 300	1 400
—	LTR4X	HCFC-22, R-407C	A1	X	X		R-1234ze(E)/32/125/134a (31/28/25/16)	85,1		1 200	1 300
—	N-20	HCFC-22, R-407C	A1	X	X		R-134a/1234ze(E)/1234yf/32/125 (31,5/30/13,5/12,5/12,5)	96,7		890	950
—	D52Y	HCFC-22, R-407C	A2L	X	X		R-1234yf/125/32 (60/25/15)	97,8		890	970

—	L-20	HCFC-22, R-407C	A2L	X			R-32/1234ze(E)/152a (45/35/20)	67,8		330	350	
—	LTR6A	HCFC-22, R-407C	A2L	X	X		R-1234ze(E)/32/744 (63/30/7)	77,6		200	210	
R-444B	L-20a	HCFC-22, R-407C	A2L	X	X	X	X	R-32/1234ze(E)/152a (41,5/48,5/10)	72,8	-44,6/ -34,9	300	310
—	ARM-32a	HCFC-22, R-404A, R-407C	A1	X			R-125/32/134a/1234yf (30/25/25/20)	86,9		1 400	1 600	
R-442A		HCFC-22, R-404A, R-407C	A1	X			R-32/125/134a/152a/227ea (31,0/31,0/30,0/3,0/5,0)	81,8	-46,5/ -39,9	1 800	1 900	
R-449B		HCFC-22, R-404A, R-407C	A1				R-32/125/1234yf/134a (25,2/24,3/23,2/27,3)	86,4	-46,1/ -40,2	1 300	1 400	
R-449C*	DR-93	HCFC-22, R-407C	A1			X	R-32/125/1234yf/134a (20/20/31/29)	90,3	-45,5/ -38,5	1 100	1 200	
R-453A	RS-70	HCFC-22, R-407C	A1				R-32/125/134a/227ea/600/601a (20,0/20,0/53,8/5,0/0,6/0,6)	88,8	-42,2/ -35,0	1 600	1 700	
R-407H*		HCFC-22, R-407C	A1				R-32/125/134a (32,5/15,0/52,5)	79,1	-44,6/ -37,6	1 400	1 500	
R-449A	DR-33 (XP40)	R-404A	A1	X	X		R-32/125/1234yf/134a (24,3/24,7/25,3/25,7)	87,2	-46,0/ -39,9	1 300	1 400	
—	N-40a	R-404A	A1	X			R-32/125/134a/1234ze(E)/1234yf (25/25/21/20/9)	87		1 200	1 300	
—	N-40b	R-404A	A1	X			R-1234yf/32/125/134a (30/25/25/20)	87,1		1 200	1 300	
R-452A	DR-34 (XP44)	R-404A	A1	X			R-1234yf/32/125 (30/11/59)	103,5	-47,0/ -43,2	1 900	2 100	
R-452C**	ARM-35	R-404A	A1				R-32/125/1234yf (12,5/61,0/26,5)	101,9	-47,8/ -44,4	2 000	2 200	
R-448A	N-40c	R-404A	A1	X			R-32/125/1234yf/134a/1234ze(E) (26,0/26,0/20,0/21,0/7,0)	86,3	-45,9/ -39,8	1 300	1 400	
—	R32/R134a	R-404A	A2L	X			R-32/134a (50/50)	68,9		990	1 000	
—	ARM-31a	R-404A	A2L	X			R-1234yf/32/134a (51/28/21)	83,9		460	480	
—	L-40	R-404A	A2L	X	X		R-32/1234ze(E)/1234yf/152a (40/30/20/10)	73,6		290	300	
R-454A	DR-7 <sup>0</sup>	R-404A	A2L	X	X		R-1234yf/32 (65/35)	80,5	-48,4/ -41,6	240	250	
R-454C*	DR-3	R-404A	A2L	X	X	X	X	R-1234yf/32 (78,5/21,5)	90,8	-45,8/ -38,0	150	150
R-454A	D2Y-65	R-404A	A2L	X	X		R-1234yf/32 (65/35)	80,5	-48,4/ -41,6	240	250	
R-457A**	ARM-20a	R-404A	A2L				R-32/1234yf/152a (18/70/12)	87,6		140	150	

—	ARM-30a	R-404A	A2L	X		R-1234yf/32 (71/29)	84,7		200	200		
R-455A	HDR-110	R-404A	A2L	X		R-32/1234yf/744 (21,5/75,5/3)	87,5	-51,6/ -39,1	150	150		
—	R32/R134a	R-410A	A2L	X		R-32/134a (95/5)	53,3		710	740		
—	R32/R152a	R-410A	A2L	X		R-32/152a (95/5)	52,6		650	680		
—	DR-5	R-410A	A2L	X		R-32/1234yf (72,5/27,5)	61,2		490	510		
—	L-41a	R-410A	A2L	X		R-32/1234yf/1234ze(E) (73/15/12)	61		490	510		
—	L-41b	R-410A	A2L	X		R-32/1234ze(E) (73/27)	61		490	510		
—	ARM-70a	R-410A	A2L	X		R-32/1234yf/134a (50/40/10)	70,9		470	490		
—	HPR1D	R-410A	A2L	X	X	R-32/1234ze(E)/744 (60/34/6)	63		410	420		
—	D2Y-60	R-410A	A2L	X	X	R-1234yf/32 (60/40)	77,2		270	280		
R-454B	DR-5A	R-410A	A2L	X	X	X	X	R-32/1234yf (68,9/31,1)	62,6	-50,9/ -50,0	470	490
R-452B**	DR-55 (XL55)	R-410A	A2L			X	R-32/1234yf/125 (67/26/7)	63,5	-50,9/ -50,0	680	710	
R-446A	L-41-1	R-410A	A2L	X			R-32/1234ze(E)/600 (68,0/29,0/3,0)	62	-49,4/ -44,0	460	480	
R-447A	L-41-2	R-410A	A2L	X	X	X	X	R-32/125/1234ze(E) (68,0/3,5/28,5)	63	-49,3/ -44,2	570	600
R-447B**	L-41z	R-410A	A2L				R-32/125/1234ze(E) (68,0/8,0/24,0)	63,1	-50,3/ -46,2	710	750	

Notes:

Fluids given with a green background are fluids which were not mentioned in the XXVI/9 Task Force report.

\* Indicates refrigerants pending official ASHRAE 34 approval, submitted June 2015.

\*\* Indicates refrigerants pending official ASHRAE 34 approval, submitted January 2016.

◊ DR-7 has changed nominal composition slightly from originally R-1234yf/32 (64/36) to R-1234yf/32 (65/35).

**Table 2-5: Currently commonly used pure substances for reference**

Refrigerant Designation	Safety Class	Chemical Formula	Chemical Name	Molecular Weight	Boiling Point (°C)	ATEL/ODL (kg/m <sup>3</sup> )	Atmospheric Lifetime (Years)	Radiative Efficiency (W/m/ppm)	ODP		
									GWP 100 Year (RTOC)	GWP 100 Year (IPCC5)	
HCFC-22	A1	CHClF <sub>2</sub>	chlorodifluoromethane	86,5	-41	0,21	12	0,21	1 760	1 780	0,034
HCFC-123	B1	CHCl <sub>2</sub> CF <sub>3</sub>	2,2-dichloro-1,1,1-trifluoroethane	152,9	27	0,057	1,3	0,15	79	79	0,01
HFC-134a	A1	CH <sub>2</sub> FCF <sub>3</sub>	1,1,1,2-tetrafluoroethane	102,0	-26	0,21	14	0,16	1 300	1 360	
HC-290	A3	CH <sub>3</sub> CH <sub>2</sub> CH <sub>3</sub>	propane	44,1	-42	0,09	12,5 days				5
HC-600a	A3	CH(CH <sub>3</sub> ) <sub>2</sub> CH <sub>3</sub>	2-methyl-propane (isobutane)	58,1	-12	0,059	6,0 days				~20
R-717	B2L	NH <sub>3</sub>	ammonia	17,0	-33	0,000 22					
R-744	A1	CO <sub>2</sub>	carbon dioxide	44,0	-78 <sup>o</sup>	0,072			1	1	

**Table 2-6: Currently commonly used blend refrigerants for reference**

Refrigerant Designation	Safety Class	Refrigerant Composition (Mass %)	Molecular Weight	Bubble / Dew or Normal Boiling Point (°C)	ATEL/ODL (kg/m <sup>3</sup> )	ODP		
						GWP 100 Year (IPCC)	GWP 100 Year (RTOC)	
R-404A	A1	R-125/143a/134a (44,0/52,0/4,0)	97,6	-46,6/-45,8	0,52	3 900	4 200	
R-407A	A1	R-32/125/134a (20,0/40,0/40,0)	90,1	-45,2/-38,7	0,31	1 900	2 100	
R-407C	A1	R-32/125/134a (23,0/25,0/52,0)	86,2	-43,8/-36,7	0,29	1 600	1 700	
R-407F	A1	R-32/125/134a (30,0/30,0/40,0)	82,1	-46,1/-39,7	0,32	1 700	1 800	
R-410A	A1	R-32/125 (50,0/50,0)	72,6	-51,6/-51,5	0,42	1 900	2 100	
R-507A	A1	R-125/143a (50,0/50,0)	98,9	-47,1/-47,1	0,53	4 000	4 300	

As in the previous Decision XXVI/9 Task Force report, the data sources for Tables 2-3 through 2-6 are as follows:

- “GWP (RTOC)” values are taken from the 2014 RTOC report (UNEP, 2014) where available (they are based on (WMO, 2014)); where not available the value is calculated based on values for pure fluids from the 2014 RTOC report (UNEP, 2014).
- “GWP (IPCC5)” values are taken from the IPCC AR5 report (IPCC, 2014) for pure fluids; for mixtures values are calculated based values for pure fluids from the IPCC AR5 report (IPCC, 2014).
- For Tables 2-3 and 2-4, refrigerant designations, safety classes and compositions are taken from the AHRI AREP program where available, otherwise from ASHRAE 34 public review (ASHRAE, 2015).

- All other data in Tables 2-3 through 2-6 are taken from the 2014 RTOC report (UNEP, 2014).

### **2.3 Refrigerant classification and standards**

Refrigerants are classified by the refrigerant standard ISO 817 and ASHRAE 34 into 8 classes depending on toxicity and flammability, for instance: A1, A2L, A3 or B2L. The first, a letter A or B, indicates the toxicity of the fluid:

- A, lower chronic toxicity, have an occupational exposure limit of 400 ppm or greater
- B, higher chronic toxicity, have an occupational exposure limit of less than 400 ppm

The suffix 1, 2L, 2 or 3 indicates the flammability:

- 1, no flame propagation, measured at 60 °C
- 2L, lower flammability, burning velocity not higher than 10cm/s, energy of combustion below 19 MJ/kg and not flammable below 3.5 % volume concentration.
- 2, flammable, energy of combustion below 19 MJ/kg and not flammable below 3.5 % volume concentration.
- 3, higher flammability.

These safety classes are used by the system safety standards, such as ISO 5149, IEC 60335-2-24, IEC 60335-2-40, IEC 60335-2-89, EN378 and ASHRAE 15.

With the introduction and potentially wide use of refrigerants that are flammable, have higher toxicity and/or operate at notably higher pressures than the conventional ODS refrigerants or alternative non-flammable HFC refrigerants, consideration of safety matters has become more important. Accordingly, more attention is presently being paid to the requirements of safety standards and regulations that directly relate to refrigerants that exhibit these characteristics.

For instance, the safety standards sets upper limits on how much refrigerant charge is allowed in a refrigerant circuit, primarily depending on the safety class, location of the equipment, and on the type of people who have access to the equipment; the amount of charge is related to the cooling or heating capacity of the equipment. Using a wall mounted split A/C unit in a 30 m<sup>2</sup> room as an example, the safety standard, in this case IEC 6335-2-40, allows 0.413 kg of HC-290 per refrigeration circuit, while for HFC-32 it allows 5.6 kg charge, due to the different flammability characteristics of the substances. Clearly a more than 10 times higher charge allows higher cooling capacity with HFC-32. It also requires a higher level of optimising to account for the low charge limitation when using HC-290.

### **2.4 Likelihood of new molecules and new radically different blends**

There are alternative refrigerants available today with negligible ODP and (lower or) low GWP, but for some applications it can be challenging to reach the same lifetime cost level of the systems while keeping the same performance. The search for new alternative fluids may yield more economical system designs, but as will be explained below, the prospects of discovering new, radically different fluids are minimal.

The alternative refrigerants must have suitable thermodynamic properties, which determine the efficiency and capacity of the system. In addition, they need to satisfy several other criteria, such as zero ODP, low GWP, low toxicity, stability in the system, materials compatibility, acceptable cost, and, if possible, non-flammability, lower flammability or low-risk due to flammability. These requirements are difficult to balance.

The list of proposed R-410A and HCFC-22 replacement candidates includes single-component refrigerants (HFC-32, HC-290, HC-1270, R-717, R-744). The list also includes blends, which, in addition to the listed single-component candidates, comprise the so-called hydrofluoroolefins (unsaturated HFCs) such as HFO-1234yf and HFO-1234ze(E), along with traditional (saturated) HFC refrigerants to achieve the desired attributes of the blend, e.g., low GWP, lower flammability, or lubricant compatibility. Through ongoing evaluation studies, the performance potentials of these alternatives are being established.

Significant efforts have been done in the past to find new fluids. A recent study (McLinden, 2015) started with a database of over 150 million chemicals, screening the more than 56,000 small molecules and finding none of them ideal. It can be concluded from the study that the prospects of discovering new chemicals that would offer better performance than the fluids currently known are minimal.

## **2.5 Road to availability of alternative refrigerants**

As discussed in the Task Force Decision XXVI/9 Report (UNEP, 2015), developing a new fluid is a process where uncertainties are addressed, both regarding what is technically feasible and what can be accepted by the market. It is a process structured in discrete steps, where some are visible to the industry. The commercialisation of a new molecule is complicated and can take significant time, while for mixtures consisting of existing molecules the commercialisation is much faster. Once the fluid is launched in the market, the availability is largely controlled by where there is a market need.

The technical uncertainty includes how to produce the fluid, and whether the preferred properties can be attained. The market uncertainty includes uncertainty about what properties the customer prefers, and what fluids the competitors will market.

The development process requires a series of investments, such as researching the toxicity of candidate fluids, or doing field tests at potential customers with a candidate fluid. The investment pattern is similar from fluid to fluid, and companies therefore manage the process with a state-gate process (Cooper, 1988). The state-gate process uses a “gate” or decision point placed just in-front of each major investment, so that management can decide whether or not to accept the next investment or stop the development project. While the exact gates are not visible from outside the company, some of the steps will be visible in the market. Examples of such steps could be:

- Research, possibly in collaboration with a few selected system builders;
- Fluid (with a research acronym) released for small scale testing in industry test programs;
- R-number applied for through ASHRAE 34 (or ISO 817) and is normally accepted;
- Testing in the market to see whether the market is interested in larger capacities;
- Broad market launch (large scale production set-up);
- Submission and acceptance under pertinent government regulations (e.g., REACH or SNAP);
- Market adoption, where the market actually starts using the refrigerant in larger quantities.

Within the context of development of low GWP refrigerants, one of the most important incentives is the occurrence of relevant legislation that hinders competing fluids or opens pathways for new fluids and creates some measure of certainty for investments into the market.

The investment sizes and time needed for each step for new molecules (pure refrigerants) are much larger and longer than for refrigerant mixtures. Research and toxicity evaluation are

expensive in the early phases, and the production set in the later stages, are expensive for new molecules. While for new mixtures, the major uncertainty is related to the market, and the large investments are primarily on research, especially market research, to find a composition which matches the needs of the customers as well as possible, and on the market launch with investments in marketing.

This means that the commercialisation of a new fluid can take 10 years, while for mixtures the commercialisation takes closer to 5 years. An issue for the new mixtures is that many contain one of the two new molecules, HFO-1234yf or HFO-1234ze(E), which may have had only limited production until recently.

Once the fluid is launched in the market, companies will invest where they see the greatest market potential. There is a limit to how many different refrigerants customers, service companies, and sales channels in a given market will accept. Market shares obtained in the early phase tends to be relatively easy to sustain, which is why companies can be very picky about where they launch a product. Although current availability to the markets and market launch plans for specific fluids are proprietary information, there is however the general rule of thumb that new fluids will be available where a sufficiently large share of users request it.

Two examples of the step from commercial productions to market launch in specific markets are as follows:

- Commercial production of HFO-1234ze(E) started at the end 2014 in manufacturing plants in the US. It is now already commercially used in chillers by companies in the US, EU and Japan; besides and it is also applied in one-component foam and some aerosol propellant applications. Within two years after the start of commercial production, it is currently commercially available in the US, Europe and most of Asia.
- Commercial production of HCFO-1233zd(E) started by mid-year of 2014 in plants located in the USA. It is used in low pressure centrifugal chillers, which have been released in Europe, the Middle East and other 50 Hz markets; and it is also used in foam applications as a replacement for HFC-245fa. Within two years after the start of commercial production, it is currently commercially available in the US, Europe and most of Asia.

## **2.6 Energy efficiency in relation to refrigerants**

Assessing the energy efficiency associated with a refrigerant is a complicated process, and the results depend on the approach taken. Energy efficiency of refrigeration systems is, in addition to the refrigerant choice, related to system configuration, component efficiencies, operating conditions, operating profile, system capacity, and system hardware, among others, which makes a consistent comparison difficult in many instances.

One approach is to start with a target refrigerant and use a system architecture suitable for this specific refrigerant, while comparing it with a reference system for the refrigerant to be replaced.

Another approach is to screen for alternative refrigerants suitable for a given system architecture. The common methods for determining the efficiency in this case can be placed into one of three categories:

- theoretical and semi-theoretical cycle simulations
- detailed equipment simulation models, and
- laboratory tests of the equipment.

In a refrigerant selection process, great reliance is placed on cycle simulations for selecting best candidate fluids for further examination either by equipment simulation models or tests of actual equipment.

Most often, cycle simulations employ a refrigerant's thermodynamic properties along with fixed values for temperatures inside the system and fixed compressor isentropic efficiency. These models are popular among refrigeration practitioners because they are simple in principle and easy to use. However, the shortcomings to be kept in mind include not taking into account the heat transfer properties and pressure drops in a system. Detailed simulation models do not have this shortcoming (Domanski, 2006).

Laboratory tests provide the 'most trusted' information about performance of a refrigerant in a given system. It must be recognized that tests of a new refrigerant in a system optimized for a different refrigerant do not demonstrate the performance potential of the refrigerant tested (Abdelaziz, 2015). In addition to system 'soft-optimization', which includes adjustment of the refrigerant charge and expansion device, 'hard optimization' is necessary, which includes, among others, optimization of the compressor (including the size), refrigerant circuitry in the evaporator and condenser, and the overall system balance.

Hard optimization is a rather involved process. Usually, it is most effectively implemented by concurrent detailed simulations and extensive testing. It can be particularly complicated with blends of significant temperature glide, which offer special challenges and opportunities in heat exchanger design. Hence, overall system design and successful optimization play a significant role in achieving the refrigerant performance potential in a commercialized product. In practice the hard optimization is also limited by the cost of the system, as the success in the market depends on a cost/performance trade-off. In addition, it is also constrained by commercial availability (e.g., manufacturing ability) for certain components, such as availability of preferred compressor displacement, heat exchanger dimensioning and capability to produce preferred circuitry.

To illustrate the difficulties of assessing the energy efficiency associated with a refrigerant, consider the tests under high ambient temperature conditions described in Chapter 5 of this report:

- Testing temperatures differs from test program to test program.
- Obviously no single temperature can accurately match a real geographical location, so the results do not relate directly to the actual energy consumption in a real situation.
- The units (including technologies) used for testing varied within the same test programs.
- In some tests only the refrigerant is changed, in others the oil or even the compressor are changed.
- Differences in test protocols further contributed to differences in results, for example, adjusting the expansion device, adjusting the charge, or adjusting compressor displacement to match compressor and heat exchanger capacity.
- The cost/performance ratio is an important factor (see above) but it is difficult to analyse in the test programs as other long term parameters need to be considered.

## **2.7 Climate impact related to refrigerants<sup>2</sup>**

There are a number of difficulties in assessing the climate impact including the difficulties of obtaining reliable and accurate data on system leakage rates and determining the carbon emissions generated, now and in the future, and in producing the energy necessary to power the R/AC and HP system.

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<sup>2</sup> This section includes substantial contributions from J. Steven Brown, Ph.D., P.E., of The Catholic University of America, Washington, D.C., USA

Climate impact related to refrigerants consists of direct and indirect contributions. The direct contribution is a function of a refrigerant’s GWP, charge amount and leakage rates (annual, catastrophic, and during servicing and decommissioning) from the air-conditioning and refrigeration (R/AC and HP) equipment. The indirect contribution accounts for the CO<sub>2</sub>-equivalent emissions generated during the production of the energy consumed by the R/AC and HP equipment, its operating characteristics and the emissions factor of the local electricity production. The relative importance of the direct and indirect contributions will depend on the type of system. Systems that are “more leaky”, e.g., automotive vehicle air conditioning, typically have larger relative contributions from direct warming than would “tighter systems”, e.g., hermetically sealed chiller systems, although this can be offset for systems that have much shorter operating periods or where power is supplied from a source with low carbon content.

There are several metrics that measure the total emissions from a system. Most common are Total Equivalent Warming Impact (TEWI) and Life Cycle Climate Performance (LCCP) which attempts to quantify the total global warming impact by evaluating the R/AC and heat pump systems during their lifetime from “cradle to grave” (IIR, 2016). Sometimes, a TEWI calculation may be simplified by neglecting broader effects including manufacture of the refrigerant and equipment, and disposal of the refrigerant and equipment after decommissioning. More in-depth analyses not usually performed also look at the emissions associated with the production and disposal of the equipment, e.g., including the mining and recycling of the metal used to manufacture compressors, heat exchangers, and other components.

To summarize, the most important factors determining the climate impact are:

- The GWP of the refrigerant multiplied with the amount leaking from the system, this is the direct contribution.
- Energy consumption of the system multiplied with the amount of CO<sub>2</sub> generated per unit of energy, this is part of the indirect contribution.

The uncertainty on energy consumption and leakage makes determining the total climate impact difficult.

## 2.8 The GWP classification issue

To minimize direct climate impact, a lower GWP refrigerant can be used. The RTOC 2014 Assessment Report included a taxonomy of GWP values, including what constitutes high, medium, and low GWP (again given in Table 2-7 below). This taxonomy is based on fixed GWP values.

Table 2-7 defines “low” as smaller than 300 and “high” as more than 1000. There are sources that define low as lower than 25, as lower than 100, or as lower than 150 (which results from the 2006 EU MAC directive). It will be clear that “high”, “medium” and “low” are qualifiers, related to a scale, and that a number definition of these levels would be a non-technical choice. This also because it is somehow related to what is acceptable in specific applications.

**Table 2-7: Classification of 100 year GWP levels**

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

For instance, there is a relationship between the pressure, the GWP and the flammability of a refrigerant, as illustrated in Table 2-8, which is also from the RTOC 2014 Assessment Report (UNEP, 2014). The trend can be described as “the higher the pressure, the higher the minimum GWP which is needed for fluids to be non-flammable”. The exception to this relationship is R-717 and R-744, which do not fit this pattern. Therefore, what could be an “acceptable” GWP for a high pressure fluid replacing R-410A may not be “acceptable” for a low pressure fluid replacing HFC-134a. But this does not relate to a definition of a GWP classification in an absolute sense.

**Table 2-8: 100 year GWPs for synthetic refrigerants and hydrocarbons**

Safety Class	Range of GWP for Alternatives to		
	HFC-134a	HCFC-22, R-404A, R-407C, and R-507A	R-410A
A1	540 – 900	950 – 1600	
A2L	≤ 110	200 – 970	280 – 740
A3	14 – 20	1,8 – 5	

The two refrigerants that do not fit this pattern, both being in the category with ultra-low GWP, are R-717 and R-744. These are for many applications considered as alternatives to the current higher GWP HFCs. Though toxic in principle, R-744 is a safety class A1 refrigerant, while R-717 is in class B2L.

## 2.9 Environmentally sustainable and environmentally sound

The alternatives described under “low” or “lower” GWP here aim at satisfying a criterion of “environmentally sustainable” or “environmentally sound” (as this classification was used in Decision XXVI/9, taken in 2014).

*“By environmental sustainability we mean meeting current human needs without undermining the capacity of the environment to provide for those needs over the long term.”* ([http://www.unmillenniumproject.org/documents/EnvironSust\\_summary.pdf](http://www.unmillenniumproject.org/documents/EnvironSust_summary.pdf)).

None of the substances proposed as refrigerants are without potentially adverse impacts to the environment if the emissions are large enough (with the exception of water and air, neither of which can be widely applied). A good example is R-744 (CO<sub>2</sub>) which has no ODP and a very low GWP, however its emissions related to energy production are the primary contributor to global warming. What the environment and humanity is able or willing to handle is a policy decision, and so is the fraction of the environmental load allowed to be related to refrigerant emissions. One option to consider might be setting certain limits on direct refrigerant emissions relative to the IPCC 2050 scenarios. One could propose that a maximum of 1% of total GHG emissions could be an acceptable contribution of refrigerants and foam blowing agents. However, even with this type of policy approach the question remains of how emissions should be distributed between various application sectors within this very “broad” industry. Further, determining how much GHGs (HFCs) could be produced, and over what time frame, and how banks of these chemicals would be addressed such that the emissions through 2050 met this criterion, would involve establishing highly uncertain assumptions (e.g., leak rates) which could be very different between those various applications.

The following definition for “environmentally sound” is often used: *“An environmentally sound product or manufacturing process is a product or process that, from beginning to end, is in essential harmony with its environment and the associated ecological factors”* (<http://www.businessdictionary.com/definition/environmentally-sound.html>)

Article 10, paragraph (c) of the Kyoto Protocol (as decided in 1997) reiterated that all Parties shall: “co-operate in the promotion of effective modalities for the development, application and diffusion of, and take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies, know-how, practices and processes pertinent to climate change, in particular to developing countries, including the formulation of policies and programmes for the effective transfer of environmentally sound technologies that are publicly owned or in the public domain and the creation of an enabling environment for the private sector, to promote and enhance the transfer of, and access to, environmentally sound technologies.”

The IPCC in its AR5 report (IPCC, 2014) describes barriers for the spread of environmentally sound technologies (ESTs), as follows: “The spread of proven environmentally sound technologies that would diffuse through commercial transactions may be limited because of existing barriers. Barriers to the transfer of environmentally sound technologies arise at each stage of the process. These vary according to the specific context, for example from sector to sector and can manifest themselves differently in developed countries, developing countries and countries with economies in transition.” The IPCC report provides an extensive overview of the most important barriers in developed, developing and transition economies that could impede the transfer of environmentally sound technologies to mitigate and adapt to climate change. Governments can promote technology transfer by reducing these barriers.

## 2.10 References

- |                 |  |
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### **3 Update on R/AC alternative refrigerants and technologies**

This is a new chapter in this second version of the Task Force report (comparable to the updated chapter in the XXVI/9 TF report, September 2015). It presents information on alternative refrigerants for the various types of R/AC equipment using them as well as information on (NIK-Not In Kind) alternative technologies (see section 3.9). It also gives the latest developments for the use of efficient CO<sub>2</sub> technology (see section 3.10) and elaborates on the use of standards with regard to the safe use of refrigerants in the R/AC industry (see section 3.11).

#### **3.1 Domestic Appliances**

HC-600a and HFC-134a continue to be the primary refrigerant options for production of new equipment. It is projected that, by 2020, about 75% of new refrigerator production will use HC-600a, most of the rest will use HFC-134a, and a small share may apply unsaturated HFC refrigerants such as HFO-1234yf.

Globally, the activity undertaken so far on HFO-1234yf in domestic refrigerator applications remains very limited and is not being pursued with high priority, due to cost implications. The use of HFO-1234yf in a domestic freezer has been tested as a proof of concept.

The Association of Home Appliance Manufacturers (AHAM) of North America has recently announced a voluntary goal to phase down HFC-134a in household refrigerators and freezers after 2024. It is not yet clear whether manufacturers will choose HC-600a (class A2) or HFO-1234yf (class A2L) as both are flammable and still have to adhere to current and emerging safety and energy efficiency standards.

In the proposed USA Significant New Alternatives Policy (SNAP) listing of 18 April 2016, HFC-134a in domestic appliances is listed as undesirable as of 1/1/2021. The EU F-gas regulation 517/2014 prohibits the use of HFC-134a in domestic appliances as of 1/1/2015. This implies that the change to a low GWP refrigerant (defined as GWP <150 in 517/2014), away from HFC-134a, is a real issue here.

The heat pump clothes (laundry) dryer (HPCD) sales using HFC-134a are rapidly growing in the EU. HPCDs using R-407C and HC-290 have also been introduced. New research with R-744 shows significant efficiency gain may be possible. Alternative refrigerant solutions that are being explored include HC-600a and low GWP HFOs.

#### **3.2 Commercial Refrigeration**

While the F-gas regulation 517/2014 is now effective in Europe, in the United States, the Environmental Protection Agency (EPA), as already mentioned above, published a final rule for change of status of refrigerants in several applications under its SNAP program. Of significance were three changes of status: (1) for supermarket systems, (2) for condensing units and (3) one for self-contained coolers and freezers. In all of these applications, the high GWP HFC blend R-404A is not allowed in new equipment starting in January 1, 2017 for supermarkets, January 1, 2018 for condensing units and January 1, 2019 or 2020 for certain self-contained systems. Canada has signalled its intention to do something similar, and the US state of California is looking to the European F-gas regulation for its regulation. These are examples of governments that have started down the path of not allowing high GWP HFC refrigerants or HFC based blends in new equipment.

Lower GWP refrigerants and HFC blends (both class A1 and class A2L) are also being approved for use in various equipment types. The recent impact of these developments is

summarized below for various refrigerants as relevant to commercial refrigeration equipment.

In supermarkets, blends such as R-448A, R-449-A, R-449B, R-450A, and R-513A are now beginning to grow in use, starting with Europe and the US. Component manufacturers (compressors, valves, controls etc.) are releasing new products and approving existing products for use with these new refrigerants which range from half to a third of the GWP of the refrigerants that they are replacing.

The same holds true for condensing units and self-contained equipment. In the self-contained equipment category, early trials with HFO-1234yf and HFO-1234ze(E) have begun as well. The use of R-407A and R-407F (at approximately half the GWP of R-404A and with similar performance in systems) continues to grow in many parts of the world.

Refrigerants such as R-744 are increasingly being used in supermarket systems worldwide – both in cascaded systems (R-744 for low temperature cascaded with a second refrigerant like HFC-134a or similar and R-717 in limited cases) and in transcritical systems. Transcritical systems are being researched extensively to reduce their energy penalty at high ambient conditions through the use of component and system technologies such as ejector, adiabatic condensing, sub-cooling and parallel compression. R-744 is also beginning to see its use in walk-in applications with condensing units. Self-contained systems are increasingly moving from R-404A, HCFC-22 and HFC-134a to HC-290 or R-744. Charge limits continue to limit the size of the equipment possible with the hydrocarbon refrigerant.

### **3.3 Industrial Systems**

In the time since the release of the 2014 RTOC Assessment report, a number of overarching trends have been identified and are expected to be included in the 2018 Assessment report. The biggest trend in industrial refrigeration, which also forms an extensive challenge, is the constant focus on refrigerant charge reduction. Another big trend in the market is the heat pump market development. Industrial heat pumps use heat that is considered waste in other parts of production processes. An example is the dairy sector, where milk is both cooled and heated in different sequences. The pasteurization process requires temperatures around 70 to 80°C. Different technologies are used to achieve these temperatures.

For industrial processes, high temperature heat pumps are required, with temperatures to be produced of up to about 100 °C, sometimes even up to 180°C. Water Vapour Recompression (VRC, process recovering low heat steam at low pressure and compressing it to a high pressure and high temperature) is gaining a lot of attention.

District energy concepts (District Heating combined with District Cooling, «DC») are growing all over the world. In Europe, the two countries where the DC concept is most applied are France and Sweden. There is now more emphasis on applying DC in the Middle East post the 2014 assessment since it has the largest DC growth potential in the world. Recently the Multilateral Fund Executive Committee approved demonstration projects in the area. Implementing agencies UNIDO/UNEP are preparing demonstration projects in Egypt, Kuwait and Colombia to help establish “New Technologies”, legislation and benefits of DC for these areas. District heating and DC are growing in many markets, including in Article 5 Parties. DC can be driven by vapour compression or absorption (which fits into NIK) but in any case it requires significant investments in infrastructure. This is the reason why they are economically viable only when new buildings or new buildings networks are involved.

In some Parties, industrial refrigeration systems have been widely based on HCFC-22. Also in Article 5 Parties, the trend is now to abandon it and look for drop-in alternatives or for new refrigerant solutions.

### **3.4 Transport refrigeration**

R-452A has been introduced during 2015 as a customer option on new truck and trailer refrigeration units (it is a blend consisting of HFC-32, HFC-125 and HFO-1234yf). R-404A continues to be offered as well for its wide availability. R-452A has similar cooling capacity, fuel efficiency, reliability and refrigerant charge as R-404A, but it offers a 45% GWP reduction. The features supporting R-452A in transport refrigeration include non-flammability and low compressor discharge temperatures. By January 2016, one manufacturer has sold 1500+ units with R-452A already. The close property match of R-452A to R-404A gives customers the option to retrofit their existing fleets. The conversion does not require component changes and it can be carried out in the field during the life of the product.

In addition, activities are ongoing to assess R-744 and other non-flammable (A1) lower GWP solutions such as R-448A and R-449A. R-513A, R-513B, and R-456A are being considered as future drop-in solutions for HFC-134a that is utilized in some refrigerated vans and a large number of marine containers. These blends have approximately 50% of the GWP of HFC-134a. R&D is ongoing, but no products have been released so far based on these refrigerants.

Flammable (A3) and lower flammable (A2L) refrigerant research has continued, aiming at producing publicly available and technically sound references to support code and standard activities with regard to transport systems. König and Bararu (2014) have shown that frequency of hazard and probabilities of fatalities for the global reefer container fleet would be below  $10^{-6}$  (one in a million) if adequate design changes were in place and best practice guidelines were established. In February 2016, the first meeting took place to develop the International Organisation for Standardisation (ISO) 20854 safety standard for refrigerating systems using flammable (A2) and lower flammable (A2L) refrigerants in marine containers. The feasibility of using HC-290 in trucks has been demonstrated in a demo unit in South Africa and was presented at the MOP-27 in Dubai in 2015. The benefits are an improved energy performance and lower life cycle CO<sub>2</sub> emissions. The project included a risk assessment, careful components selection, and leak simulation tests.

An energy optimization of a cryogenic system has entered a commercial testing phase in the United Kingdom (UK). The system uses liquid nitrogen to provide cooling through its expansion and to power a Dearman engine supplying a vapour compression cycle. A second generation machine is being developed but this has not yet reached a commercially viable stage.

A UK supermarket chain continues carrying out trials of an R-744 refrigerated trailer since 2013. They revealed that they have subsequently acquired a second R-744 trailer that can operate at different temperatures and this will be joined by a third in 2016. Since 2012, companies shipping and leasing reefer containers have continued to trial R-744 units from the same manufacturer.

The German and French railways have continued to look at air cycle systems as alternatives to vapour compression systems. Deutsche Bahn (DB) has equipped the first car of an Intercity Express (ICE) train in March 2015 while Société Nationale des Chemins de Fer (SNCF) has set up a 24-months demonstration program in a regional train.

### **3.5 Air-to-air air conditioners and heat pumps**

Air conditioners, including reversible air heating heat pumps (generally defined as “reversible heat pumps”), range in size from 1 kW to 750 kW although the majority are less than 70 kW. The most populous are non-ducted single splits, which are produced in excess of 100 million units per year. Whilst nearly all air conditioners manufactured prior to 2000 used HCFC-22, all products sold within non-Article 5 Parties now use non-ODS refrigerants, albeit largely without the use of low-GWP alternatives. For most products, R-410A is used. Whilst the production of air conditioners using HCFC-22 remains the dominant option within Article 5 Parties there is a substantial shift in many countries to move to HFCs and HCs, approximately one half of all units produced globally use non-ODP refrigerants. Nevertheless, the majority of the installed unit population still uses HCFC-22; an estimated two-thirds of a billion HCFC-22 air conditioners are operating worldwide, representing approximately one million tonnes of HCFC-22.

The most substantial recent developments are related to the increased rate of substitution of HCFC-22 and the greater consideration of use of medium and low GWP alternatives. Previously, medium and low GWP alternatives were not being given major consideration (except HCs such as HC-290) whereas now additional manufacturers are adopting HCs and there is also uptake of HFC-32, especially in Japan where in 2014 100% of residential split air conditioner production was switched to HFC-32. Several enterprises – in Japan, and recently in other Parties as well, – are promoting and selling air conditioners using HFC-32 outside of Japan. Many enterprises are also considering and evaluating new HFC/HFO blends, such as mixtures of various compositions of HFC-32, HFC-125, HFC-134a, HFO-1234yf and HFO-1234ze(E). Broad testing has been carried out of these mixtures within various collaborative industry projects and the results are being made available on a regular basis. Whilst R-744 remains to be applied in larger types of systems within more temperature climates, there has not been any significant shift in increasing adoption of the technology.

China has completed the conversion of 18 production lines to HC-290 as part of their HPMP and portable units are being sold widely. In India, at least one plant has produced several hundred thousand HC-290 split air conditioners. There is also additional information relating to different alternatives performance under high ambient conditions. Nevertheless, some enterprises within the Middle East still see R-407C and HFC-134a as favourable alternatives to HCFC-22.

In light of the fact that almost all medium and low GWP alternatives are flammable there has been significant progress with the development of new requirements for safety standards (particularly for increasing refrigerant charge size), with working groups addressing A2, A2L and A3 refrigerants at both IEC and ISO level. Due to the complexities of the process it is unclear by when amendments will be finally published.

### **3.6 Water heating heat pumps**

In Europe, Japan and the US, the legislation on minimum energy efficiency for space heating and water heating heat pumps became active and has limited the number of air to water heat pumps that can be placed on the market.

For space heating heat pumps in the EU, the minimum energy efficiency was set as a primary energy efficiency based on seasonal efficiency, placed in an average European climate with a design temperature at -10°C, including standby losses. From September 2015 on, all space heating heat pumps shall have a primary energy efficiency of 100%. For low temperature space heating heat pumps it shall be 115%. This results in a seasonal coefficient of performance (SCOP) of respectively 2.5 and 2.875. From September 2017 onwards, the values shall be 110% (SCOP of 2.75) and 125% (SCOP of 3.125). The seasonal efficiency is based on a specific temperature pattern and includes standby energy losses. For water heating

heat pumps the requirements are less restrictive except for larger systems where the requirements will have restrictions as of September 2018. For the moment, there is no drastic impact on the refrigerant currently used.

HFC-32 has been just introduced by one manufacturer in Japan as the refrigerant for water heating systems (mainly R-744 products are sold in the market). Unlike R-744, which can produce hot water with temperatures up to 90°C, the temperature of the water is limited to 65°C. The main purpose is to offer a cost competitive and high energy efficiency solution for families with lifestyles suited to operations of this system.

### **3.7 Chillers**

The components, refrigeration cycles used, systems, and application of chillers remains largely unchanged from the 2014 RTOC Assessment Report or since 1980 for that matter with exception of increased use of variable-speed drives. Vapour compression technology dominates all chiller types, and there has been little progress towards commercialisation of magnetic refrigeration based chillers and other not-in-kind technologies. However, absorption chillers are, and will continue to be, part of the global mix of chillers. In all regions, there is a demand for higher performance chillers and the systems that use them, at both full and partial load. Some manufacturers are offering newly designed compressors, have expanded the use of variable speed drives and permanent magnet motors, and are using more sophisticated control systems. Manufacturers, consumers, and regulators alike have had an ongoing interest in low GWP refrigerants with high thermodynamic efficiency. The slow movement to new refrigerants reflects the high cost of product development and tooling changes, as well as the uncertainty in the supply of new refrigerants by chemical producers who also face huge investments and regulatory hurdles. None-the-less, chiller manufacturers seem to be gravitating to lower GWP alternative refrigerants, and have introduced a number of new products that use them.

The 2104 RTOC Assessment Report gave a complete discussion of the trade-offs and research efforts associated with use of lower GWP refrigerants. As noted in the report, in order to be acceptable, new refrigerants should result in products with energy efficiencies that are equal to or better than the refrigerants replaced. Secondly, the global warming effects from chillers are dominated by the energy-related component from their power consumption. Total Equivalent Warming Impact (TEWI) and Life Cycle Climate Performance (LCCP) models typically show that more than 95% of the climate effect is due to energy consumption. The direct global warming effects from refrigerant emissions are significantly smaller since direct emissions have been significantly reduced in recent years through lower charge systems, low-leak designs, manufacturing and testing improvements, and improved service practices.

Chillers have traditionally used an array of refrigerants due to the economics associated with high performance compressors as well as physical size and manufacturing constraints over the range of capacities provided by chillers. Table 9-1 of the 2014 RTOC Assessment Report gave a discussion and complete listing of all chiller types by size, compressor type, and refrigerants used.

After years of research and screening tests, an array of choices is emerging. Some commercialization has started and recent new product introductions indicate that a change has started (shown in Table 3-1).

**Table 3-1 Emerging refrigerants used in Chillers**

<b>Product</b>	<b>Refrigerants presently in use</b>	<b>Emerging refrigerants</b>
Large chillers with centrifugal compressors using low pressure refrigerants	CFC-11 <sup>2</sup> HCFC-123 <sup>1</sup> HFC-245fa	HCFO-1233zd(E) R-514A
Large chillers with centrifugal compressors using medium pressure refrigerants	CFC-12 <sup>2</sup> HFC-134a	R-513A HFO-1234yf HFO-1234ze(E)
Mid-size chillers with positive displacement (screw) compressors	CFC-12 <sup>2</sup> HFC-134a	R-513A HFO-1234yf <sup>3</sup> HFO-1234ze(E) <sup>3</sup>
Small chillers with positive displacement (scroll or recip) compressors	HCFC-22 <sup>2</sup> R-407C R-410A	HFC-32 <sup>3</sup> R-452B <sup>3</sup>

1. Phase-out in new equipment in 2020
2. Phased out but may still be used for servicing in Article 5 Parties
3. Classified as A2L refrigerant (lower flammable)

The emerging refrigerants may not be the final selections. With high efficiency as a primary customer requirement, new product introductions will use refrigerants that likely preserve or improve thermodynamic efficiency with significantly reduced GWPs. A number of refrigerants are listed as safety class 2L (flammable with flame propagation speeds of 10 cm/s or less). Some Parties, notably the U.S., have not yet implemented the necessary product standards and code changes to use these refrigerants in the occupied space or in large machinery rooms without the burdensome requirements of safety class 2 or 3, highly flammable refrigerants. Even with codes and standards changes, some additional application cost may be expected. Taken together with generally higher refrigerant costs, this means that the cost of new chillers with lower GWP refrigerants is likely higher. Manufacturers typically pass along additional costs, and therefore the price is likely higher, which typically will dampen the demand as long as the existing product is not discontinued.

Regulation is taking a leading role in mandating the adoption of new refrigerants with lower GWPs. There is continued pressure for the use of lower GWP refrigerants in all Parties and industry is responding. For example, AHRI (the manufacturer’s trade association in the US) and NRDC (the National Resources Defense Council, Washington, D.C.) recently agreed to discontinue sale of chillers using higher GWP refrigerants HFC-134a, R-410A and R-407C by 1/1/2025. This agreement is consistent with the emerging refrigerants listed in Table 3-1. The agreement also provides support to the US EPA’s proposal to ban all 3 refrigerants from new production chillers, although the EPA proposed timeline is somewhat quicker. The time to 2025 will allow manufacturers to complete the design and implementation of full product lines, and work on cost reductions. At the same time, refrigerant producers will need to increase capacity to meet demand, and put products into the product service infrastructure. Ideally, as the product changes occur, major disruptions will be avoided.

One can also not overlook the role that zero or near-zero GWP refrigerants such as R-717, R-718, and HC-290, and absorption chillers may play. As noted in the 2014 RTOC Assessment Report, these alternatives have been available for some time, and new choices may emerge. It is impossible to predict the market mix that may emerge, especially in view of future government regulations or incentives.

As far as drop-in alternatives or retrofits are concerned, it is too early to tell if manufacturers will offer retrofit packages for use in upgrading existing chillers with the emerging lower GWP refrigerants. While technically possible, it would not be likely for several reasons. First, all compressor types are optimized for the specific refrigerant used. Substituting a different refrigerant usually results in a loss of capacity, efficiency or both. Second, the pressure ratio for fixed displacement compressors may limit the ability of the compressor to reach the appropriate pressure rise when a different refrigerant is used. A similar phenomenon is found in centrifugal compressors when changing refrigerants, but may be overcome with a change in impellers or speed when a variable speed drive is used. Third, many of the emerging refrigerants are safety class 2L. Use of a safety class 2L refrigerant to replace a safety class 1 refrigerant may require significant changes to meet the building codes and standards, as well as product standards (such as UL, listing to a product standard). These things taken together would likely discourage retrofits.

### **3.8 Vehicle air conditioning**

Since the 2014 RTOC Assessment Report, no new alternatives have been introduced in light-duty mobile air conditioners (MACs). The penetration of HFO-1234yf for new vehicles has continued and has spread to many additional models, primarily in non-Article 5 Parties, but is still far from complete. HFC-134a continues to be used in the majority of new vehicles, especially in vehicles used in Article 5 Parties. Regulations and announcements of such - including the MAC Directive of 2006 in the EU, credit system and model year 2021 HFC-134a phase-out in the US, the Canadian consideration of bans and HFC phasedowns, and the Japanese target GWP of 150 by 2023, - continues to be primary factors influencing this trend. In addition, development of R-744 MACs has continued and appears imminent, with announcements from Mercedes-Benz to use it in new S-class and E-class models for the EU beginning in 2017, and indications that Audi A8 and Volkswagen Phaeton models will also use R-744 in 2017.

Other alternatives that were discussed in the 2014 RTOC Assessment report, - including hydrocarbons, HFC-152a and additional HFC/HFO blends R-444A and R-445A, - have not received much additional consideration and appear unlikely to be chosen for new vehicles in the near future.

The trend in electrified drivetrains continues, with hybrids and battery-electric vehicles capturing more of the market. This is important in terms of refrigerant as these vehicles will increase the desire for heat pump (heating and cooling) systems in lieu of cooling-only systems. More advanced designs integrating battery and/or electronics cooling with the passenger comfort system are likely to be introduced.

Buses still rely primarily on HFC-134a and R-407C for passenger comfort. Some vehicles using R-744 are operating, and their use, while currently low (perhaps about 20 buses), is increasing but is limited by the availability of open-type compressors. The trend to hybrid electric buses will allow hermetic or semi-hermetic compressors, making the use of R-744 more likely.

Heavy Duty trucks still rely on HFC-134a for driver comfort. Some versions are likely to introduce HFO-1234yf soon.

### **3.9 Not-In-Kind technologies**

This chapter looks into technologies that do not employ vapour compression technology. They are called Not-In-Kind-Technologies (NIK). Vapour compression technology has been the dominant technology for all R/AC applications in the last 100 years. Nevertheless, during

past years several other technologies have been developed. The development status of those technologies can be classified as:

- R&D status
- Emerging technology
- Commercially available

Recently, the U.S. Department of Energy (U.S. DoE, 2014) developed a study to characterize and evaluate alternatives to vapour-compression technology to serve future residential and commercial HVAC applications. Provided below are some of the main aspects of this study.

NIK technology classifications are divided into three groups according to their particular driving energy. Those are:

- Thermally driven.
- Electro- mechanically driven.
- Solid State driven.

Seventeen NIK technologies from these 3 groups were compared in the study to a baseline vapour compression technology, considering the following criteria:

- Energy savings potential.
- Non-energy benefits.
- Cost/complexity.
- Heating and cooling capabilities.
- Development status.
- Market barriers.

Based on these criteria they were classified as i) most promising, ii) very promising, iii) moderately promising, and iv) least promising:

- Most promising: membrane heat pump, thermo-elastic;
- Very promising: evaporative liquid desiccant A/C, magneto-caloric, Vuilleumier heat pump;
- Moderately promising: evaporative cooling, thermo-electric, ground-coupled solid desiccant A/C, absorption heat pump, duplex-Stirling heat pump, thermo-acoustic, adsorption heat pump, thermo-tunneling;
- Least promising: stand-alone solid desiccant A/C, stand-alone liquid desiccant A/C, ejector heat pump, Brayton heat pump.

The present status, the development of prototypes and equipment and the expected technical progress of some NIK technologies are as follows:

#### *Thermo-elastic and Membrane Technologies:*

A one TR (3.52 kW) window air conditioner prototype that operates on thermo-elastic technology is undergoing testing. In another facility, one manufacturer developed a one TR (3.52 kW) prototype space- conditioning system that operates on Membrane Heat Pump technology using this two stage (latent and sensible) technology. The manufacturer predicts an EER of 26 Btu/Whr or greater.

#### *Absorption, Evaporative and Evaporative Liquid Desiccant Technologies:*

Absorption heat pumps are commercially available and have an inherent advantage since they can operate on low heat energy exergy thus saving on precious peak electric power. Evaporative cooling has always been an attractive alternative in Hot-Dry conditions, although Indirect/Direct evaporative cooling can be used in both dry and humid hot conditions, its water consumption rates can be a risk in arid conditions. Evaporative Liquid Desiccant technology, a R&D technology, also consumes water and careful selection is needed in regions where water is scarce.

*Ground coupled Solid Desiccant AC Magneto-caloric and Vuilleumier Heat Pump technologies.*

Ground coupled Solid Desiccant AC is also a R&D technology and uses (low exergy) thermal energy. Magneto-caloric and Vuilleumier Heat Pump technologies are both in the emerging phase and are promising technologies.

### **3.10 Developments of CO<sub>2</sub> technology**

Applying CO<sub>2</sub> (R-744) as a working fluid is common in hot water and industrial heat pumps, light commercial beverage cooling and especially in supermarket refrigeration.

Due to the thermodynamic properties of CO<sub>2</sub>, throttling losses compared to conventional low-pressure fluids are significantly higher, particularly at elevated heat rejection temperatures common at higher ambient temperatures where the energy efficiency of the CO<sub>2</sub> units is lower.

Introducing an internal heat exchanger can help to reduce the throttling losses. In addition, utilising the kinetic energy of the fluid flowing from the high- to the low-pressure side can save compressor work instead of dissipating it in the throttling process. Two apparatuses are able to perform such work recovery, expanders and ejectors.

Expanders use the throttling energy to assist the compressor and are comparable with compressors with respect to cost and complexity.

Ejectors are more comparable to expansion devices, however, they use the expansion of the high-pressure fluid to entrain and compress a low-pressure fluid by means of momentum transfer between the two streams inside the ejector without moving parts. Ejectors are suitable for dedicated applications due to their high robustness, reliability and potential low cost.

As reported by Elbel and Lawrence (2016), the work recovery efficiency of CO<sub>2</sub> ejectors is generally in the range of 20-30%, which means that 20-30% of the normally dissipated expansion work is applied to unload the compressor by pre-compressing the suction stream from suction inlet pressure (evaporator outlet) to the separator pressure (compressor inlet). Unloading the compressor is not the only benefit of an ejector, using it to simultaneously pump additional liquid through the evaporators, i.e. overfeeding them, avoids dry-out and improves the evaporator and system performance significantly. This increases the required suction pressure of the compressor twice, firstly due to the elevated evaporation temperature (flooded evaporation) and the pre-compression of the evaporator outlet fluid.

For commercial refrigeration applications, as in supermarkets, ejector systems enabling continuously flooded evaporator operation are commercially available. There are more than 40 ejector supported CO<sub>2</sub> installations around the globe. The first pilot systems applying additional compressor unloading by pre-compressing of medium temperature vapour (from chilled food display cabinets) are successfully operated for several years in Switzerland (Schönenberger et al. 2014).

The multi-ejector is an add-on enhancement technology increasing the energy efficiency at high ambient temperatures to a state of the art CO<sub>2</sub> booster system with parallel compression. The parallel compression booster system represents a development step towards higher energy efficiency compared to the traditional booster systems with flash gas by-pass. Based on the experimental investigations in laboratories and field tests of the CO<sub>2</sub> supermarket systems, a seasonal energy efficiency improvement of 10% is obtained between a CO<sub>2</sub> booster and a similar system with parallel compression. At high ambient temperatures, another 20% improvement is achievable when adding the multi-ejector technology to a well-

designed CO<sub>2</sub> parallel compression system. Global supermarket chains, operating CO<sub>2</sub> ejector supported supermarkets in Spain, have measured an annual energy saving of 25% compared to the previous HFC unit installed prior to the remodelling of the supermarket.

Utilization of heat recovery for space heating (where needed) and hot water production is an important part of the refrigeration systems and can be done with CO<sub>2</sub> without any large extra effort.

CO<sub>2</sub> ejector technology is under development for other applications such as industrial or commercial cold storage refrigeration systems, transport refrigeration systems, industrial heat pump applications, chillers, etc.

### **3.11 Standards in the R/AC industry**

For the refrigeration, air-conditioning and heat-pump industry the two most important standardisation organisations for international standards are the International Organization for Standardisation (ISO) and the International Electro-technical Commission (IEC). In some cases, standards from nationally based organisations will be more recognised in the field (e.g., ASHRAE, UL and SAE in the United States). In these cases, efforts may be made to harmonise with ISO and IEC standards as appropriate.

ISO has published two standards of high relevance to the topic of refrigerants: (1) “ISO 817 Refrigerants - Designation and safety classification” and (2) “ISO 5149 Refrigerating systems and heat pumps - Safety and environmental requirements”. ISO 5149 is the primary standard for larger systems. IEC has published relevant application specific standards as parts of the standard “IEC 60335 Household and similar electrical appliances – Safety”, for instance “IEC 60335-2-40 Household and similar electrical appliances - Safety - Part 2-40: Particular requirements for electrical heat pumps, air-conditioners and dehumidifiers”. The IEC application standards are typically used for factory build systems, while the ISO 5149 is typically used for larger systems.

The safety standards covers topics such as:

- Refrigerant safety: Definitions and charge limits and definitions.
- Construction: Approval of components, piping, joints and assemblies, pressure testing and tightness requirements, safety valves and switches, setting and selection, avoidance of ignition sources for flammables.
- Installation: Machine rooms, other installation sites, ventilation.
- Maintenance: Safe practices, avoid leaking refrigerants

Some of these topics, especially the charge limits, have profound influence on which refrigerants are considered safe to use in what applications.

The text of a standard is produced by a Working Group, a sub-committee of the Technical Committee of either ISO or IEC responsible for all standards related to refrigerating systems safety. In shorthand this is ISO/TC86/SC1 or IEC/TC61D/SC61. The technical committee members are nominated representatives of national standards bodies (NSB) and the committee business is conducted by ballot, with votes cast by the head of delegation from each country on behalf of their NSB. In contrast, the members of a WG are nominated experts who do not represent a country or NSB and who do not need to be members of the TC. The WG strives to meet face-to-face, and participation of experts in the standardisation working groups is typically sponsored by the employer of the expert. Membership of the Technical Committee is open to representatives of all member countries (ISO has 161 members, while IEC has 83 members and associated members).

The international standards preparation processes comprise several defined stages requiring alternate input from NSBs and Working Group members. A committee draft is prepared by the WG and circulated to NSBs for comment. The comments received are resolved to the best of the WG's ability in discussion, within a consensus process and the resultant draft standard is sent to the NSB's for vote. The rules for voting are complex but clearly defined. The standard is only accepted if several criteria are met. In some cases, particularly if a large number of comments are received to the draft standard, the text will go back to the working group for review and will then be recirculated as a second draft. Once the text has been refined, the standard will be reissued as a final draft for vote by the NSB's. If the votes meet the criteria then the text will proceed to publication.

### **3.12 References**

- Elbel and Lawrence, 2016    Review of recent developments in advanced ejector technology. 2016. *Int. J. Refrigeration*, Volume 62, February 2016, pp. 1-18, ISSN 0140-7007
- Schönenberger et al., 2014    Experience with ejectors implemented in a R-744 booster system operating in a supermarket. 2014. 11th IIR GL Conference, Hangzhou, China (paper 19)
- U.S. DoE, 2014                Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies



## **4 Alternatives to refrigeration systems on fishing vessels**

This new chapter responds to the decision request to provide new and updated information, as this is available, related to “the availability of alternatives for replacement and retrofit of refrigeration systems in fishing vessels, including in small island countries.” Related to this chapter, Annex 2 contains additional background information on refrigeration systems in the fishing industry (with a special focus on the situation of the Pacific Islands region).

### **4.1 Introduction**

In order to respond to the following question asked within the Decision XXVII/4 of the Twenty-seventh Meeting of the Parties:

- (a) *Update, where necessary, and provide new information on alternatives to ozone-depleting substances, including not-in-kind alternatives, based on the guidance and assessment criteria provided in subparagraph 1 (a) of decision XXVI/9, and taking into account the most recent findings on the suitability of alternatives under high-ambient temperatures, highlighting in particular :*
  - (ii) *the availability of alternatives for replacement and retrofit of refrigeration systems in fishing vessels, including in small island countries;*

a Working Group was established within the TEAP Decision XXVII/4 Task Force.

As their first action, the members of the Working Group, aiming at clarifying the problems being experienced by the fishing industry, compiled a questionnaire to be circulated to Parties in order that an understanding of their needs could be ascertained. Responses to the questionnaire as well as further investigation of worldwide fishing practices, refrigeration systems and techniques employed were considered by the Working Group in the development of this chapter (see Annex 2 for a broader description).

### **4.2 Considerations and options for replacement and retrofit of refrigeration systems in fishing vessels**

As a summary of the analysis performed on the world fishing industry, with a particular attention on the situation in the Pacific Islands region, the following are important considerations of the options for replacement and retrofit of refrigeration systems on fishing vessels:

- 70% of the global fishing fleet continues to use HCFC-22 as its main refrigerant. Therefore the main challenge for the industry is to find a feasible transition from HCFC-22 to low-GWP alternatives.
- Considering that 70% of the global fishing fleet is based in Asia/Pacific, this challenge becomes even more important for Asia/Pacific Parties and specifically for the Pacific Island region, whose economy is heavily dependent on their fishing industry.
- Based on several parameters (age of vessels, availability of alternatives, technical and economic feasibility of conversions, meeting regulatory requirements of product importer), the transition from HCFC-22 to low-GWP alternatives can be implemented following four different options as further discussed in the following sections, with rating provided according to the degree of financial, technical and regulatory risk, and in Annex 2:
  - Option 1 – Non-halocarbon refrigerants
  - Option 2 - Refrigerant replacement with plant adjustments
  - Option 3 – Refrigerant drop-in
  - Option 4 - Maintaining HCFC-22

#### 4.2.1 Option 1 – Non-halocarbon refrigerants (R-717 and R-744)

Current technology present several interesting options, catering for almost all the industry requirements. Systems with ammonia (R-717), carbon dioxide (R-744) or ammonia/carbon dioxide cascade cover almost all the possible applications. Due to the costs and modifications involved when transiting from an HCFC-22 plant to a non-halocarbon refrigerant, R-717 options cannot be considered a viable solution for the replacement or retrofit of refrigeration plants on existing vessels considered here. However, their choice is probably the right one when new ships are considered or when rebuilding can be accepted. Running an ammonia plant requires skilled personnel. R-744 option can be a good solution also for existing vessels as demonstrated by recent experiences. Cost of systems for conversion to R-717 and R-744 options compete with HFC systems in the markets where they so far have been sold.

	Financial considerations		Technology risk (Complexity and performance)	Regulatory and environmental risk (10 years horizon)
	Capital investment	Operating expenses		
<b>Option 1 – Non-halocarbon refrigerants</b>				
R-717 system	<b>Medium</b>	<b>Medium</b>	<b>High</b>	<b>Nil</b>
	Requires new ship with separate machine room or rebuilding	Potential improvement in efficiency. Require competence, but inexpensive refrigerant	Highly complex relative to on-board capabilities. Additional safety risk of ammonia (lower flammable and toxic). Training required in new markets	No environmental policy risk throughout expected life of equipment.
R-717/R-744 cascade system	<b>Medium</b>	<b>Medium</b>	<b>High</b>	<b>Nil</b>
	Requires new ship with separate machine room or rebuilding	Potential improvement in efficiency. High maintenance cost due to complexity. Require competence, but inexpensive refrigerant	Highly complex relative to on-board capabilities. Additional safety risk of ammonia (lower flammable and toxic), Training required in new markets	No environmental policy risk throughout expected life of equipment.
R-744 system	<b>Medium</b>	<b>Medium</b>	<b>Medium</b>	<b>Nil</b>
	Suitable for existing vessels with replacement of system	Potential improvement in efficiency at the expenses of complexity. Require competence, but inexpensive refrigerant	Some complexity relative to on-board capabilities. Training required in new markets	No environmental policy risk throughout expected life of equipment.

#### 4.2.2 Option 2 – Refrigerant replacement with plant adjustments

The conversion of an existing plant to a halocarbon refrigerant is a technically and economically feasible option, provided a low-GWP fluid is available for the task. Even if many HFC blends are presently under scrutiny, there is no solution ready at the moment and it is not possible, at this stage, to name a refrigerant that will be the definitive low-GWP substitute to HCFC-22. As is well known, the situation is evolving rapidly and it may be reasonable, nevertheless, to expect in the medium term that a solution will emerge for this type of conversion. The economics of the operation will, of course, depend on the cost of the new refrigerant. Most likely, the possible alternatives will be flammable in category A2 or A2L, thus requiring adequate safety considerations and precautions.

	Financial considerations		Technology risk (Complexity and performance)	Regulatory and environmental risk (10 years horizon)
	Capital investment	Operating expenses		
	Medium	Unknown	Unknown	Unknown
<b>Option 2 – Refrigerant replacement with plant adjustments</b>				
Conventional refrigeration plant system operating with low-GWP HFC blend	Suitable for existing vessels with change of components and adjustments	Cost of refrigerants at present unknown flammability must be addressed	No significant change in type of technology and components	Environmental policy risk throughout expected life of equipment unknown at present

#### 4.2.3 Option 3 – Refrigerant drop-in

For systems with less than 10 to 15 years' service life, a retrofit using a drop-in refrigerant becomes a feasible option, provided there is such a drop-in. At present, however, there is no low-GWP HFC available on the market that can be used as drop-in for on-board systems. As mentioned above, the situation with alternatives is evolving rapidly so that alternatives for this option may become more apparent in the near future.

	Financial considerations		Technology risk (Complexity and performance)	Regulatory and environmental risk (10 years horizon)
	Capital investment	Operating expenses		
	Unknown	Unknown	Unknown	Unknown
<b>Option 3 – Refrigerant drop-in</b>				
Conventional refrigeration plant system operating with low-GWP HFC blend	Requires improvement of refrigerant containment	Cost of refrigerants at present unknown flammability must be addressed	No significant change in type of technology and components	Environmental policy risk throughout expected life of equipment unknown at present

#### 4.2.4 Option 4 – Maintaining HCFC-22

Considering the current problems in finding proper solutions for the retrofit of on-board systems equipped with HCFC-22, one reasonable option could be to keep using HCFC-22 in the system for a few more years, until the end of the ship life cycle or until a cost and environmentally effective solution becomes available. The time horizon for this type of option should be no more than 4-5 years and the target should be those on-board plants with more than 10-15 years' service life remaining. Maintaining HCFC-22 would require the contextual execution of some actions that increase operational efficiency.

One aspect to be considered is how to meet regulatory requirement of product importers, especially when non-flagged vessels are involved.

	Financial considerations		Technology risk (Complexity and performance)	Regulatory and environmental risk (10 years horizon)
	Capital investment	Operating expenses		
	Low	High	Low	Very high
<b>Option 4 – Maintaining HCFC-22</b>				
Existing plant, operating with HCFC-22, with improved containment Short term solution (max 4-5 years) May not be practical for all vessels	Requires improvement of refrigerant containment	HCFC-22 price expected to increase	No change in technology Limited supply of HCFC-22 in emergency	HFC-22 phase-out in advanced stages

#### 4.2.5 Additional considerations

Some additional considerations with regard to replacement and retrofit of refrigerant systems in fishing vessels include the following:

- The only sector where both replacement and retrofit are currently missing a real and final solution is the ultra-low temperature refrigeration, needed for the conservation of sashimi and sushi grade tuna.
- The only sector where both replacement and retrofit are currently missing a real and final solution is the ultra-low temperature refrigeration (lower than -50°C evaporation), that may be needed in some systems for the conservation of sashimi and sushi grade tuna.
- High Ambient Temperature issues do not pose a problem for this specific sector as refrigeration systems are generally cooled by sea water.
- Not-In-Kind technologies (defined as those refrigeration techniques which do not use vapour compression reverse cycle), even though presenting some interesting options for application within the fishing industry, are not expected to be commercially available for the sector in the short term.

## 5 Suitability of alternatives under High Ambient Temperature (HAT) conditions

Based on comments from Parties on TEAP’s first report to OEWG-37, this revised chapter provides a more balanced discussion (both positive and negative) of the results as well as additional information on the three testing programs for refrigerants under HAT conditions and includes the following changes and additions:

- Further discussion on the discussion of the methods for considering the impact of the high ambient temperatures on the design of R/AC equipment (see section 5.1); and
- Further information on the reports published for the three projects, which tested alternative refrigerants at temperatures above 35°C and including tabulated summaries of each of the three projects (see section 5.2).

### 5.1 Influence of HAT conditions on R/AC equipment design

As mentioned previously in the TF reports, HAT conditions are an important issue for the design of R/AC systems. Ambient temperatures are also used in cooling load calculation and building envelope design.

As the ambient temperature increases, system load increases and capacity decreases. With increasing ambient temperatures, the condensing pressure and compressor discharge temperatures also increase, thus leading to possible reliability issues. ISO and EN (European Standards) prescribe pressures corresponding to certain design temperatures for the safe operation of a system. This information is required by design engineers to specify material and pipe wall thickness requirements in a system. Table 5-1 is taken from EN378-2:2008 and the equivalent ISO 5149 based on IEC 60721-2-1.

*Table 5-1: Specified Design Temperatures*

Ambient Conditions	< 32°C	< 38°C	< 43°C	< 55°C
High pressure side with air cooled condenser	55°C	59°C	63°C	67°C
Low pressure side with heat exchanger exposed to ambient temperature	32°C	38°C	43°C	55°C

While normally systems are designed for 35°C (T1 in ISO 5151:2010) with appropriate performance (cf. for example, under standards requirements) up to 43°C in some Parties, the high ambient temperature condition requires a design at 46°C (T3 in ISO 5151:2010) with appropriate operation up to 52°C.

High humidity is an important issue even with lower than 35°C temperature conditions for certain Parties. This is because Parties that have high humidity, need high cooling load and thus bigger A/C units when considering the fresh air loads requirement during the selection of the air conditioning units, especially with humidity levels above 60%.

Earlier Task Force reports ((UNEP, 2015) and the March version of the XXVII/4 TF report) already presented methods to assess temperature conditions using incidence of number of hours, weather profiles, cooling degree days, or bin weather data. These methods can again be summarized as follows.

“**Incidence of Ambient Temperatures**” is a design method that is based on 0.4%, 1%, 2% and 5% of the time per year --for the last 10 years-- (corresponding to 35, 88, 175 and 438 hours per year) that the temperature exceeds 35, 40 or 45°C. It is currently the most used method for determining design conditions for air conditioning and refrigeration, where design tables exist for most cities around the world. Most experts and consultants use this method

when they have to make estimates for the cooling capacity of A/C and R equipment. A few use the 0.4 % number, others use 1% or 2 %, but the 5% number (438 hours a year above 35°C) is the most often used.

The “**Climate Zones**” method, is where a map of the world in the ASHRAE Standard 169-2013 defines the various climate zones. Zones defined vary from zone A0 (extremely hot humid) down to climate zone 2B (hot dry). The definition of a climate zone is based on the criteria of Cooling Degree Days (CDD). This indicator uses daily temperature data from weather stations over a period of 15 to 30 years to give a typical average year. The most recent data is Typical Meteorological Year (TMY) defined as TMY 3 for the period 1991-2010, and compares the daily average outdoor temperature with a defined baseline temperature for indoor comfort, in this case 18.3°C (65 F). For example, if the average temperature on a particular day is 26°C (78 F), then that day counts as 13 cooling degree days, as a building’s interior would need to be cooled by 7.2°C (13 F) to reach 18.3°C (65 F).

This method takes in consideration the wet bulb temperature (humidity) in each country; It has an added advantage in that it differentiates between the Dry and Humid conditions in countries.

The “**Bin Weather**” Method is based on the system operating pressure. EN378-2:2008 (European Standards) and ISO 5149 (based on IEC 60721-2) prescribe pressures corresponding to certain design temperatures for the safe operation of a system. This information is required by design engineers to specify material and pipe wall thickness requirements in a system. EN378 specifies design conditions at 32, 38, 43, and 55°C but does not specify what is a high ambient temperature. This method is a bit complicated and needs specifying a lot of factors (pressure, density... etc.) which necessitates a lot of data analysis to derive the required final data. It is based on the system pressure values, which can be calculated from the actual design temperature.

Using data from a data base giving temperature measurements in many Parties in the world, some Parties have developed a method for selecting Parties with a high ambient temperature according to their average peak ambient temperature per month during a year<sup>3</sup>. Information on this approach for defining HAT Parties was shared with the Task Force, but as this approach was still under discussion by Parties at OEWG-37, the Task Force only notes this information is available without any further review or evaluation.

## **5.2 Results from research projects**

Most of the research and development has traditionally been made at the “standard ambient” of 35°C dry bulb temperature; even lower temperatures are used for some tests (e.g., under Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 210/240). The performance of units at different ambient temperatures would then be simulated or extrapolated. The status of the three research projects testing refrigerant alternatives used in specific equipment operating under high ambient temperature conditions were all made public

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<sup>3</sup> The US and some Parties discussed a preliminary proposal at OEWG-37 that uses as criterion an average of at least two months per year over 10 consecutive years of a peak monthly average temperature above 35°C. Countrywide values in the dataset are calculated by taking a spatially weighted average of all weather stations within a country. The data were extracted from countrywide values in a dataset that are available from the Center of Environmental Data Analysis (CEDA). “Peak monthly average temperature” is calculated by finding the high temperature for each day in the month and averaging those daily highs to get an average peak temperature value for the month. The data source cited above refers to this as monthly average daily maximum temperature, and there are other ways to describe this criterion.

during the period late 2015/early 2016 giving detailed technical results. The three projects are:

- “Promoting low GWP Refrigerants for Air-Conditioning Sectors in High-Ambient Temperature Countries” (PRAHA) and “Egyptian Project for Refrigerant Alternatives” (EGYPRA);
- the Oak Ridge National Laboratory (ORNL) “High-Ambient-Temperature Evaluation Program for Low-Global Warming Potential (Low-GWP) Refrigerants”, Phase I (and ongoing Phase II); and
- The AHRI Low GWP Alternative Refrigerants Evaluation Program (AREP) Phase I (and ongoing Phase II).

### 5.2.1 *PRAHA project*

“Promoting low GWP Refrigerants for Air-Conditioning Sectors in High-Ambient Temperature Countries” (PRAHA). PRAHA, which was launched by UNEP/UNIDO in 2013 and completed in 2015, involved custom made prototypes built by manufacturers based in the Gulf Cooperation Council countries and tested at an independent lab. The project is implemented at the regional level in consultation with National Ozone Units of Bahrain, Iraq, Kuwait, Qatar, Oman, Saudi Arabia, and the UAE to ensure incorporating the project outputs within the HCFC Phase-out Management Plans (HPMPs) particularly for the preparation of post 2015 policies and action-plans. The project tested 14 prototypes using 5 refrigerants and 9 base units running with HCFC-22 or R-410A.

Building up on PRAHA and the linkage to country phase-out plans, Egypt adopted a similar initiative as part of the HPMP to test refrigerant alternatives for air-conditioning units built in Egypt. The initiative EGYBRA tests more blends in different applications. The initiative was launched back in June 2014 and is expected to have the results by the end of 2016.

Both projects built custom made units and testing was done at independent labs at 35, 46, and 50°C ambient temperatures for PRAHA and an additional 27°C for EGYBRA, with an “endurance” test at 55°C ambient to ensure continuous operation for two hours when units are run at that temperature. The proposed refrigerants are shown in table 5-2 below:

**Table 5-2: Alternative refrigerants used in PRAHA and EGYBRA projects**

<b>Comparable to HCFC-22</b>	<b>Comparable to R-410A</b>
R-290	HFC-32
R-444B (L-20)	R-447A (L-41-1)
DR-3	R-454B (DR-5A)
R-457A (ARM-20a)	ARM-71a

Table 5-3 shows the result from the testing of the prototypes and their comparison to their respective base units. The table shows the type of equipment tested, the laboratory at which it was tested, the baseline refrigerant against which the prototype is compared, and the constraints and the modifications that were included with the prototype. The table then compares each type of alternative refrigerant to the base unit for COP (efficiency) and capacity at 35°C and a higher ambient temperature which in this case is 50°C.

**Table 5-3 PRAHA results for cooling capacity and efficiency as percentage compared to the baseline units**

Equipment type	Lab utilized	Baseline refrigerant	Prototype Criterion	Refrigerant tested	COP % comp to baseline @ 35°C	Capacity % comp to baseline @ 35°C	COP % comp to baseline @ 50°C	Capacity % comp to baseline @ 50°C
18,000 Btu/hr. Window Unit	Intertek - USA	HCFC-22 COP = 3.14 at 35°C and 2.26 at 50°C for OEM A COP = 2.76 at 35°C and 2.02 at 50°C for OEM B	Custom built prototypes to fit in the same box dimension as the base unit. Expansion device and charge amount designed to meet a minimum specified EER	L-20 (OEM A)	-11%	9%	-10%	7%
				L-20 (OEM B)	-2%	-6%	-5%	-10%
				DR-3 (OEM A)	-9%	2%	-2%	1%
20,000 Btu/hr. split system	Intertek - USA	HCFC-22 COP = 2.75 at 35°C and 1.94 at 50°C for OEM C COP = 2.52 at 35°C for OEM D	Custom built prototypes to fit in the same box dimension as the base unit. Expansion device and charge amount designed to meet a minimum specified EER	HC-290 (OEM C)	4%	8%	-2%	5%
				L-20 (OEM D)	-19%	7%	-76%	-78%
				DR-3 (OEM D)	-27%	-33%	-28%	-31%
24,000 Btu/hr. split system	Intertek - USA	R-410A COP = 3.52 at 35°C and 2.30 at 50°C for OEM E COP = 3.08 at 35°C and 2.02 at 50°C for OEM F	Custom built prototypes to fit in the same box dimension as the base unit. Expansion device and charge amount designed to meet a minimum specified EER	HFC-32 (OEM E)	-1%	15%	-2%	16%
				HFC-32 (OEM F)	-9%	8%	-22%	-1%
				L-41 (OEM E)	-10%	20%	-7%	22%
36,000 Btu/hr. Ducted Split	Intertek - USA	HCFC-22 COP = 2.83 at 35°C and 1.91 at 50°C for OEM G	Custom built prototypes to fit in the same box dimension as the base unit. Expansion device and charge amount designed to meet a minimum specified EER	L-20 (OEM G)	0%	-7%	2%	-5%
				DR-3 (OEM G)	-18%	-25%	-13%	-21%
36,000 Btu/hr. Ducted Split	Intertek - USA	R-410A COP = 2.79 at 35°C and 1.84 at 50°C for OEM G	Custom built prototypes to fit in the same box dimension as the base unit. Expansion device and charge amount designed to meet a minimum specified EER	HFC-32 (OEM G)	-1%	-4%	-12%	-18%
90,000 Btu/hr. Rooftop by Intertek	Intertek -USA	HCFC-22 COP = 2.95 at 35°C and 2.07 at 50°C for OEM H	Custom built prototypes to fit in the same box dimension as the base unit. Expansion device and charge amount designed to meet a minimum specified EER	L-20 (OEM H)	1%	6%	-3%	5%
				DR-3 (OEM H)	-3%	-1%	-6%	-4%

Notes on the terms in the table:

- 1 Efficiency (COP) is measured in Watts of cooling per Watt of input;
- 2 PRAHA did measurements at 35, 46 and 50°C ambient temperatures;
- 3 For a full description of refrigerant alternatives and their GWP values, please refer to the relevant chapter on refrigerants in this report;
- 4 Test conditions are as follows: For 35°C ambient, indoor 26.67°C and 50% relative humidity (AHRI –A. For 50°C ambient, indoor 29°C and 50% relative humidity
- 5 Cells shaded grey show results that are not consistent with other results for the same refrigerant and could be the results of optimization or design issues.

The outcomes of the PRAHA project, other than the testing results, are:

- There is a need to do risk assessment studies at HAT conditions in Parties that experience HAT conditions;
- There is a need for a full product re-design taking into consideration the technical issues of heat exchanger optimisation, expansion device selection, charge optimisation, excessive pressure, temperature glide, flammability, oil, and energy efficiency issues;
- The economic impact is still to be considered when the availability and cost of components have been determined by market factors. Today's price on the market of components is not representative for the cost in the longer term, so alternative methods have to be used to analyse future cost;
- There is need for field testing of the units once a design and alternative refrigerants have been selected by the concerned original equipment manufacturers (OEMs).

For EGYPRA, all prototypes are ready and have been tested at the respective manufacturers. The process of testing the prototypes and base units at the independent lab will start soon and results are expected at the end of the year.

The work by PRAHA and EGYPRA will facilitate the technology transfer and the exchange of experience with low-GWP alternatives for air-conditioning applications operating in high-ambient temperature Parties. The other indirect objective is to encourage the development of local/regional codes and standards that ease the introduction of alternatives needing special safety or handling considerations, and to ensure that national and regional energy efficiency programs are linked to the adoption of low-GWP long term alternatives (PRAHA, 2013).

### 5.2.2 ORNL Project

“High-Ambient-Temperature Evaluation Program for Low-Global Warming Potential (Low-GWP) Refrigerants” by the Oak Ridge National Laboratory (ORNL). ORNL conducted tests using two “soft-optimized” ductless mini-split air conditioners having a cooling capacity of 5.25 kWh (1.5 TR). One unit which was designed to operate with HCFC-22 refrigerant was used for alternative refrigerants that are equivalent in characteristics to HCFC-22, while the other which was designed to use R-410A refrigerant tested the R-410A alternatives. Eighty-four tests were conducted in total for a total of 10 alternative refrigerants at ambient temperatures varying from 27 to 55°C.

**Table 5-4: Alternative refrigerants used in ORNL Project**

Comparable to HCFC-22	Comparable to R-410A
N-20b	HFC-32
DR-3	R-447A (L-41-1)
ARM-20b	DR-55
R-444B (L-20a)	ARM-71a
R-290	HPR-2A

Table 5-5 shows the results for the ORNL project taken from the various reports available online. ORNL tested two base units and then changed the refrigerant as well as certain components and settings to test the alternative refrigerants.

**Table 5-5 ORNL results for capacity and efficiency as percentage compared to the baseline units**

Equipment Type	Lab utilized	Baseline Refrigerant	Equipment Criterion	Refriger. Tested	COP % comp to baseline @ 35°C	Capacity % comp to baseline @ 35°C	COP % comp to baseline @ 52°C	Capacity % comp to baseline @ 52°C
18,000 Btu/hr. Split unit (Carrier)	ORNL	HCFC-22 COP = 3.07 at 35°C and 1.98 at 52°C	Same machine to test all refrigerants. Criteria: matching superheat and sub cooling to base unit. Changing expansion devise. Charge level optimized at 35C	N-20B	-13%	-14%	-11%	-15%
				DR-3	-16%	-12%	-14%	-12%
				ARM-20B	-12%	-3%	-11%	-3%
				R-444B (L-20A)	-11%	-9%	-7%	-4%
				HC-290	7%	-8%	7%	-4%
18,000 Btu/hr. split unit (Carrier)	ORNL	R-410A COP = 3.4 at 35°C and 2.07 at 52°C	Same machine to test all refrigerants. Criteria: matching superheat and sub cooling to base unit. Changing expansion devise. Charge level optimized at 35C	HFC-32	4%	5%	5%	11%
				DR-55	3%	-3%	3%	0%
				R-447A (L-41)	-5%	-14%	3%	-6%
				ARM-71a	-1%	-8%	2%	-4%
				HPR-2A	-2%	-9%	5%	-1%

**Notes on the terms in the table**

- 1 Efficiency (COP) is measured in Watts of cooling per Watt of input;
- 2 ORNL did measurements at 27.8, 35, 52 and 55°C ambient temperatures;
- 3 For a full description of refrigerant alternatives and their GWP values, please refer to the relevant chapter on refrigerants in this report;
- 4 Test conditions are as follows: For 35°C ambient, indoor 26.7/19.4°C (AHRI-A). For 52°C ambient, indoor = 29/19°C.

The ORNL/TM-1015/536 report has the following conclusion appearing as part of its Executive Summary (reproduced here without changes):

*“The test results from this evaluation program demonstrate that there are several viable alternatives to both R-22 and R-410A at high ambient temperatures. In some cases, there was a significant improvement in the performance of the alternatives over that of the baseline, in terms of both COP and cooling capacity. In other cases, the performance of the alternatives fell within 10% of the baseline, which suggests that parity with baseline performance would likely be possible through additional engineering design.*

*The R-22 alternative refrigerants showed promising results at high ambient temperatures: although both of the A1 alternative refrigerants lagged in performance, some of the A2L refrigerants showed capacity within 5% and efficiency within approximately 10% of the baseline system. The A3 refrigerant (R-290) exhibited higher efficiency consistently; however, it did not match the cooling capacity of the baseline system. The most promising A2L refrigerants exhibited slightly higher compressor discharge temperatures, while the A3 refrigerant exhibited lower compressor discharge temperatures.*

*The R-410A alternative refrigerants are all in the A2L safety category. Most of them showed significant potential as replacements. R-32 was the only refrigerant that showed consistently better capacity and efficiency; however, it resulted in compressor discharge temperatures*

that were 12–21°C higher than those observed for the baseline refrigerant. These higher temperatures may negatively impact compressor reliability. DR-55 and HPR-2A had higher COPs than the baseline and matched the capacity of the baseline at both the hot and extreme test conditions. R-447A and ARM-71a had lower cooling capacity than the baseline at all ambient conditions. The system efficiency of R-447A showed improvement over the baseline at high ambient temperatures; for ARM-71a, the efficiency was similar to the baseline at all test conditions.

*The efficiency and capacity of the alternative refrigerants could be expected to improve through design modifications that manufacturers would conduct before introducing a new product to market. However, given that the scope of this study covered only soft-optimized testing, no detailed assessment can be made of the extent of potential improvements through design changes. Within the bounds of what is possible in optimizing the units for soft-optimized tests, the ORNL test plan included only minor optimizations, including refrigerant charge, capillary tube length, and lubricant change. Therefore, these are conservative results that probably could be improved through further optimization. Additional optimization, including heat transfer circuiting and proper compressor sizing and selection, would likely yield better performance results for all of the alternative refrigerants.*

*Losses in cooling capacity are typically easier to recover through engineering optimization than are losses in COP. The primary practical limit to improvements in capacity is the physical size of the unit; but that is not expected to be a significant concern in this case, based on the magnitude of the capacity losses exhibited in this evaluation program. Thus, the COP losses and the increases in compressor discharge temperature are particularly important results of this testing program, in that these variables will be the primary focus of future optimization efforts.*

*This performance evaluation shows that viable replacements exist for both R-22 and R-410A at high ambient temperatures. Multiple alternatives for R-22 performed well. Many R-410A alternatives matched or exceeded the performance of R-410A. These low-GWP alternative refrigerants may be considered as prime candidate refrigerants for high ambient temperature applications. Before commercialization, engineering optimization carried out by manufacturers can address performance loss, the increase in compressor discharge temperature that many alternatives exhibited (particularly the R-410A alternatives), and any safety concerns associated with flammable alternatives.” (Abdelaziz, 2015)*

**Phase II:** ORNL started the second phase of the program testing “Low GWP Refrigerants in High Ambient Temperature Countries” in February 2016, covering roof-top air conditioners in this phase. Results will be published in the second half of 2016.

### **5.2.3 AREP Project**

“Low GWP Alternative Refrigerants Evaluation Program” (AREP) Phase-II. The project was launched by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) is a cooperative research program to identify suitable alternatives to high GWP refrigerants without prioritizing them. In the first phase of the project, 21 international companies evaluated 38 refrigerant candidates for replacing HCFC-22 and three HFCs, R-410A, HFC-134a, and R-404A (Amrane, 2013), in applications varying from air conditioners and heat pumps (both package, split and variable refrigerant flow), chillers (screw and centrifugal), refrigeration (commercial and ice machines), refrigerated transport, and bus air-conditioning. Phase II tested 17 refrigerants plus doing more tests at high ambient temperature conditions.

**Table 5-6: AREP Phase II low-GWP High Ambient testing**

AREP Phase II Low-GWP High Ambient Test Matrix										
Product	Test companies	High Ambient Conditions	Baseline Refrigerant	ARM-71a	DR-5A	DR-55	HPR2 A	L-41-1	L-41-2	HFC-32
34 MBH chiller	Armines	115F	R-410A		X			X	X	X
14 SEER 3-ton HP	Carrier	125F	R-410A	X	X		X	X	X	
13 SEER 3-ton HP	Danfoss	115F and 125F	R-410A		X				X*	X**
14 SEER 3-ton split HP	Goodman	115F and 125F	R-410A							X***
5-ton packaged	Lennox	115F	R-410A	X	X	X	X		X	X
4-ton packaged	Trane	125F	R-410A		X	X				X
6-ton packaged	Zamilac	125F	R-410A							X

\* L-41-2 at wet suction, no HAT

\*\*HFC-32 with same charge and with optimized charge

\*\*\* HFC-32 with standard POE oil and with prototype POE oil

For high ambient testing, seven entities tested three residential split units, four rooftops, one chiller, and several compressors. The results were compared to baseline of R-410A units. Refrigerant candidates are shown in table 5-8 below (Schultz, 2016a). Refrigerants were tested at 115 F (46.1°C) and 125 F (52.6°C). The tests were either a drop-in or a soft optimization with a change in refrigerant charge and/or expansion device.

AREP-II was conducted by several entities with different test protocols which contributed to differences in results. The different tests varied from drop-in to soft-optimized tests adjusting the expansion device for similar superheat, or adjusting the charge for a similar sub-cooling. The results shown below are extracted from the test reports of AREP-II that are available publically on-line.

**Table 5-7 AREP-II results for capacity and efficiency as percentage compared to the baseline units**

Equipment Type	Company	Baseline Refrigerant	Prototype Criterion	Refrigerant Tested	COP % comp to baseline @ 35°C	Capacity % comp to baseline @ 35°C	COP % comp to baseline @ 51.6°C	Capacity % comp to baseline @ 51.6°C
36,000 Btu/hr. Split heat pump	Carrier Indianapolis	R-410A COP = 3.55 at 35°C and 1.87 at 51.6°C	Criteria: Matching superheat and sub cooling to base unit. Charge level determined by criteria and held constant for all temperatures tested	ARM-71A	-1%	-8%	7%	-3%
				R-454A (DR-5A)	-1%	-6%	6%	-1%
				HPR2A	-4%	-11%	3%	-4%
				R-446A (L-41-1)	-2%	-10%	-1%	-3%
				R-447A (L-41-2)	-1%	-7%	-1%	-4%
48,500 Btu/hr. Rooftop	Ingersoll Rand Clarksville	R-410A COP = 3.31 at 35°C, 2.00 at 48.9°C and 1.80 at 51.6°C	Adjustable expansion device, Variable Frequency drive matching the capacity with base unit. Varying indoor conditions	DR-55	4%	0%	3%	0%
				HFC-32	6%	1%	NA	NA
				DR-5A	5%	1%	7%	3%
72,000 Btu/hr. Rooftop	Zamil KSA	R-410A COP = 3.57 at 35°C and 2.06 at 51.6°C	Criteria maintained same superheat and sub cooling as base unit by changing expansion devise and adjusting charge. Oil is also different	HFC-32	2%	9%	10%	16%
34,000 Btu/hr. split	Goodman USA	R-410A COP = 3.53 at 35°C and 1.82 at 51.6°C	Tested HFC-32 unit with POE oil and withy prototype oil for the same expansion devise and charge determined by superheat	HFC-32 with prototype oil	3%	7%	13%	14%
60,000 Btu/hr. Rooftop	Lennox USA	R-410A COP = 3.87 at 35°C and 2.07 at 51.6°C	Matching superheat and sub cooling	L-41-2	3%	-7%	10%	-1%
				ARM-71A	3%	-4%	10%	2%
				HPR2A	1%	-5%	8%	1%
				DR-5A	1%	-4%	2%	-3%
				HFC-32	-10%	-4%	-9%	-1%

**Notes on terms in the table:**

- 1 Efficiency (COP) is measured in Watts of cooling per Watt of input
- 2 PRAHA did measurements at 35, 46 and 50°C ambient temperatures
- 3 For a full description of refrigerant alternatives and their GWP values, please refer to the relevant chapter on refrigerants in this report
- 4 Test conditions are as follows: For 35°C ambient, indoor 26.67°C and 50% relative humidity (AHRI -A). For 50°C ambient, indoor 29°C and 50% relative humidity
- 5 Cells shaded grey show results that are not consistent with other results for the same refrigerant and could be the results of optimization or design issues

The conclusion from AREP-II (Schultz, 2016a) is that general trends in HAT performance are similar for all alternative refrigerants. Systems with alternatives generally provided similar to higher capacities than R-410A systems at HAT conditions, i.e., showing a smaller decrease in capacity as ambient temperatures increase

#### **5.2.4 General remarks on the three research projects**

The March TF XXVII/4 report noted that tests under HAT conditions described above illustrate the difficulties of assessing the energy efficiency associated with a refrigerant, considering:

- Testing temperatures differs from test program to test program;
- Obviously no single temperature can accurately match a real geographical location, so the results do not relate directly to the actual energy consumption in a real situation;
- The units used for testing vary within the same test programs;
- In some tests only the refrigerant is changed, in others the oil is changed or even the compressor;
- Differences in test protocols further contributed to differences in results, for example: adjusting the expansion device for similar evaporator superheat, adjusting the charge for a similar sub-cooling, or adjusting compressor displacement to match compressor capacity to heat exchanger capacity.

In evaluating the three projects, the following conclusions and comments can be drawn from the technical data presented in the capacity and efficiency tables:

- The measured efficiency of the alternative refrigerants is in the vicinity of plus or minus 15% of the base units to which they were compared;
- The R-410A alternatives give results that are close to the performance of R-410A at HAT. However, the performance of R-410A at HAT is lower than HCFC-22 due to the characteristic of the refrigerant;
- The performance of the prototypes can be further improved through optimization of components and design parameters;
- The safety aspect is important for the high ambient temperature countries as the refrigerant charge is higher than for units operating in lower ambient temperatures.
- The efficiency and capacity of the alternative prototypes are two aspects of the comparison. A more complete comparison would also include a cost comparison; however, there is not enough data on cost, neither for some of the alternative refrigerants nor of the components to have a measurable comparison;
- While efficiency is important to meet the regulatory minimum energy performance standards (MEPS), the capacity of air conditioners at HAT conditions is of utmost importance in order to provide the required indoor comfort when these conditions happen.
- As a general rule, the cost of the equipment depends on the characteristics of the refrigerant and the performance of the equipment at high ambient temperatures. For example, if the capacity of the equipment at HAT is 10% lower for the required efficiency, then a larger machine is needed to meet the required load making the equipment more expensive;
- ORNL and PRAHA came to slightly different conclusion about the performance of alternative refrigerants vs. HCFC-22 with PRAHA generally showing better results. This is due to the fact that the PRAHA prototypes were custom built, while ORNL uses the base unit with some optimisation. From this it can be concluded that results can be improved with customisation. The engineering level of the unit is more important than the refrigerant characteristic.

### 5.3 Further considerations

Chapter 7 of the September 2015 XXVI/9 Task Force Report (UNEP, 2015) discussed additional topics related to HAT conditions: a definition of options for HAT conditions, design considerations, research projects, energy efficiency and regulations related to energy efficiency, current/future alternative chemicals and technologies for air conditioning under HAT conditions, and considerations for refrigeration systems under HAT conditions including not-in-kind technologies (UNEP, 2015). That information is not repeated here, but in view of the initial results of the testing under HAT conditions discussed above, some of those considerations are further highlighted below.

**On energy efficiency:** In regions with HAT conditions, legislations which set minimum energy performance standard (MEPS) values on air conditioners are emerging quickly. Most of the Parties require third party verification of declared performance. Higher minimum energy efficiencies are being announced on a regular basis, and this tendency may continue. As examples, Bahrain recently announced MEPS values and regulation of labelling air conditioners and Saudi Arabia is moving closer to releasing their regulation for large air conditioners and chillers expected in the second quarter of 2016.

When selecting new refrigerants, it is important to consider further increases on the current minimum energy efficiency requirements. To the extent increases in MEPS are not met by current models, this offers the opportunity for manufacturers to implement new refrigerants while redesigning equipment for those new refrigerants.

**On design and availability:** The design for HAT conditions needs special care to avoid excessive condensing temperatures and getting close to the critical temperature for each type of refrigerant. Other issues such as safety, refrigerant charge quantity, and improving the energy efficiency for both partial and full load have to be taken into consideration

In HAT conditions, the cooling load of a conditioned space can be up to three times that for moderate climates. Therefore, larger capacity refrigeration systems may be needed which implies a larger refrigerant charge. Due to the requirements for charge limitation according to certain safety standards, the possible product portfolio suitable for high ambient conditions is more limited than for average climate conditions when using the same safety standards.

As concluded from the testing projects, special design of both components and products is needed for the new alternatives to meet the performance of systems in both capacity as well as efficiency requirements. While the commercialization process of refrigerants can take up to ten years, as seen from chapter 2, the commercialization of products using these alternatives will take further time.

As HCFC-22 air conditioning products get phased-out for some applications, the industry is turning to available technology using higher GWP refrigerants with higher discharge pressures such as R-410A or comparable pressures like R-407C, depending on the application. One exception is HFC-32 which has seen a limited release for room air conditioners following the change-over in Japan. HC-290 products, which have potential due to the favourable performance of HC-290 compared to HCFC-22 at HAT conditions, are not yet commercially available in many Parties although some of the local suppliers are busy researching and designing such products.

**On retrofits:** It is important to note that any change of refrigerant in an existing design requires careful considerations. Theoretical calculations can give an idea about what is generally to be expected with a change in refrigerant, but specific details on the system design are needed. Modifying the electrical connections to meet the requirements needed for flammable refrigerants is an additional cost that needs to be taken into consideration. This

cost is the same for class A3 or class A2L refrigerants and mostly due to changing the location of the controls in order to reduce the risk of a spark.

For HAT conditions, the design and sizing of the heat exchanger will impact how the system capacity and energy efficiency is influenced by a change in refrigerant. For system builders this means that each system design needs to be optimized for each type of refrigerant. This requires an investment similar to what has been spent on optimizing the system for the current refrigerant, and for highly cost optimized systems this investment might be considerable.

**On safety:** Standards for the new refrigerants (that are mostly flammable), such as ISO 5149, EN 378, IEC 60335-2-40 for air conditioners and heat pump systems and IEC 60335-2-89 for some commercial refrigeration appliances, are available, although IEC 60335-2-89 needs to be adapted to allow larger charges of flammable refrigerants that are required for the bigger capacities of air conditioners working at HAT conditions. IEC standards are a de facto legal requirement in several Parties as the Certification Body (CB) scheme is the actual requirement for import and sales of products. In some Parties, the implementation of old standards in the legislation, for instance building codes or other mandatory safety regulations, blocks the uptake of especially flammable refrigerants.

Another important aspect of safety standards is that their value is tied to the degree of compliance, and this makes training of system builders and service technicians an important part of implementing safety standards. The cost of the above certification, including the third-party certification cost and including the training cost, should be considered.

Although risk assessment work on flammable refrigerants is an on-going research in some Parties, there is a need for a comprehensive risk assessment for class A3 and A2L refrigerant alternatives at installation, servicing and decommissioning practices at HAT conditions and when field testing the units.

## 5.4 References

- |                 |  |
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## 6 **BAU and MIT scenarios for Article 5 and non-Article 5 Parties for 1990-2050: Refrigeration and Air Conditioning**

This chapter contains the same presentation of scenarios as the March 2016 version of the XXVII/4 Task Force report. Based on comments from Parties on that report at OEWG-37, this revised chapter also contains the following changes and additions:

- Consideration of existing regulations as well pending regulations in non-Article 5 Parties and the impact of the latter (see section 6.1);
- Comparison of the demand in non-Article 5 Parties between a BAU scenario with regulations considered (up to 2050) and without regulations considered (up to 2030) (see section 6.4.1 and Figure 6-3);
- A revised table on growth percentages for the various R/AC subsectors, for both the new manufacturing and the total demand (in the March version of the XVII/4 TF report certain percentages of decreasing HCFC demand had been included in the total percentages by mistake) (see section 6.2 and Table 6-1);
- Additional information on the production of various HFCs, not only the important ones for the R/AC sector (see section 6.3 and Table 6-2);
- Addition of an 18-year manufacturing conversion period for the Article 5 MIT-3 scenario and its impact on total demand (see section 6.5);
- Related to this chapter, Annex 3 to this report provides an overview of final regulations from the EU, USA, and Japan addressing HFCs considered for the scenarios and Annex 4 contains updated tables for total, new manufacturing, and servicing demand; and
- Costs estimates have not changed as presented in previous Task Force reports.

The chapter is organized as follows:

- 6.1 Expansion of scenarios
- 6.2 Method used for calculation
- 6.3 HFC consumption and production data
- 6.4 Non-Article 5 scenarios
- 6.5 Article 5 scenarios
- 6.6 Demand and benefit numbers

### 6.1 **Expansion of scenarios**

The previous Decision XXVI/9 paragraph 1 (c) asks to revise the scenarios: “Taking into account the uptake of various existing technologies, revise the scenarios for current and future demand elaborated in the October 2014 final report on additional information on alternatives to ozone-depleting substances of the Technology and Economic Assessment Panel’s task force on decision XXV/5, and improve information related to costs and benefits with regard to the criteria set out in paragraph 1 (a) of the present decision, including reference to progress identified under stage I and stage II of HCFC Phase-out Management Plans”.

The current Decision XXVII/4 requests to expand the scenarios to the period 1990-2050, twenty years after 2030 which was the last year in the scenarios used in the XXVI/9 Task Force report (UNEP, 2015).

The following scenarios have again been calculated, which apply to the R/AC sector only for this first report of the XXVII/4 Task Force submitted to OEWG-37:

- a. A BAU scenario: The Task Force is aware of various regulations and actions as well as pending regulations applied by Parties. This implies that the F-gas regulation in the European Union (EU) and regulations in the United States (US), making certain HFCs unacceptable for certain sub-sectors by specific dates, have been considered as their impacts are very specific to the R/AC sectors and sub-sectors (see also Annex 3, where specific elements of these regulations are given; the final regulation of Japan has not been incorporated in the BAU scenarios considered in this study). This

implies that, in the business-as usual (BAU) calculation, certain high GWP substances in specific subsectors are replaced by low or lower GWP substances. In this way it responds to comments the XXVI/9 Task Force already received at OEWG-36 and at MOP-27. The changes incorporated mainly apply to commercial refrigeration and, to a small degree, to stationary air conditioning. In Article 5 Parties, economic growth percentages expected for the period 2015-2050 are virtually the same as the ones in the XXVI/9 report. In this report, the impact of a BAU scenario without and with certain national or regional legislations is shown.

- b. An MIT-3 scenario: A 2020 *completion of* conversion in non-Article 5 Parties of all R/AC sub-sectors and the start of the manufacturing conversion of all R/AC sub-sectors in 2020 in Article 5 Parties, now with consequences for the period 2020-2050.
- c. An MIT-4 scenario: This is the same as the MIT-3 scenario, but with the assumption of 2025 for the start of the manufacturing conversion for stationary AC in Article 5 Parties, now with consequences for the period 2020-2050.
- d. An MIT-5 scenario: This is the same as the MIT-3 scenario, but with the assumption of a 2025 *completion of* conversion in non-Article 5 Parties of all R/AC sub-sectors and the start of the manufacturing conversion of all R/AC sub-sectors in 2025 in Article 5 Parties, now with consequences for the period 2020-2050

For Article 5 Parties, manufacturing conversion projects would need preparation to be funded; it would also take a certain period of time before conversion projects would have been approved by a funding authority, so that they can be initiated. Finally, experience with CFCs and HCFCs has shown that, the slower the conversion of manufacturing, the longer the servicing tail will be, i.e., the longer servicing of equipment will be required (see sections 6.5.3 and 6.5.5 taken from (UNEP, 2015)).

In this chapter the 1990-2050 scenarios will be given in the following sequence. First, the BAU scenario for non-Article 5 Parties will be dealt with, which will be analysed in tonnes and ktonnes CO<sub>2</sub>-eq. This is then followed by the MIT-3 and MIT-5 scenarios for non-Article 5 Parties; new manufacturing and servicing figures are given in ktonnes CO<sub>2</sub>-eq. (not in tonnes). As a next step, the Article 5 scenarios are given. Again, first the BAU scenario for Article 5 Parties will be dealt with, which will be presented in tonnes and ktonnes CO<sub>2</sub>-eq. This is then followed by the MIT-3, MIT-4 and MIT-5 scenarios for Article 5 Parties; new manufacturing and servicing figures are given in tonnes and in ktonnes CO<sub>2</sub>-eq.

## 6.2 Method used for calculation

A “bottom-up” method has been used to predict the demand for R/AC equipment, as in the XXVI/9 Task Force report (UNEP, 2015). The RTOC 2010 Assessment Report (RTOC, 2010) describes the bottom-up method used here. A bottom up method derives the size of banks from information obtained from outside (accountancy reports on trade and exports, if possible, supplemented with a trend analysis). The banks serve to calculate emissions using agreed emission parameters. As a result, the demand (or “consumption”) can be calculated, which consists of (1) what is supplied to the existing banks (i.e., to compensate for leakage), and (2) what is added to the bank (i.e., in new equipment that has been charged), less (3) what is recovered and reused from the bank (i.e., material reclaimed from equipment decommissioned). In a spreadsheet analysis, this can be seen as one stream of refrigerant into a bank with equipment that has been manufactured over a number of years. In summary, the refrigerant demand or the annual sales of new or virgin refrigerant are equal to the amount of refrigerant introduced into the R/AC sector in a country (or regions) in a given year. It includes all the chemicals used for charging or recharging equipment, whether the charging is carried out in the factory, in the field after installation, or whether it concerns recharging with the appropriate equipment during maintenance operations.

In this type of “bottom-up” approach, one therefore evaluates the consumption of a certain refrigerant based on the numbers of equipment in which the fluid is charged, e.g. refrigerators, stationary air-conditioning equipment, and so on. It requires the establishment

of an inventory of the numbers of equipment charged with substances (which then forms the total inventory, or the “bank”), and the knowledge related to their average lifetime, their emission rates, recycling, disposal, and other parameters. The annual emissions are estimated as functions of all these parameters during the entire equipment lifetime.

Further information on sub-sectors, equations used and information on how the installed base is being considered can be found in the XXVI/9 TF report (UNEP, 2015). As in this XXVI/9 report, the GWP for low GWP replacement refrigerants has been chosen as follows. In domestic refrigeration the use of isobutane is assumed with a very low GWP. In cases where the replacement refrigerant is known (ammonia, hydrocarbons), very low GWP factors have been used. For commercial refrigeration, one can assume the use of carbon dioxide, pure low-GWP refrigerants or refrigerant blends in supermarkets, low GWP hydrocarbons in mass produced units, blends or carbon dioxide in condensing units (where an average GWP of 300 is used). For stationary AC as a whole, an average GWP of 300 has also been used (as an estimated average between very low GWP refrigerants and others, such as HFC-32 and various blends under investigation). The choice has been made on the basis of an averaging exercise, not related to GWP considerations presented in Table 2-6. In Mobile Air Conditioners (MACs), replacement refrigerants are assumed to have negligible GWP.

**Table 6-1: Growth rates for high-GWP HFC demands in the various R/AC sub-sectors (manufacturing and total) during the periods 2010-2020, 2020-2030 and 2030-2050**

<b>Non-Article 5 Parties</b>				
<b>Sub-sector</b>		<b>2010-2020</b>	<b>2020-2030</b>	<b>2030-2050</b>
Domestic refrigeration	Manufact.	-6.0%	-1.5%	3%
	Total	-6.0%	-1.5%	3%
Commercial refrigeration	Manufact.	-10.5%	0.1%	3%
	Total	-2.0%	-5.5%	2.1%
Industrial refrigeration	Manufact.	-2.1%	-1.8%	3%
	Total	0%	-1.2%	1.8%
Transport refrigeration	Manufact.	-9.5%	-4%	3%
	Total	-1.3%	-0.2%	0.9%
Stationary AC	Manufact.	5.8%	3%	3%
	Total	8.5%	2.8%	2.7%
Mobile AC	Manufact.	-12.5%	3.3%	3%
	Total	-3.6%	-5.5%	1.9%
<b>Article 5 Parties</b>				
<b>Sub-sector</b>		<b>2010-2020</b>	<b>2020-2030</b>	<b>2030-2050</b>
Domestic refrigeration	Manufact.	5.8%	5.8%	4.5%
	Total	4.8%	5.8%	4.5%
Commercial refrigeration	Manufact.	12.9%	8.6%	4.5%
	Total	16.5%	9.6%	5.1%
Industrial refrigeration	Manufact.	8.8%	6.8%	3.7%
	Total	6.1%	6.1%	4.2%
Transport refrigeration	Manufact.	5.8%	4.5%	4.5%
	Total	9.5%	5.7%	4.4%
Stationary AC	Manufact.	15.8%	6.0%	1.5%
	Total	17.7%	8.3%	3.0%
Mobile AC	Manufact.	5.0%	5.0%	5.0%
	Total	6.4%	5.0%	5.0%

*Note: this table is different from the one in the March 2016 TF report, since some negative growth in HCFC demand was taken into account in the first 10 (20) years (2010-2030) in Article 5 Parties*

Growth rates for equipment production have been slightly changed (in two cases) compared to the rates used in the XXVI/9 Task Force report, in order to give a more realistic approach in the period after 2030. In this report, the growth rates apply as given in Table 6-1 above.

A number of considerations substantially complicate the calculations. This includes the preference to apply certain alternatives in specific equipment (and often under certain conditions), combined with the fact that the R/AC banks -the amounts present in the equipment- need recharging (i.e., servicing) over the entire lifetime of the equipment. Details on lifetime and annual leakage are given in (Table 5-2 in) the XXVI/9 report (UNEP, 2015).

The calculation method covers the period from 1990 until 2050, the latter year as requested in Decision XXVII/4. Table 6-1 gives the growth rates assumed for new manufacturing in the various R/AC sub-sectors, as well as for the total demand (manufacturing and servicing). The growth rate assumed in the manufacturing sector is only one parameter in the scenario calculations. The total demand for a sub-sector is calculated using parameters such as equipment lifetime, equipment leakage, charge at new manufacturing etc. This implies that, if the annual growth rate in a manufacturing sub-sector would be 1-5%, the annual growth rate of the total demand for that subsector can be a few percent higher, e.g., varying from 2 up to 5-6%. These percentages can also be derived from the BAU Tables 6-7 and 6-8 and from the more detailed tables as given in Annex 4.

Depending on the application sector, uncertainties are different either because activity data include different uncertainties or because emission factors may vary significantly from one Party to the other. The 2010 RTOC Assessment Report (RTOC, 2010) describes a simple approach that gives a quality index expressed in percentages. Further elaboration can be found in the XXVI/9 report. Uncertainties in banks are estimated at 12.5-22.5%, uncertainties in emissions 12.8-37%, specific numbers are dependent on the sub-sector. For the total R/AC sector, the uncertainty range in the demand calculated ranges from *-10% to +30%*.

The bank of refrigerants is substantially larger (10-20 times) than the annual demand. In fact the bank as calculated determines the amount of emissions, dependent on leakage assumptions during operation. The total demand is the sum of the amount used for new manufacturing and for re-charging to balance the refrigerant lost via all emissions types. Banks of refrigerants could be given for regions and/or for certain Parties as used in the model, but the amounts that would then be presented would not contribute to a better understanding of the demand, which is the essential parameter in this chapter that deals with demand scenarios.

As already mentioned in the Decision XXVI/9 TF September Update Report (UNEP, 2015), estimates should be cross-checked with reported HFC consumption and production data, specified per refrigerant. For the most recent cross-check, information can be found below.

### **6.3 HFC production and demand (consumption) data**

Estimates for global 2012 and 2015 production of the relevant HFC chemicals can be made by combining UNFCCC data, manufacturer's estimates for production capacity as well as global emission data. This was already given in the XXVI/9 Task Force report (UNEP, 2015).

Data on HFC emissions are reported annually by developed countries, i.e., the Annex I Parties under the UNFCCC Kyoto Protocol; these emission data are estimated (calculated) by national agencies.

HFC consumption and production data are also reported by developed countries, i.e., the Annex I Parties to the UNFCCC. Even when certain consumption and production data are missing (i.e., data not reported by some countries, or reported as HFCs in general), these reports enable a first estimate for the production of most HFCs in the Annex I Parties to be made.

Estimates for HFC production in the Article 5 Parties are often made by non-Article 5 chemical manufacturers (Kuijpers, 2015). Based on global consumption calculations, estimates for HFC production were also made by McCulloch (2015). Furthermore, global

emissions data for several HFCs are available from certain literature sources, e.g. from Montzka (2015). Recently, Chinese HFC (and HCFC) production data up to the year 2013 were reported by Kaixiang (2015).

Further HFC production estimates from Chinese manufacturers were also obtained in the period May-July 2015 (Kuijpers, 2015). The HFCs considered above are HFC-32, HFC-125, HFC-134a and HFC-143a, but also HFC-152a, HFC-227ea, HFC-236fa and HFC-245fa.

However, this report uses almost the same estimates (as in the XXVI/9 report) for HFC production of the *four* main HFCs (the ones important for R/AC) in Table 6-2 below (the estimated production of HFC-134a in one country has been added that was not included in the XXVI/9 Task Force report). As mentioned, these four HFCs are the main ones used in the R/AC sector, except for HFC-134a, which is also applied in several other sectors (such as foams, aerosols, MDIs).

The table shows a total HFC production of about 510 ktonnes for these *four* (main) HFCs, which is a forecast for the year 2015 (this can be translated to about 930 Mt CO<sub>2</sub>-eq., if calculated in climate terms). The global production capacity for these four HFCs is estimated at a much higher level, at about 750 ktonnes (Campbell, 2015).

It needs to be emphasised that the global HFC production (for these four main HFCs) determined in this way is estimated to have a  $\pm 10\%$  uncertainty for the separate HFC chemicals, which implies that the 510 ktonnes value roughly has a 5% uncertainty value (495-535 ktonnes).

Estimated global production quantities for HFC-152a, HFC-227ea, HFC-236fa and HFC-245fa are around 170 ktonnes, of which more than 50% of the total concerns HFC-152a production (Kaixiang, 2015, Kuijpers, 2015) (the total can be translated into about 150 Mt CO<sub>2</sub>-eq. in climate terms).

**Table 6-2: Estimates for global HFC production (for HFC-32, -125, -134a and -143a)**

Gg (ktonnes) for HFCs (per year)	(Montzka, 2015) Emissions year 2012	UNFCCC based estimate for non-A5 prod. (2012)	Estimate for non-A5 production (for 2015)	Estimate from various sources A5 production (for 2015)	Estimate global production year 2015 (*)
HFC-32	16 (21**)	≈ 22	23	71	94
HFC-125	41	< 30	31.5	98.5	130
HFC-134a	173	< 100	97	161^	258
HFC-143a	21	<10	11	17	28

Note: (\*) Global production is equal to non-Article 5 plus Article 5 (China, minor other) production

Note: (\*\*) Estimate from Rigby (2013)

Note: (^) New value for this report, due to the addition of the HFC-134a production quantity in one Article 5 Party

These production data for certain years are reasonably reliable global estimates and have been used in order to check the demand data determined via the bottom-up method used, where details are given in the sections below for the R/AC sector.

For the R/AC sector as a whole, the total bottom-up demand that has been calculated for the year 2015 for non-Article 5 Parties (200.5 ktonnes) and Article 5 Parties (272.9 ktonnes) equals 473.4 ktonnes. This relates to the four main HFCs given in Table 6-2. It would imply that about 37 ktonnes of HFCs (mainly HFC-134a) are used (globally) in sectors other than R/AC; these other sectors would mainly be foams, medical and technical aerosols. One needs to take into account that both the production estimates and the bottom up calculated R/AC demand have uncertainties, as mentioned above.

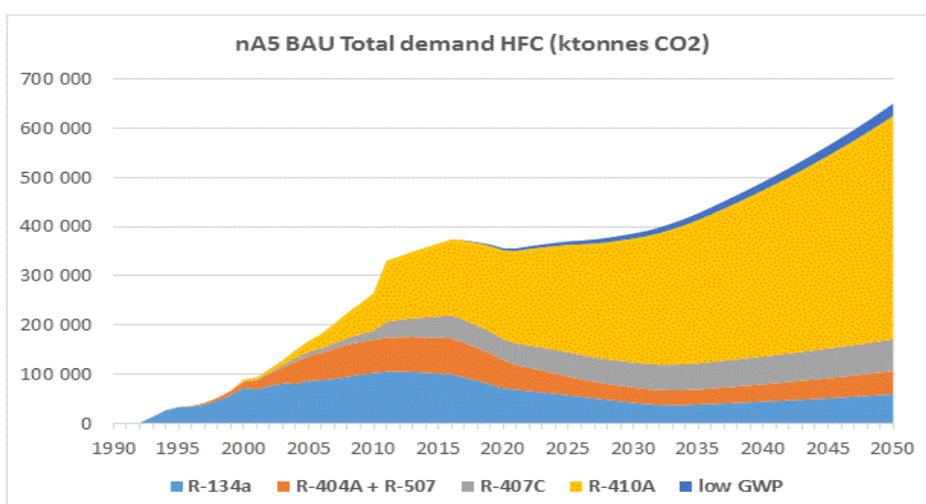
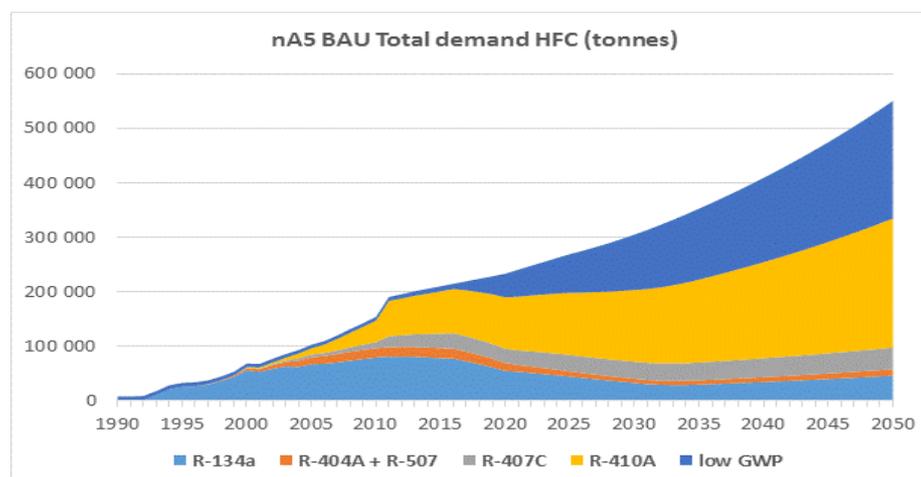
The value of 37 ktonnes used in sectors other than R/AC will be further investigated in the update September 2016 TF report.

## 6.4 Non-Article 5 scenarios up to 2050

### 6.4.1 BAU scenario

The figures below present the results of the Non-Article 5 scenario calculations:

- Non-Article 5 BAU scenario with subdivision for refrigerants.
- Non-Article 5 BAU scenario with subdivision for the various R/AC sub-sectors.

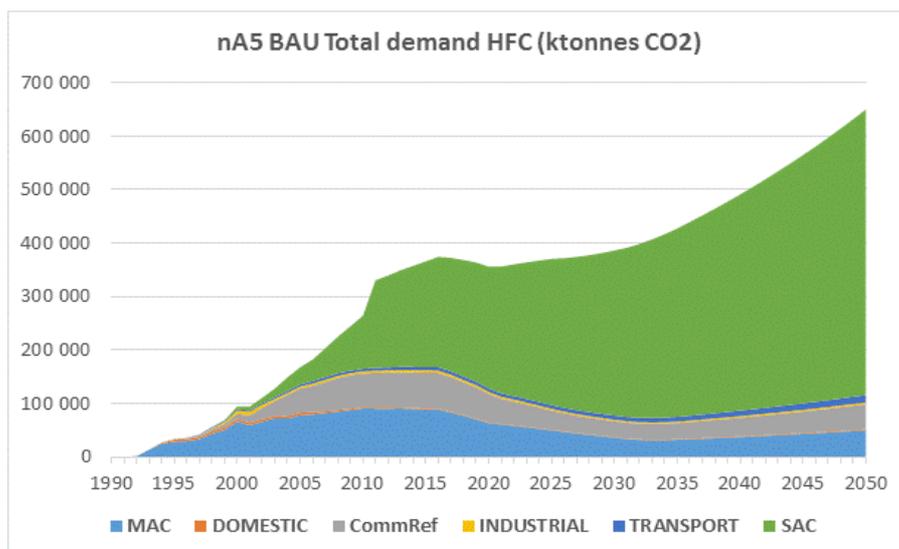
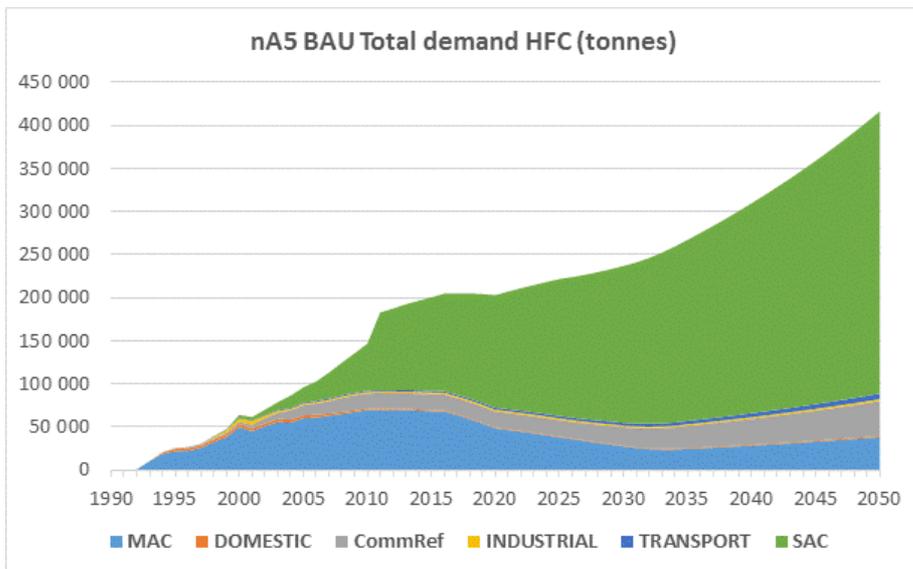


**Figure 6-1: Non-Article 5 BAU scenario with subdivision for the various refrigerants or refrigerant blends in tonnes and ktonnes CO<sub>2</sub>-eq.**

Figure 6-1 shows the current and projected future non-Article 5 refrigerant BAU demand, with a subdivision for the commonly used high-GWP refrigerants and low-GWP refrigerants. The demand is given in tonnes and in GWP weighted terms (in ktonnes CO<sub>2</sub>-eq.). The amount of low-GWP refrigerants in the BAU scenario increases rapidly after 2020, because the BAU scenario includes the EU F-gas regulation as well as the US measures that enter into force as of 2016-2021 (e.g. low GWP in manufacturing of MACs). Over the period 2010-2050, the importance of R-410A and also R-407C for stationary AC becomes more and more dominant, with an increase of a factor 2 in tonnes and in GWP weighted tonnes between 2015 and 2050.

Figure 6-2 shows the non-Article 5 refrigerant BAU demand, with a subdivision for the different R/AC sub-sectors (n.b., all graphs start in the year 1990). The demand is given in tonnes and in ktonnes CO<sub>2</sub>-eq.). By 2030-2050, stationary AC accounts for more than 80% of

the GWP adjusted tonnage (even when using low growth percentages, as given in Table 6-1). This is due to the fact that only a small amount of regulatory restrictions have been built in.

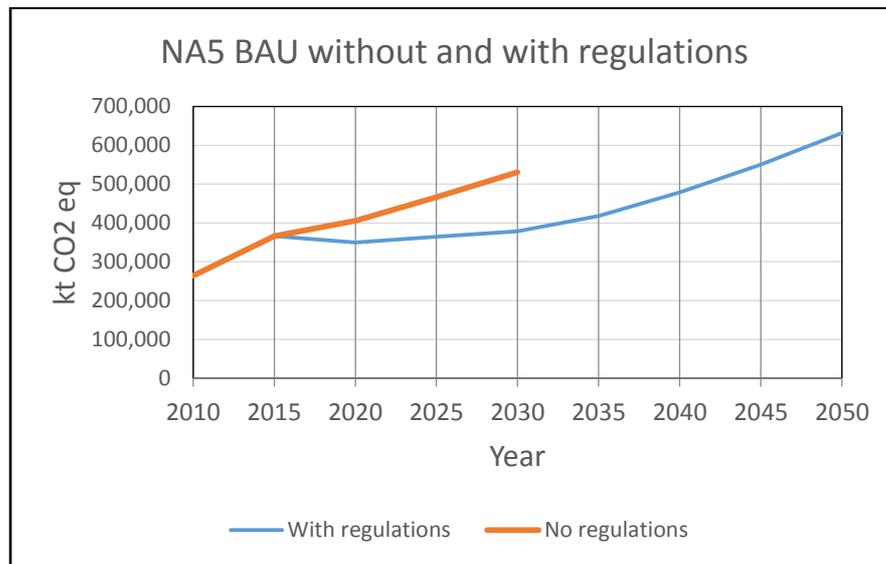


**Figure 6-2: Non-Article 5 BAU scenario; subdivision for the various R/AC sub-sectors**

It is interesting to compare the Non-Article 5 BAU scenario without and with certain regulations; it then shows the impact of these regulations over the time period considered (in fact the values for these two types of BAU scenarios can be found in the Annexes of the XXVI/9 Task Force and this XXVII/4 Task Force report. Annex 3 gives the summary table with the regulations for the EU, USA and Japan. In the BAU scenario in this report the EU and US regulations, making certain HFCs unacceptable for certain sub-sectors by specific dates, have been applied as their impacts are very specific related to the R/AC sectors and sub-sectors.

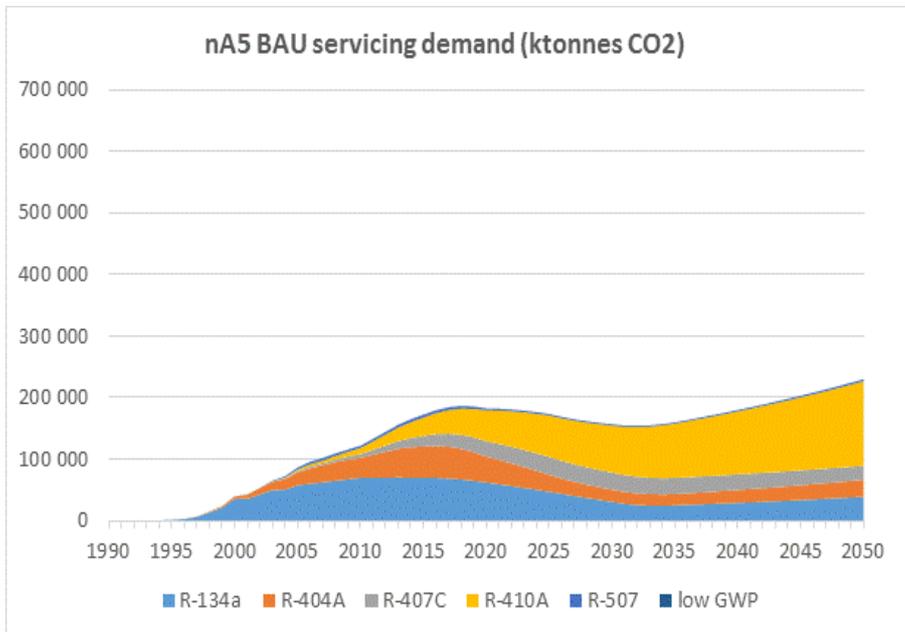
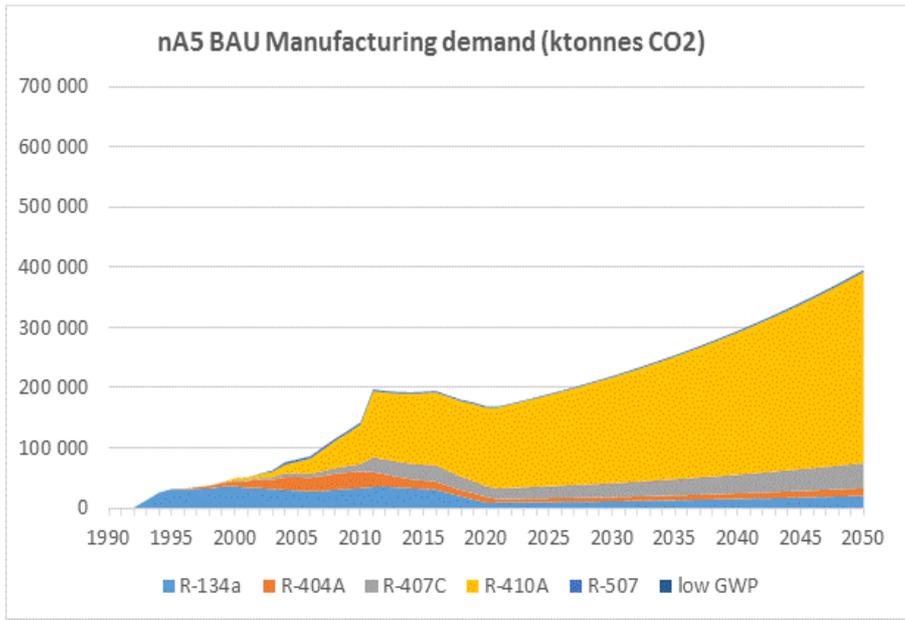
Figure 6-3 shows the impact of regulations on the BAU demand. The demand is expected to be lower as of 2015 when certain regulations enter into force, the difference will increase after 2019-2020 when more regulations are assumed to be in place and the impact of the servicing demand becomes more visible. The difference between both types of BAU demand is in the order of 140 Mt CO<sub>2</sub>-eq. in the year 2030. The demand with regulations does not

increase much between the years 2015 and 2030, after which the growth in certain commercial refrigeration subsector and particularly in the stationary AC subsector are determining.



**Figure 6-3: Non-Article 5 BAU scenario without and with consideration of national and regional regulations (without regulations until 2030; with regulations until 2050)**

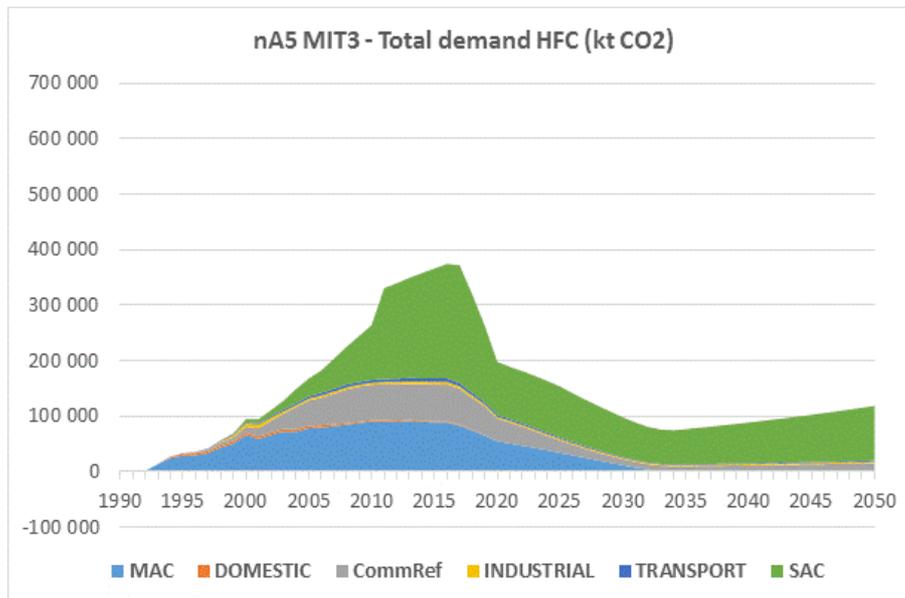
Figure 6-4 below is in principle the same as in the XXVI/9 report (UNEP, 2015). It is surprising that, with the assumptions used, the percentage of R-404A in manufacturing decreases sharply, servicing remains (with the assumptions on the servicing percentage) and increases again after 2033 due to economic growth. The low GWP fraction remains very moderate in ktonnes CO<sub>2</sub>-eq., but that number implies a much larger percentage in tonnes.



**Figure 6-4: New manufacturing and servicing parts of the non-Article 5 BAU scenario with a subdivision for the various R/AC sub-sectors**

**6.4.2 MIT-3 scenario**

The following figures are for the MIT-3 scenario, for non-Article 5 Parties, in the various R/AC sub-sectors. This is the scenario where all sub-sectors are assumed to have converted by the year 2020. The total demand, the new manufacturing and the servicing demand are shown in Figs 6-5, 6-6, and 6-7.



**Figure 6-5: Total demand for the Non-Article 5 MIT-3 scenario with a subdivision for the various R/AC sub-sectors**

In MIT-3, the conversion in all sub-sectors to replace high-GWP refrigerants with a variety of refrigerants with an average GWP of 300 is assumed to be complete by 2020. Manufacturing capacity is converted in equal portions per year during the period 2017-2020. This is a major difference with the BAU scenario in which stationary AC is not addressed in this manner.

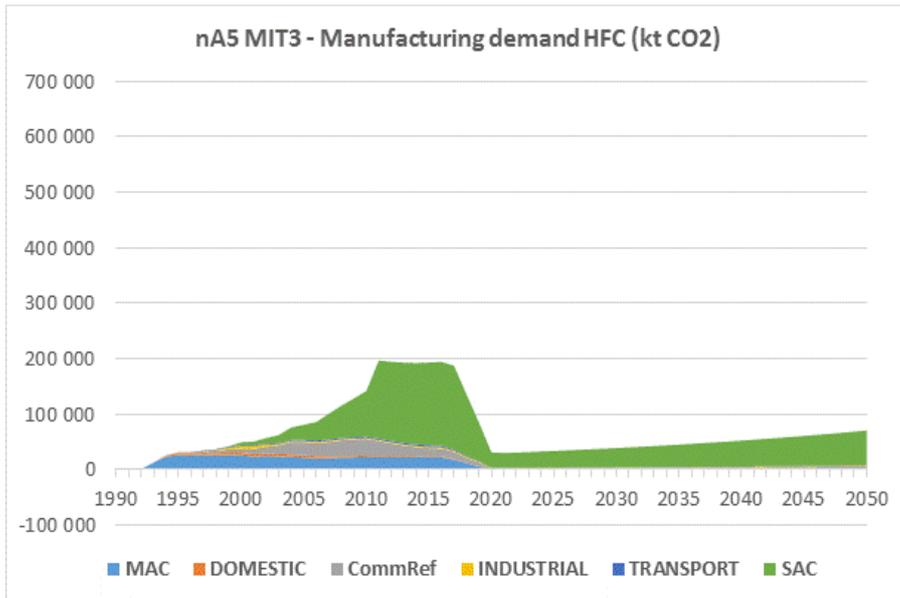
Figure 6-5 shows the steep decrease in the years before 2020, after which the curve flattens due to continued servicing needs. Since some high-GWP equipment will have been manufactured until 2020, and has an average 12 year lifetime, supplies of high-GWP refrigerants will continue to be required in decreasing amounts until about 2032.

During 2010-2015, stationary AC and commercial refrigeration demands are assumed to increase quickly (see above). With transition in new manufacturing as of 2020, high-GWP refrigerants in these sector decrease, being replaced by low-GWP refrigerants that will account for more than 80% of total demand between 2020 and 2050.

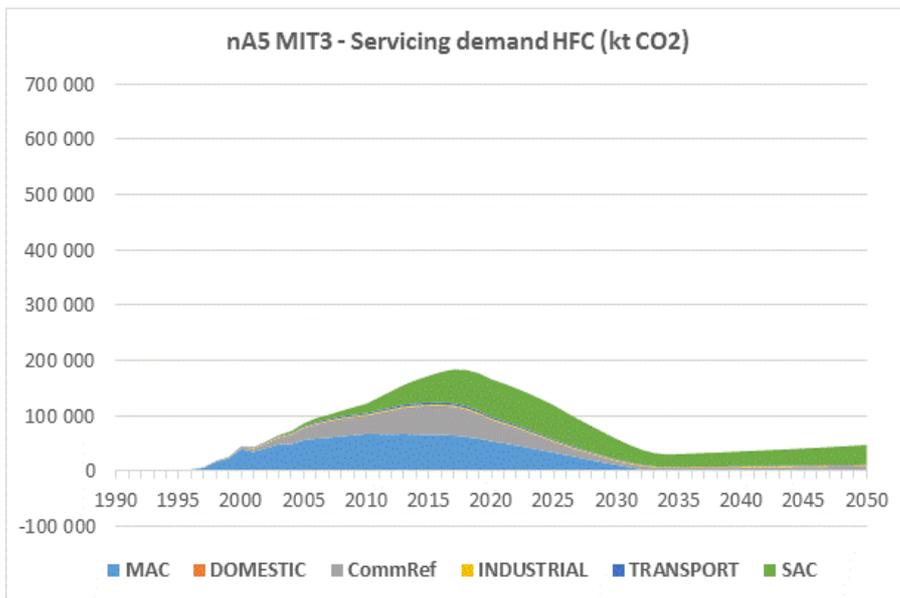
What becomes again clear here, that is that the minimum demand is reached by 2032-2033, after which the demand increases again, in particular due to growth in stationary AC.

So, there is a large improvement in climate impact, although with a GWP of 300, the large refrigerant volumes considered still have a certain climate impact.

In Figure 6-6, the new manufacturing demand for the R/AC sub-sectors for high-GWP chemicals is given. By 2020, the demand for high-GWP refrigerants in new equipment manufacture falls to < 5% of the 2019 peak.



**Figure 6-6: Non-Article 5 MIT-3 scenario for new manufacturing demand for high-GWP refrigerants in the various R/AC sub-sectors in ktonnes CO<sub>2</sub>-eq. (assuming manufacturing conversion over a period of 3 years, 2017-2020).**

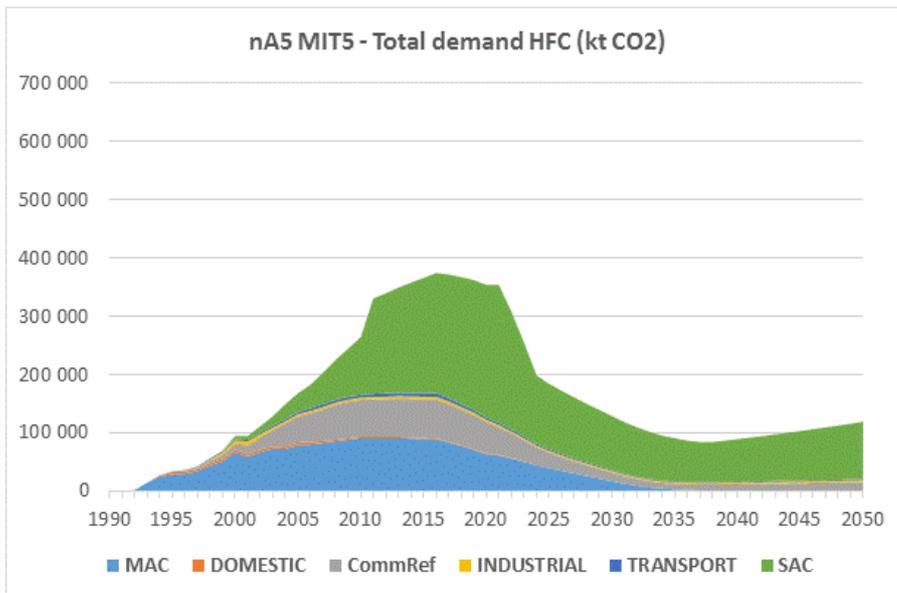


**Figure 6-7: Non-Article 5 MIT-3 scenario with the servicing demand for the various sub-sectors in ktonnes CO<sub>2</sub>-eq. (assuming manufacturing conversion over the period 2017-2020)**

Figure 6-7 shows the volumes of high-GWP refrigerants that will be needed for servicing the installed equipment in the MIT-3 scenario. This varies between sectors (see table in section above) and decreases rapidly between 2020 and 2032, increases again due to economic growth after 2033.

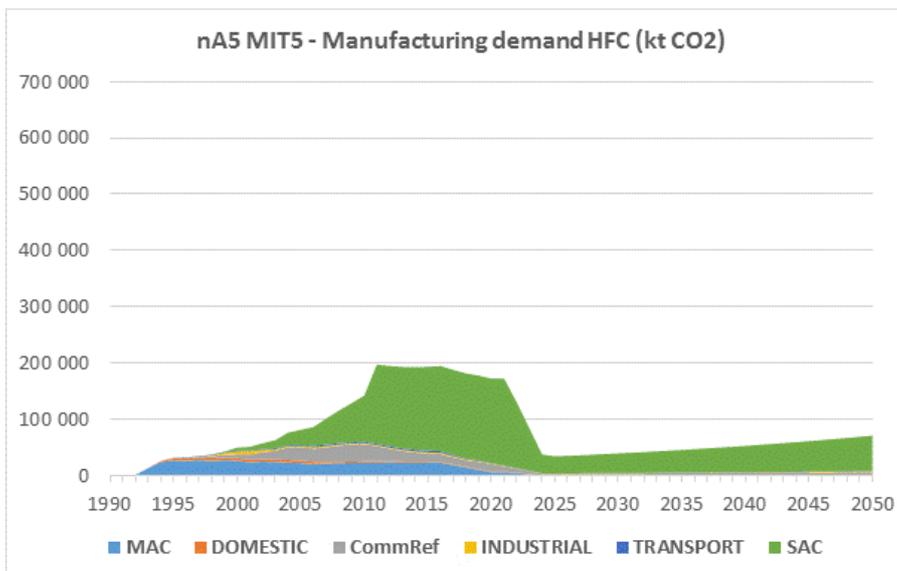
#### **6.4.3 MIT-5 scenario**

This is the scenario where, for non-Article 5 Parties, all sub-sectors are assumed to have converted by the year 2025. The total, the new manufacturing and servicing demand are shown in Figs 6-8, 6-9 and 6-10.



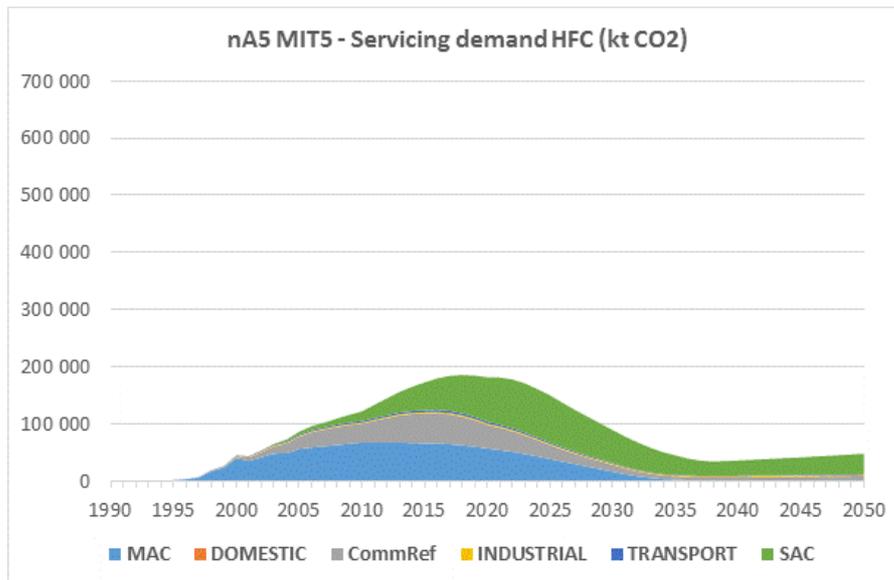
**Figure 6-8: Non-Article 5 MIT-5 scenario by R/AC sub-sectors in ktonnes CO<sub>2</sub>-eq. (compare Figure 4-4 for MIT-3)**

Figure 6-8 includes both manufacturing and servicing, and is similar to Fig 6-6 for MIT-3. Figure 6-9 shows the same data for HFCs used in new manufacturing only.



**Figure 6-9: Non-Article 5 MIT-5 scenario for new manufacturing demand for the various R/AC sub-sectors in GWP weighted terms (compare Fig. 6-6 for MIT-3)**

In 2020, demand for new manufacturing is at about 180 Mt CO<sub>2</sub>-eq, and demand for servicing is also at about 180 Mt CO<sub>2</sub>-eq, but after 2025, the picture becomes different. New manufacturing demand decreases to less than 30 Mt CO<sub>2</sub>-eq, whereas this value is reached around the year 2037 in servicing. This is an issue that needs to be borne in mind, i.e., that servicing will be delaying non-Article 5 reductions expressed in Mt CO<sub>2</sub>-eq. After a minimum in the demand in new manufacture and service, demand will increase again after 2035-2037 (5 years later than in MIT-3), due to economic growth assumed.



**Figure 6-10: Non-Article 5 MIT-5 scenario with the servicing demand for the various sub-sectors in GWP weighted terms (compare Fig. 6-7 for MIT-3)**

## 6.5 Article 5 scenarios up to 2050

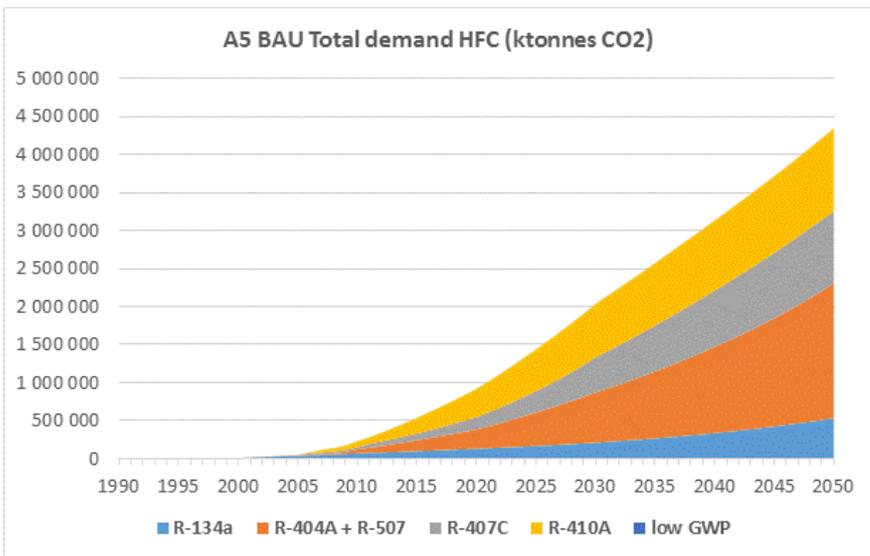
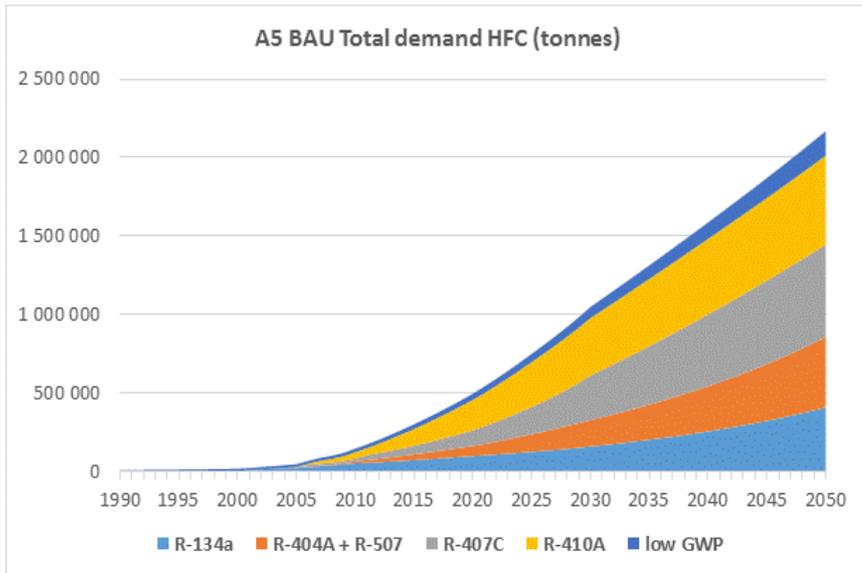
### 6.5.1 BAU scenario

Figure 6-11 below shows the Article 5 refrigerant BAU demand, with a subdivision for the different high GWP refrigerants and the low-GWP ones, both in tonnes and in GWP weighted terms (in CO<sub>2</sub>-eq.).

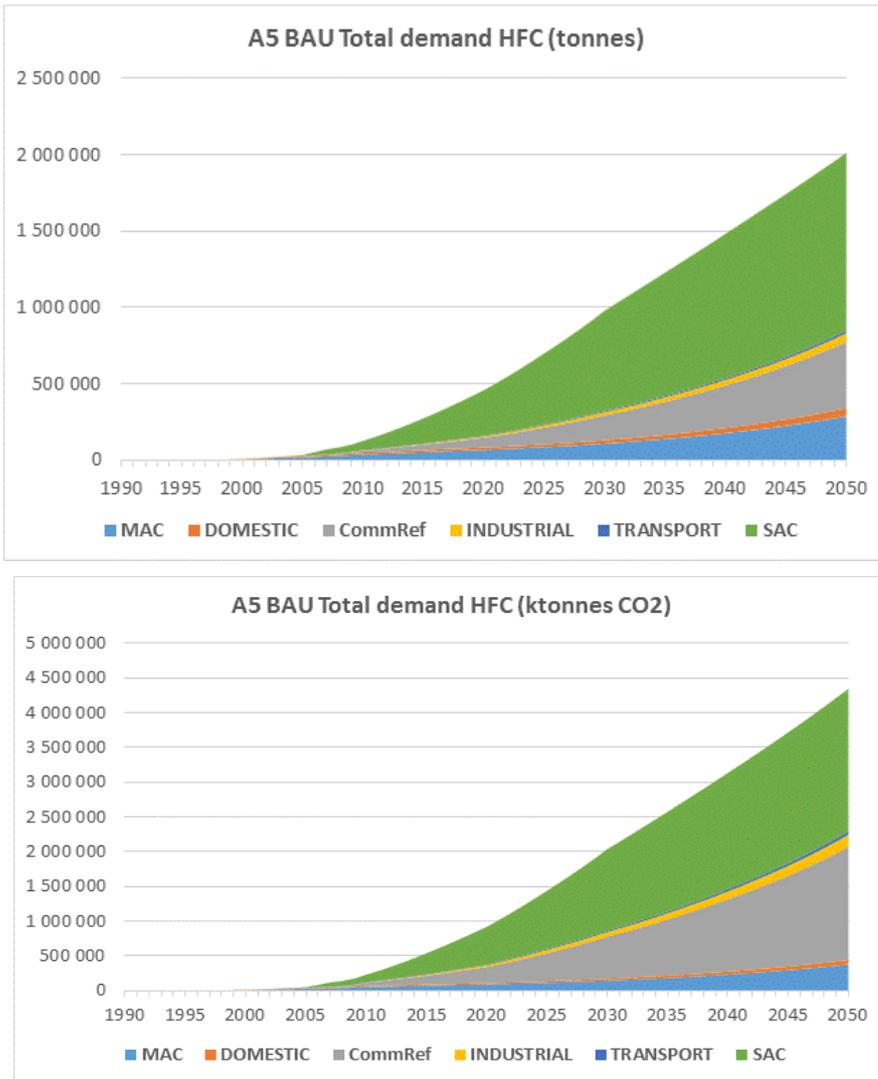
The low-GWP refrigerants applied here are again only visible in tonnes and cannot be really seen in the scale when adjusted for GWP, shown in GWP weighted terms. In the 2020-2030 period, the high-GWP refrigerant R-404A, which is used in commercial refrigeration, becomes increasingly important in GWP weighted terms.

The demand calculated for the year 2015 is about 300 ktonnes, a higher value than calculated for the BAU demand in non-Article 5 Parties (210-220 ktonnes, see above).

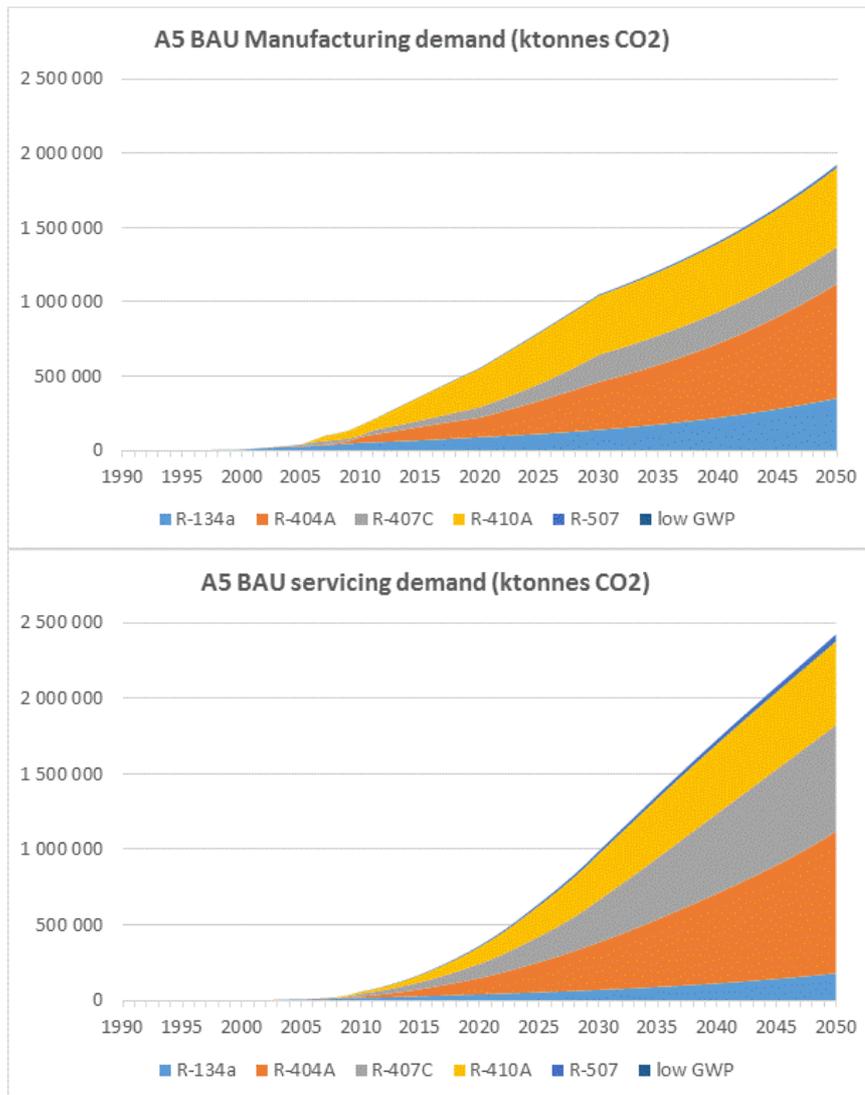
Figure 6-12 shows the Article 5 refrigerant BAU demand for the different sub-sectors. The demand is again given in tonnes and in GWP weighted terms (ktonnes CO<sub>2</sub>-eq.). The BAU model predicts that between 2015 and 2050, overall demand increases by a factor of 7-8, to about 4.5 Gt CO<sub>2</sub>. Stationary AC increases substantially, but the commercial refrigeration sub-sector also is important in GWP terms, due to the use of the high-GWP R-404A.



**Figure 6-11: Article 5 BAU scenario with a subdivision for the various refrigerants and refrigerant blends in tonnes and ktonnes CO<sub>2</sub>eq.**



**Figure 6-12: Article 5 BAU scenario with a subdivision for the various sub-sectors in tonnes and ktonnes CO<sub>2</sub>eq.**



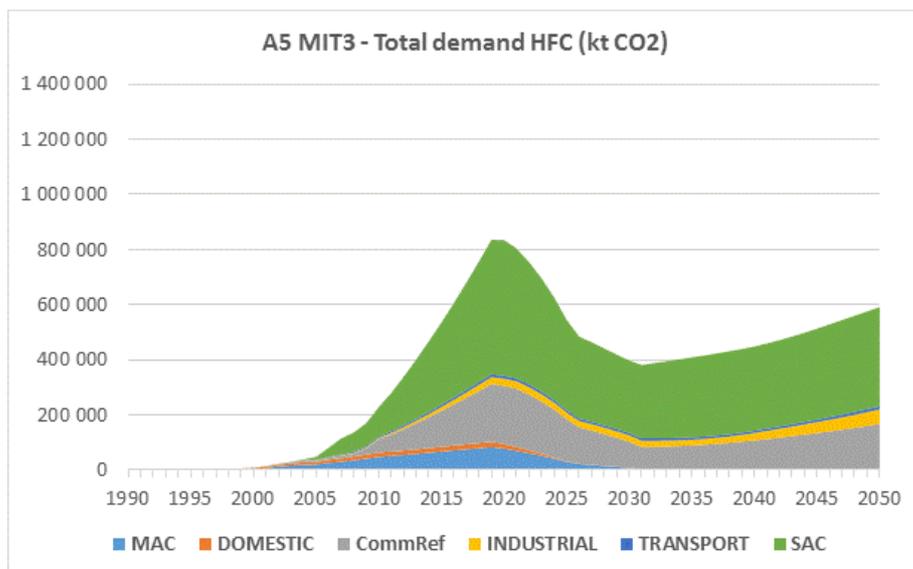
**Figure 6-13: Article 5 BAU scenario with new manufacturing and servicing demand for the various refrigerants (both in ktonnes CO<sub>2</sub>-eq.) (note the scale difference with Figs. 6-11 and 6-12)**

Figure 6-13 shows the demand for new manufacturing and for servicing. When manufacturing increases rapidly, the demand for servicing initially lags behind the volumes used for manufacturing. However, after a certain period it catches up, the servicing volumes become comparable to those used in manufacturing as follows in the BAU scenario (in ktonnes, not in ktonnes CO<sub>2</sub>-eq.):

- 2015: new manufacturing 195 kt, servicing 100 kt
- 2020: new manufacturing 300 kt, servicing 200 kt
- 2030: new manufacturing 530 kt, servicing 515 kt
- 2050: new manufacturing 915 kt, servicing 1080 kt

### 6.5.2 MIT-3 scenario

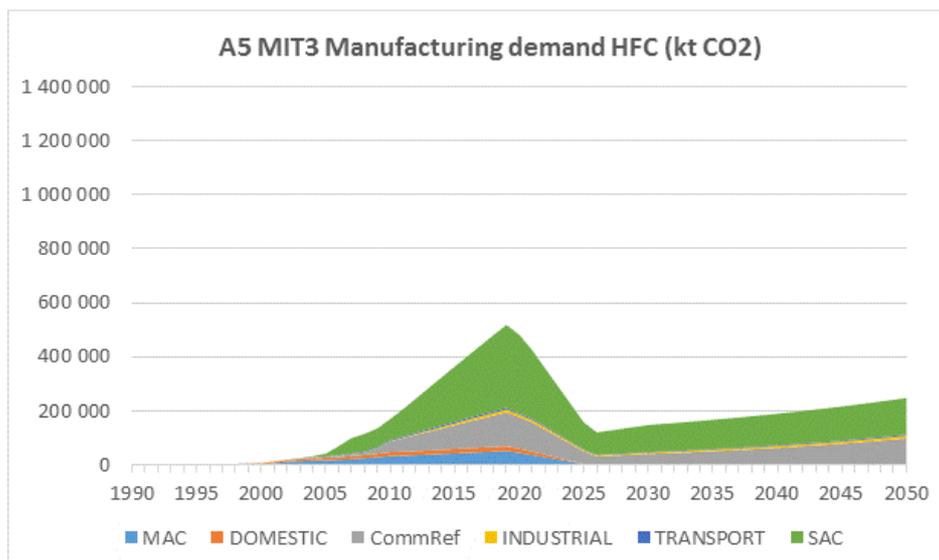
In MIT-3, as of 2020, the conversion is assumed to start in all sub-sectors to replace high-GWP refrigerants with a variety of refrigerants, with the refrigerant blends assumed to have an average GWP of 300. Conversion has been assumed to take six years for Article 5 Parties, and the manufacturing capacity is modelled to convert in equal portions per year during the period 2020-2025 (six years). The following graphs are for the Article 5 MIT-3 scenario, split into in the various R/AC sub-sectors.



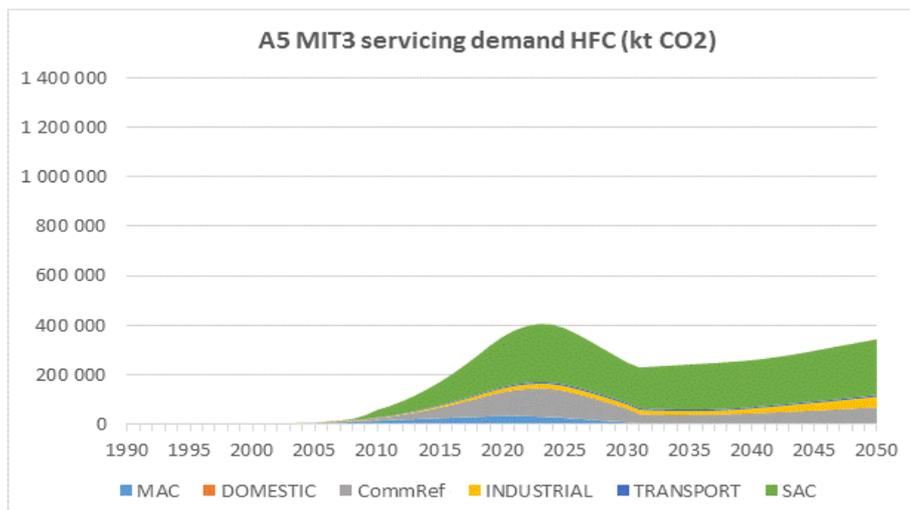
**Figure 6-14: Article 5 MIT-3 scenario with the demand for the R/AC sub-sectors, including both new manufacturing and servicing**

Figure 6-14 shows the steep decrease in the first six years as of 2020, after which the curve flattens due to continued servicing needs only. Since some high-GWP equipment will have been manufactured until 2025, and has an average 12 year lifetime, supplies of high-GWP refrigerants will be continue to be required --in decreasing amounts-- until about 2035-37. During 2010-2015, stationary AC and commercial refrigeration demands increase rapidly. With controls assumed on new manufacturing as of 2020, the high-GWP refrigerant demand in these sector decreases, being replaced by low-GWP refrigerants, which will account for 80% of total demand between after 2025-2030. This is a large improvement in climate impact, although with this GWP of 300, the large refrigerant volumes considered still have a certain climate impact, the relative importance of these refrigerants is now much lower in the GWP weighted graph. The demand increases again (even with a large percentage low GWP refrigerants) after 2032, due to assumed economic growth.

In Figure 6-15, the new manufacturing demand for the R/AC sub-sectors for high-GWP chemicals is given. By 2026, the demand for high-GWP refrigerants in new equipment manufacture falls to <20% of the 2019 peak value, then starts to increase again due to economic growth.



**Figure 6-15: Article 5 MIT-3 scenario for new manufacturing demand for high-GWP refrigerants in the various R/AC sub-sectors in ktonnes CO<sub>2</sub>-eq. (compare Fig. 6-6 for non-Article 5 manufacturing demand)**

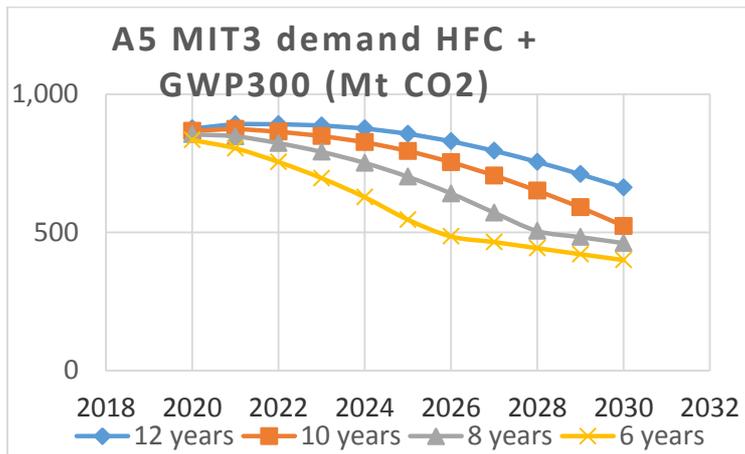


**Figure 6-16: Article 5 MIT-3 scenario with the servicing demand for the various sub-sectors in ktonnes CO<sub>2</sub>-eq. (compare Fig. 6-7 for non-Article 5 servicing demand)**

Figure 6-16 shows the amounts of high-GWP refrigerants in ktonnes CO<sub>2</sub>-eq. that will be needed for servicing the installed equipment. This varies between sectors and according to the speed of the manufacturing transition (the slower the manufacturing transition, the longer the servicing tail). Amounts (expressed in GWP weighted terms) will increase again after 2030-2032.

### 6.5.3 Impact of manufacturing conversion periods in the MIT-3 scenario

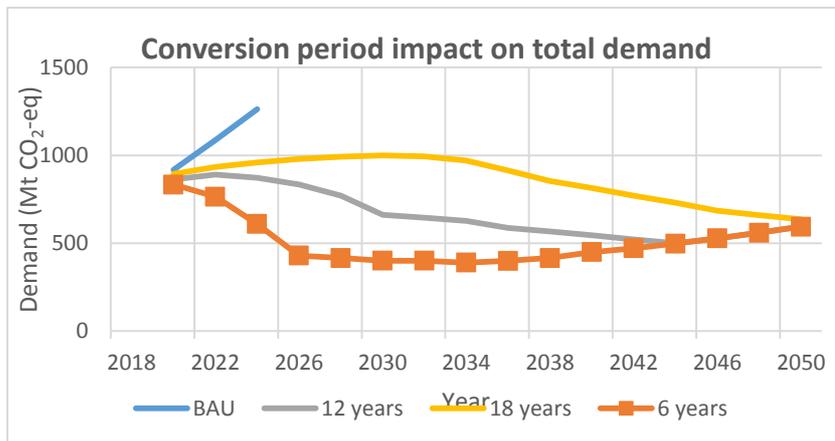
Figure 6-17 shows the demand dependent on the rate of conversion or the length of the conversion period, which is an important parameter (unchanged from what was given in (UNEP, 2015)). The six years conversion period in manufacturing for all sub-sectors results in a decrease of approximately 40% by the year 2026, and about 50% by 2030. After 2026, the remaining demand is for servicing, and only declines by about 10% over the following four years (2026-2030). At the other extreme, a twelve years manufacturing conversion period only leads to a negligible reduction by 2026, and a 25% reduction by 2030. There is a difference of about 350 Mt CO<sub>2</sub>-eq. between the 6 and 12 year manufacturing conversion periods after 2025.



**Figure 6-17: Article 5 MIT-3 demand scenario for all R/AC sectors for new manufacturing conversion periods of 6-8-10-12 years in Mt CO<sub>2</sub>-eq. (UNEP, 2015)**

A twelve year conversion period does not yield a lower demand until after 4-5 years after the start of the conversion in the year 2020. The build-up of the servicing demand (from the manufacturing that has not yet been converted) causes this increasing profile in the demand curve (2020-2025). Ten years after the start of the conversion in 2020, a demand reduction of 20-25% can be observed in this case. In the year 2026, the demand for the 12 years conversion period is almost twice as high as for the six years conversion period, which underscores that a rapid conversion will be very important. It will be clear that there is a direct relationship of the shape of the curves to the conversion period. There are also cost implications. A six year conversion period would imply twice the costs in the first six years after 2020 (2021-2026), compared to the 12 years conversion period, where the same amount will be spread over 12 years (see chapter 6 in the XXVI/9 Task Force report).

A longer period than 12 years, i.e., 18 years has been considered where it concerns the total demand compared to the 6 and 12 years conversion period. The various demands are given in Figure 6-18 (with also BAU demand as developing 2020-2024). The demand for a 18 years conversion period first increases (servicing build-up) then decreases after 2028-2030.



**Figure 6-18: Article 5 MIT-3 total demand scenarios for 6, 12 and 18 years manufacturing conversion periods (compare also Figure 6-14 and 6-17 for MIT-3, 6 years and 6-8-10-12 years conversion periods)**

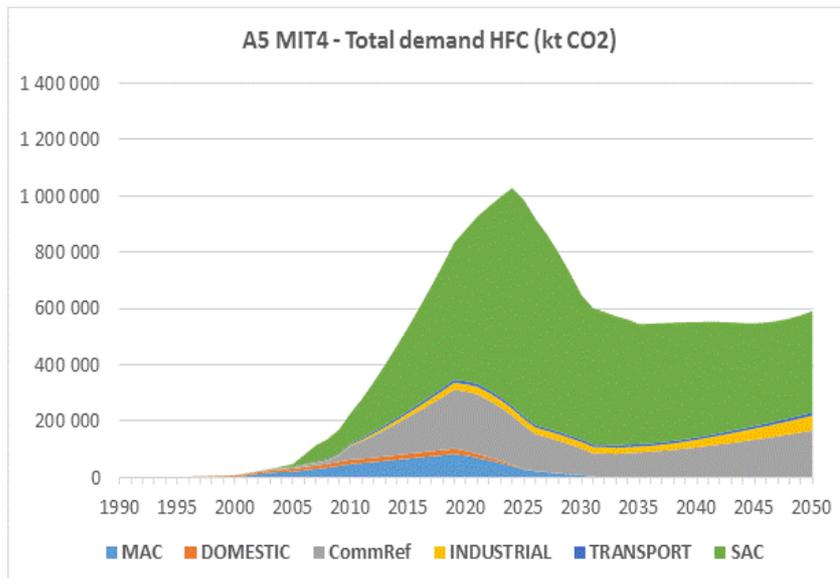
Whereas the 6 and 12 years conversion periods result in a demand decrease after 2020, the 18 years conversion period yields an almost 10% increase in demand first, until the year 2030, then starts to decrease and reaches the 2020 demand level again in the year 2037.

This is due to the build-up of servicing demand from HFC products still being manufactured, while there is economic growth for the various R/AC sub-sectors. The 6 years conversion has

no high GWP servicing demand after 2032-2034, the 12 years conversion has high GWP HFC servicing demand until 2042-2044, for the 18 years conversion period there is still some high GWP servicing demand until around 2050.

The demand for the period 2020-2050 for a 6 years conversion period is about 15,800 Mt CO<sub>2</sub>-eq., increases to 20,500 Mt CO<sub>2</sub>-eq. for a 12 years, and to 27,000 Mt CO<sub>2</sub>-eq. for a 18 years conversion period, a 70% increase compared to the 6 years conversion period.

#### 6.5.4 MIT-4 scenario

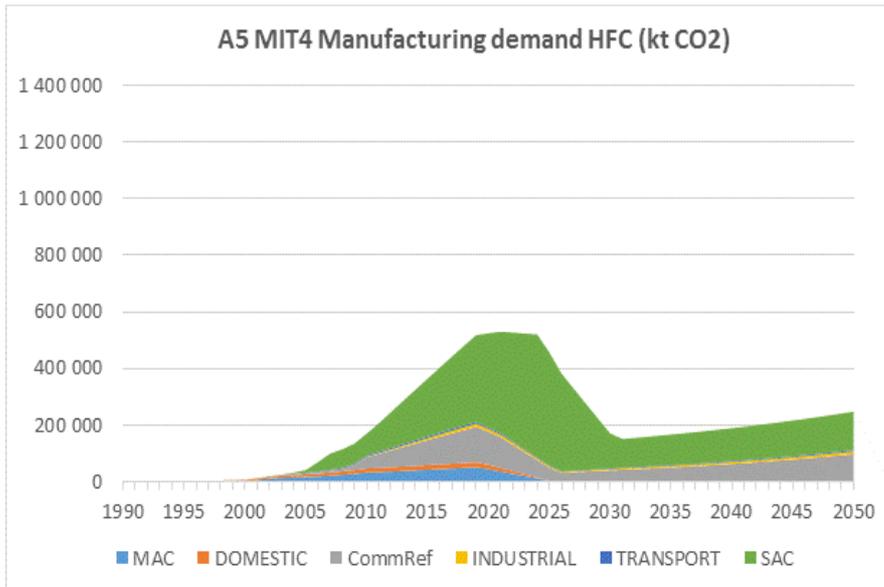


**Figure 6-19: Article 5 MIT-4 total demand scenario by R/AC sub-sectors in ktonnes CO<sub>2</sub>-eq. (compare Figure 6-14 for MIT-3)**

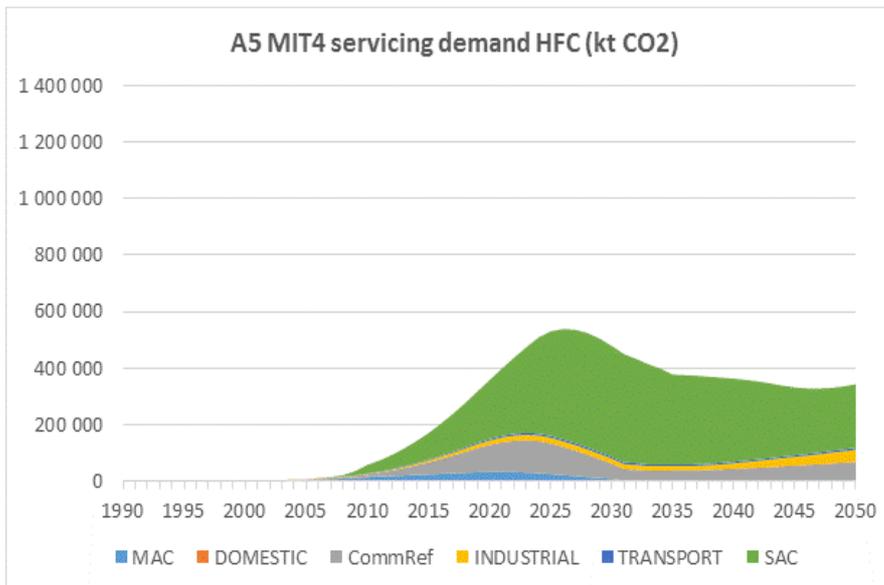
Figure 6-19 includes both manufacturing and servicing, and is the same as Fig 6-14 for MIT-3, except for the stationary AC sub-sector graph (in green), which continues to increase until 2025, before declining. MIT-4 parameters are otherwise identical to MIT-3 (replacement refrigerant blends GWP 300; 6 year manufacturing conversion).

Figure 6-20 also shows the data for HFCs used in new manufacturing only. The various sub-sectors now decline to zero new manufacturing demand at different times.

Demand in GWP weighted terms increases again after 2030-2032.



**Figure 6-20: Article 5 MIT-4 scenario for new manufacturing demand for the various R/AC sub-sectors in ktonnes CO<sub>2</sub>-eq. (compare Fig. 6-15 for MIT-3)**

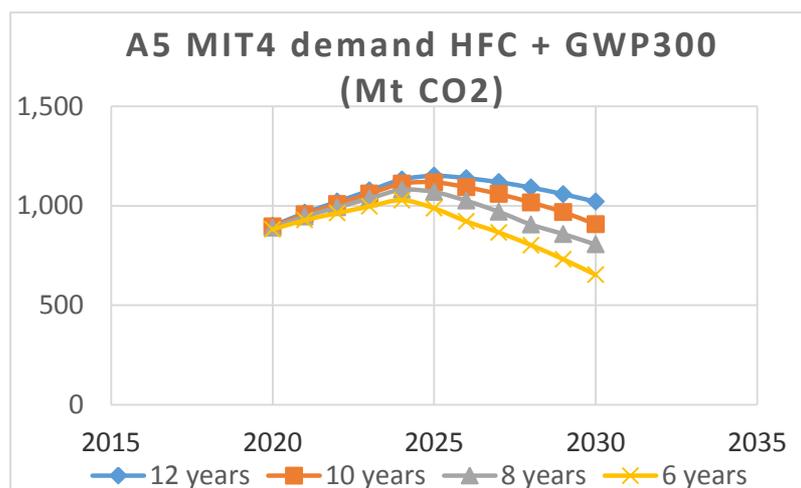


**Figure 6-21: Article 5 MIT-4 scenario with the servicing demand for the various sub-sectors in ktonnes CO<sub>2</sub>-eq. (stationary AC starting in 2025, and assuming a conversion of manufacturing over a period of six years) (compare Fig. 6-16 for MIT-3)**

In 2020-2025, demand for new manufacturing peaks at about 550 Mt CO<sub>2</sub>-eq, and demand for servicing is about 300 Mt CO<sub>2</sub>-eq, but by 2026, these values are reversed. Servicing demand peaks around 2027, at a high level of about 560 Mt CO<sub>2</sub>-eq., due to the late conversion of the stationary AC sector (assumed to rely on the refrigerants R-410A and R-407C).

The above graphs give a good impression of the impact of the stationary AC sector.

### 6.5.5 Impact of manufacturing conversion periods in the MIT-4 scenario



**Figure 6-22: Article 5 MIT-4 demand scenario for all R/AC sectors combined for new manufacturing conversion periods of 6-8-10-12 years in Mt CO<sub>2</sub>-eq. (compare Figure 6-17 for the MIT-3 scenario) (UNEP, 2015)**

Impact of the rate of manufacturing conversion: a long period of manufacturing conversion will result in an enhanced and long-lasting demand for high-GWP HFCs for servicing.

Fig. 6-22 gives the four curves for the six, eight, ten and 12 years manufacturing conversion periods for all refrigeration and AC sub-sectors together (as in (UNEP, 2015)). The delayed manufacturing conversion for stationary AC from 2020 to 2025 makes a large difference in the high-GWP demand.

For a six year conversion period, the HFC demand for MIT-3 and MIT-4 is projected for 2030 as (compare Figs. 6-17 and 6-22):

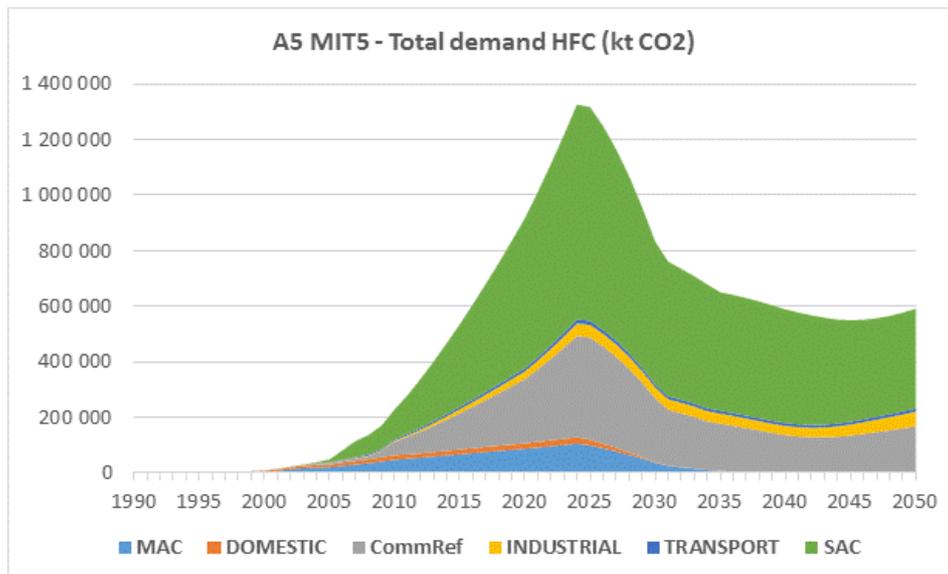
- MIT-3 (stationary AC conversion starting at 2020) - 410 Mt CO<sub>2</sub>-eq
- MIT-4 (stationary AC conversion starting at 2025) - 640 Mt CO<sub>2</sub>-eq

The delay of five years for stationary AC conversion to 2025 results in a more than 50% increase in annual HFC climate impact by the year 2030.

The MIT-4 scenario has a major adverse climate impact compared to MIT-3. There are cost implications of the MIT-4 scenario.

A delay of five years for starting SAC conversion, and a six year manufacturing conversion period, means that the overall costs have to be considered over a longer period than six years (i.e., over 12 years (rather than six years)).

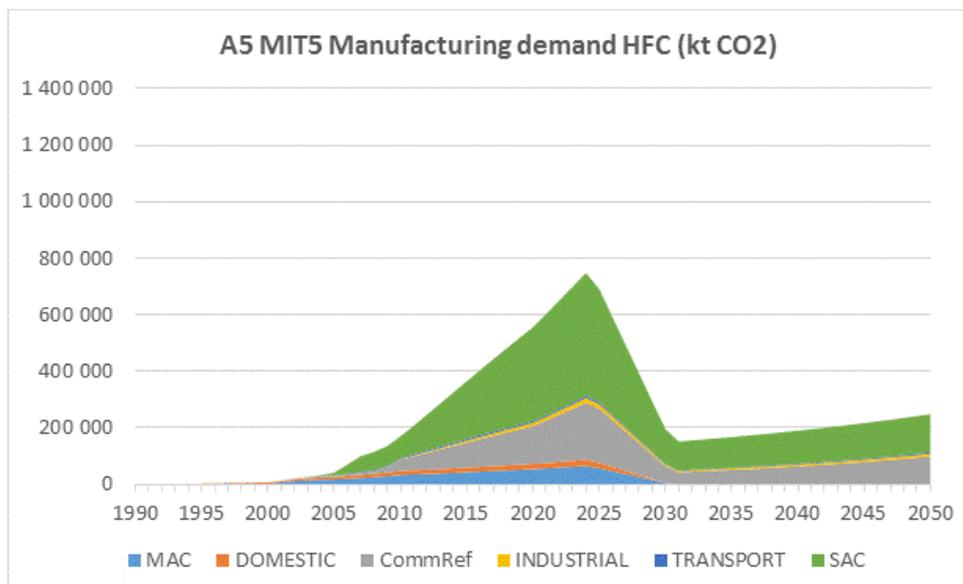
6.5.6 MIT-5 scenario



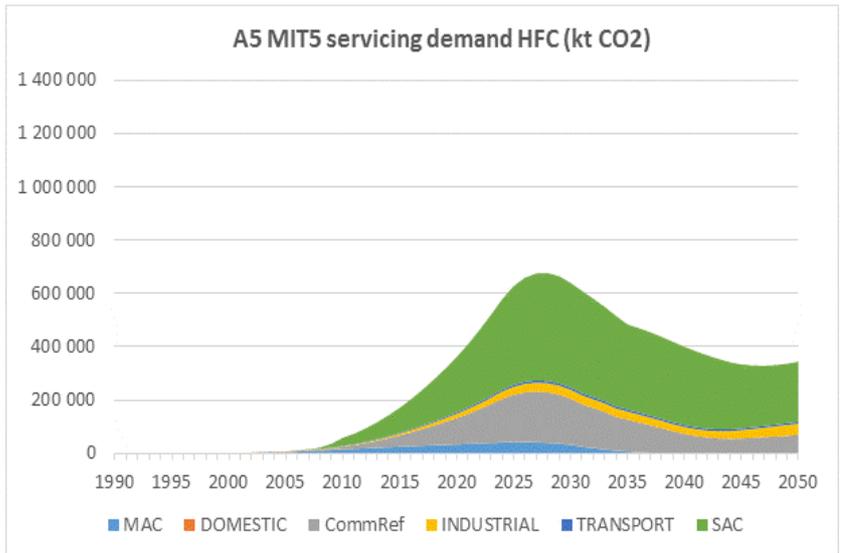
**Figure 6-23: Article 5 MIT-5 scenario by R/AC sub-sectors in ktonnes CO<sub>2</sub>-eq. (compare Figure 6-14 and 6-19 for MIT-3 and MIT-4)**

Figure 6-23 includes both manufacturing and servicing, and is similar to Figs 6-14 and 6-19 for MIT-3 and MIT-4 (replacement refrigerant blends at a GWP of 300; six year manufacturing conversion).

Figure 6-24 also shows the same data just for HFCs used in new manufacturing. All sub-sectors decline to zero new manufacturing demand at the same time (as in MIT-3).



**Figure 6-24: Article 5 MIT-5 scenario for new manufacturing demand for the various R/AC sub-sectors in ktonnes CO<sub>2</sub>-eq. (manufacturing conversion over a period of six years) (compare Figure 6-15 and 6-21 for MIT-3 and MIT-4)**

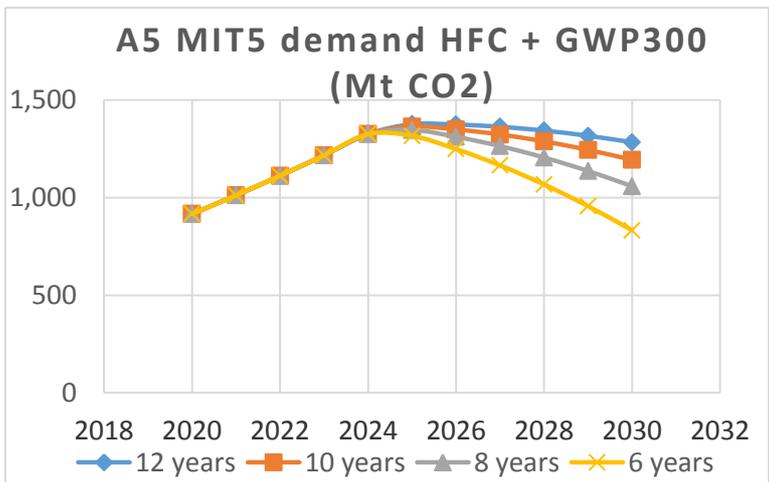


**Figure 6-25: Article 5 MIT-5 scenario with the servicing demand for the various sub-sectors in ktonnes CO<sub>2</sub>-eq. (assuming a conversion of manufacturing over a period of six years) (compare Figure 6-16 and 6-21 for MIT-3 and MIT-4)**

In 2025, demand for new manufacturing peaks at about 760 Mt CO<sub>2</sub>-eq, and demand for servicing is about 650 Mt CO<sub>2</sub>-eq. After 2030, the manufacturing demand has gone down to a little more than 100 Mt CO<sub>2</sub>-eq., then increases again due to assumed economic growth to more than 200 Mt CO<sub>2</sub>-eq.

Servicing demand peaks at about 660 Mt CO<sub>2</sub>-eq., due to the late conversions of all sub-sectors, then decreases until around 2045 to about 330 Mt CO<sub>2</sub>-eq., after which year it starts to increase again (economic growth assumed).

**6.5.7 Impact of manufacturing conversion periods in the MIT-5 scenario**



**Figure 6-26: Article 5 MIT-5 demand scenario for all R/AC sectors combined for new manufacturing conversion periods of 6-8-10-12 years (compare Figures 6-17 and 6-23 for the MIT-3 and MIT-4 scenarios) (UNEP, 2015)**

The impact of the rate of manufacturing conversion is that a long period of manufacturing conversion will result in an enhanced and long-lasting demand for high-GWP HFCs for servicing.

Fig. 6-26 gives the 4 curves for the six, eight, ten and 12 years manufacturing conversion periods for all refrigeration and AC sub-sectors together (again unchanged from what was given in (UNEP, 2015)). The delayed manufacturing conversion for all sub-sectors as of 2025 makes a large difference. While demand for a six year conversion period decreases substantially between 2025 and 2030, a 12 year conversion period only results in a small decrease between 2025 and 2030 (about 100 Mt CO<sub>2</sub>-eq.).

For a six year conversion period HFC demand is projected for 2030 for MIT-3 and MIT-5 as:

- MIT-3 (all conversions starting at 2020) - 410 Mt CO<sub>2</sub>-eq.
- MIT-5 (all conversions starting at 2025) - 810 Mt CO<sub>2</sub>-eq.

The delay of five years for all sub-sector conversions to 2025 results in roughly a 100% increase in annual weighted climate impact by the year 2030.

The MIT-5 scenario has a major adverse climate impact compared to MIT-3 (and also to some degree to MIT-4). Furthermore, cost implications of the MIT-5 scenario will therefore be larger than for MIT-3 and MIT-4. In the case of a six year manufacturing conversion period, overall costs will have to be covered over six years (expansion to 12 years does not seem desirable given the climate impact numbers).

## 6.6 Refrigerant demand and mitigation benefit numbers

On the basis of the development of the demand for the various refrigerants and their replacements for the various sub-sectors (high-GWP and low-GWP alternatives), total demand in tonnes, as well as in GWP based CO<sub>2</sub>-eq. tonnes can be calculated. The tables below extend to 2050 the non-Article 5 and Article 5 demand in tonnes and Mt CO<sub>2</sub>-eq. for BAU, MIT-3 and MIT-5 scenarios.

**Table 6-3: Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2050 in non-Article 5 Parties (tonnes)**

		2010	2015	2020	2025	2030
nA5 BAU	HFC-134a	79,097	77,977	72,872	76,869	82,356
	R-404A + R-507	17,084	18,376	18,584	19,357	22,780
	R-407C	11,195	26,802	34,942	43,946	50,402
	R-410A	39,385	77,354	94,230	114,001	131,319
	Low GWP	7,011	11,844	13,907	16,802	20,538
	<b>Total</b>	<b>153,772</b>	<b>212,353</b>	<b>234,535</b>	<b>270,975</b>	<b>307,395</b>
		2030	2035	2040	2045	2050
nA5 BAU	HFC-134a	82,356	93,316	108,107	125,265	145,166
	R-404A + R-507	22,780	26,151	30,221	34,960	40,470
	R-407C	50,402	58,256	67,534	78,291	90,760
	R-410A	131,319	151,966	176,170	204,229	236,758
	Low GWP	17,694	21,170	25,071	29,334	34,188
	<b>Total</b>	<b>307,395</b>	<b>350,859</b>	<b>407,103</b>	<b>472,079</b>	<b>547,342</b>

**Table 6-4: Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2050 in non-Article 5 Parties (ktonnes CO<sub>2</sub>-eq.)**

		2010	2015	2020	2025	2030
nA5 BAU	HFC-134a	102,825	101,370	94,733	99,930	107,064
	R-404A + R-507	67,397	72,490	73,312	76,367	89,875
	R-407C	18,135	43,419	56,606	71,193	81,652
	R-410A	75,619	148,520	180,922	218,882	252,133
	Low GWP	8	10	13	19	27
	<b>Total</b>	<b>263,984</b>	<b>365,809</b>	<b>405,586</b>	<b>466,391</b>	<b>530,751</b>
nA5 BAU	HFC-134a	107,064	121,311	140,539	162,845	188,716
	R-404A + R-507	89,875	103,180	119,238	137,936	159,679
	R-407C	81,652	94,374	109,405	126,831	147,032
	R-410A	252,133	291,774	338,246	392,120	454,575
	Low GWP	27	32	38	44	51
	<b>Total</b>	<b>530,751</b>	<b>610,671</b>	<b>707,466</b>	<b>819,776</b>	<b>950,053</b>

**Table 6-5: Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-3 scenario) for the period 2010-2050 in non-Article 5 Parties (tonnes)**

MIT-3		2010	2015	2020	2025	2030
nA5 3-year conversion 2020	HFC-134a	79,097	77,977	18,758	13,415	7,154
	R-404A + R-507	17,084	18,376	12,882	5,531	2,046
	R-407C	11,195	26,802	13,987	10,417	2,716
	R-410A	39,385	77,354	22,337	15,831	4,127
	Low GWP	7,011	11,844	133,007	189,570	252,410
	<b>Total</b>	<b>153,772</b>	<b>212,353</b>	<b>200,971</b>	<b>234,764</b>	<b>268,453</b>
		2030	2035	2040	2045	2050
nA5 3-year conversion 2020	HFC-134a	14,013	3,941	4,497	5,153	5,923
	R-404A + R-507	2,046	155	121	94	73
	R-407C	2,716	0	0	0	0
	R-410A	4,127	0	0	0	0
	Low GWP	252,410	353,069	409,796	475,307	551,172
	<b>Total</b>	<b>268,453</b>	<b>357,165</b>	<b>414,414</b>	<b>480,554</b>	<b>557,168</b>

**Table 6-6: Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-3 scenario) for the period 2010-2050 in non-Article 5 Parties (ktonnes CO<sub>2</sub>-eq.)**

MIT-3		2010	2015	2020	2025	2030
nA5 3-year conversion 2020	HFC-134a	102,825	101,370	24,384	17,441	9,301
	R-404A + R-507	67,397	72,490	50,811	21,816	8,072
	R-407C	18,135	43,419	22,660	16,876	4,401
	R-410A	75,619	148,520	42,886	30,396	7,923
	Low GWP	8	10	29,826	43,478	58,396
	<b>Total</b>	<b>263,984</b>	<b>365,809</b>	<b>170,568</b>	<b>130,007</b>	<b>88,093</b>
MIT-3		2030	2035	2040	2045	2050
nA5 3-year conversion 2020	HFC-134a	9,301	5,124	5,846	6,699	7,700
	R-404A + R-507	8,072	611	475	370	288
	R-407C	4,401	0	0	0	0
	R-410A	7,923	0	0	0	0
	Low GWP	58,396	72,898	84,498	97,948	113,542
	<b>Total</b>	<b>88,093</b>	<b>78,633</b>	<b>90,819</b>	<b>105,017</b>	<b>121,530</b>

The following can be observed for non-Article 5 Parties and the MIT-3 scenario, which results in the conversion of manufacturing by the year 2020:

- The demand for various HFCs in non-Article 5 Parties is assumed to decrease substantially between 2015 and 2030, by more than 70% in climate weighted terms, thereafter the decrease will be much slower (values are already very low);
- The demand for the stationary AC sub-sector decreases enormously between 2025 and 2030, because virtually all requirements for high-GWP refrigerants disappear. The amount of low-GWP refrigerants in climate terms now becomes very relevant (due to the remaining GWP of 300 assumed for low-GWP refrigerant blends).

A number of tables containing the demand data in tonnes and ktonnes CO<sub>2</sub>-eq. extended to 2050 for the BAU, MIT-3 and MIT-5 scenarios in Article 5 Parties are given below.

**Table 6-7: Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2050 in Article 5 Parties (tonnes)**

		2010	2015	2020	2025	2030
A5 BAU	HFC-134a	54,393	74,524	100,162	127,267	161,107
	R-404A + R-507	13,085	36,404	63,963	111,927	167,690
	R-407C	16,543	55,278	101,216	174,433	285,500
	R-410A	40,975	106,661	192,770	284,682	364,845
	Low GWP	22,430	29,318	39,132	51,975	69,915
	<b>Total</b>	<b>147,426</b>	<b>302,185</b>	<b>497,243</b>	<b>750,284</b>	<b>1,049,057</b>
		2030	2035	2040	2045	2050
A5 BAU	R134a	161,107	204,027	257,413	324,537	409,494
	R404A + R507	167,690	223,579	287,745	361,077	449,614
	R407C	285,500	372,998	457,406	532,391	587,361
	R410A	364,845	427,266	479,588	524,488	566,180
	Low GWP	69,915	85,957	104,807	127,577	155,209
	<b>Total</b>	<b>1,049,057</b>	<b>1,313,827</b>	<b>1,586,959</b>	<b>1,870,070</b>	<b>2,167,858</b>

**Table 6-8: Current and future refrigerant demand for (refrigerant) ODS alternatives (BAU scenario) for the period 2010-2050 in Article 5 Parties (ktonnes CO<sub>2</sub>-eq.)**

		2010	2015	2020	2025	2030
A5 BAU	HFC-134a	70,712	96,880	130,210	165,447	209,440
	R-404A + R-507	51,584	143,511	252,168	441,229	661,025
	R-407C	26,799	89,550	163,971	282,581	462,511
	R-410A	78,671	204,789	370,118	546,589	700,502
	Low GWP	62	115	203	314	469
	<b>Total</b>	<b>227,828</b>	<b>534,845</b>	<b>916,670</b>	<b>1,436,160</b>	<b>2,033,947</b>
		2030	2035	2040	2045	2050
A5 BAU	HFC-134a	209,440	265,234	334,637	421,897	532,343
	R-404A + R-507	661,025	881,313	1,134,195	1,423,289	1,772,283
	R-407C	462,511	604,256	740,997	862,474	951,525
	R-410A	700,502	820,350	920,809	1,007,017	1,087,066
	Low GWP	478	601	752	940	1,171
	<b>Total</b>	<b>2,033,956</b>	<b>2,571,754</b>	<b>3,131,390</b>	<b>3,715,617</b>	<b>4,344,388</b>

- The demand for various high-GWP HFCs in Article 5 Parties is (still) calculated to increase by a factor 3-4 in the BAU scenario in climate terms during 2015-2030 and by a factor of 7-8 during 2015-2050;
- The BAU scenario shows a large growth in demand for the high-GWP refrigerants R-404A, R-407C and R-410A, mainly due to the external (economic growth) factors.

**Table 6-9: Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-3 scenario) for the period 2010-2050 in Article 5 Parties (tonnes)**

MIT-3		2010	2015	2020	2025	2030
A5 6-year conversion 2020	HFC-134a	54,393	74,649	91,265	48,357	39,331
	R-404A + R-507	13,085	36,679	58,259	36,123	12,751
	R-407C	16,543	55,278	92,804	58,029	20,684
	R-410A	40,975	106,661	170,273	65,015	18,972
	Low GWP	22,430	29,318	87,522	562,500	991,332
	<b>Total</b>	<b>147,426</b>	<b>302,585</b>	<b>500,123</b>	<b>770,024</b>	<b>1,083,070</b>
MIT-3		2030	2035	2040	2045	2050
A5 6-year conversion 2020	HFC-134a	39,331	39,386	47,809	57,936	70,499
	R-404A + R-507	12,751	2,970	1,576	3,306	5,077
	R-407C	20,684	13,059	4,411	0	0
	R-410A	18,972	13,467	4,267	0	0
	Low GWP	991,332	1,244,943	1,528,895	1,808,828	2,092,281
	<b>Total</b>	<b>1,083,070</b>	<b>1,313,825</b>	<b>1,586,958</b>	<b>1,870,070</b>	<b>2,167,857</b>

**Table 6-10: Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-3 scenario) for the period 2010-2050 in Article 5 Parties (ktonnes CO<sub>2</sub>-eq.)**

		2010	2015	2020	2025	2030
A5 6-year conversion 2020	HFC-134a	70,712	96,880	117,959	61,810	49,670
	R-404A + R-507	51,584	143,511	227,693	141,897	50,899
	R-407C	26,799	89,550	150,343	94,007	33,508
	R-410A	78,671	204,789	326,924	124,828	36,425
	Low GWP	62	115	11,394	123,925	230,156
	<b>Total</b>	<b>227,828</b>	<b>534,858</b>	<b>834,313</b>	<b>546,467</b>	<b>400,658</b>
		2030	2035	2040	2045	2050
A5 6-year conversion 2020	HFC-134a	49,670	51,201	62,151	75,316	91,649
	R-404A + R-507	50,899	11,716	6,210	13,024	20,005
	R-407C	33,508	21,156	7,146	0	0
	R-410A	36,425	25,856	8,192	0	0
	Low GWP	230,156	299,573	365,941	426,394	481,920
	<b>Total</b>	<b>400,658</b>	<b>409,502</b>	<b>449,640</b>	<b>514,734</b>	<b>593,574</b>

The following can be observed for the Article 5 Parties, in the case of the MIT-3 scenario:

- The demand for various high-GWP HFCs in Article 5 Parties is estimated to increase by more than 50% between 2015 and 2020 in climate terms, however, it decreases again to the 2015 level in the year 2025;
- The most surprising result is that the demand in climate terms is reduced by only 20-25% in the year 2030, compared to 2015 (of course, it is much higher in the year 2020). This is due to the high growth assumed, in particular, for stationary AC, where, for all sub-sectors together, the use of replacement refrigerant blends with a GWP of 300 (at one million tonnes) is calculated to represent a climate impact of 230 Mt CO<sub>2</sub>-eq. in 2030;
- It should be realised that the proposed MIT-3 manufacturing conversion will be *very* demanding and the assumptions used here are based on the fact that institutional and industrial capacities can completely deal with the conversion in this timeframe.

**Table 6-11: Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-5 scenario) for the period 2010-2050 in Article 5 Parties (tonnes)**

MIT-5		2010	2015	2020	2025	2030
A5 6-year conversion 2025	HFC-134a	54,393	74,524	100,162	115,545	60,851
	R-404A + R-507	13,085	36,404	63,963	101,843	54,014
	R-407C	16,543	55,278	101,216	160,942	108,166
	R-410A	40,975	106,661	192,770	254,067	104,162
	Low GWP	22,430	29,318	39,132	117,161	714,856
	<b>Total</b>	<b>147,426</b>	<b>302,185</b>	<b>497,243</b>	<b>749,558</b>	<b>1,042,049</b>
MIT-5		2030	2035	2040	2045	2050
A5 6-year conversion 2025	HFC-134a	60,851	44,532	48,104	58,047	70,499
	R-404A + R-507	54,014	29,994	11,445	3,515	5,077
	R-407C	108,166	30,160	21,180	7,194	0
	R-410A	104,162	83,830	55,193	16,085	0
	Low GWP	714,856	1,125,310	1,451,035	1,785,231	2,092,281
	<b>Total</b>	<b>1,042,049</b>	<b>1,313,826</b>	<b>1,586,957</b>	<b>1,870,072</b>	<b>2,167,857</b>

**Table 6-12: Current and future refrigerant demand for (refrigerant) ODS alternatives (MIT-5 scenario) for the period 2010-2050 in Article 5 Parties (ktonnes CO<sub>2</sub>-eq.)**

		2010	2015	2020	2025	2030
A5 6-year conversion 2025	HFC-134a	70,712	96,880	130,210	150,208	79,106
	R-404A + R-507	51,584	143,511	252,168	401,490	213,054
	R-407C	26,799	89,550	163,791	260,727	175,229
	R-410A	78,761	204,789	370,118	487,808	199,992
	Low GWP	62	115	203	16,637	166,480
	<b>Total</b>	<b>227,828</b>	<b>534,845</b>	<b>916,670</b>	<b>1,316,870</b>	<b>833,861</b>
		2030	2035	2040	2045	2050
A5 6-year conversion 2025	HFC-134a	79,106	57,892	62,535	75,460	91,649
	R-404A + R-507	214,824	118,243	45,115	13,846	20,005
	R-407C	175,229	48,859	34,312	11,654	0
	R-410A	199,992	160,953	105,970	30,882	0
	Low GWP	166,332	265,216	342,666	419,344	481,920
	<b>Total</b>	<b>835,483</b>	<b>651,163</b>	<b>590,598</b>	<b>551,186</b>	<b>593,574</b>

In Tables 6-11 and 6-12 above, the following can be observed for the Article 5 Parties and the MIT-5 scenario:

- The MIT-5 scenario represents a much higher climate impact than the MIT-3 scenario. For the future, the question remains which scenario could or would be the most likely one that Article 5 Parties can and will follow;
- The demand for various high-GWP HFCs in Article 5 Parties is calculated to increase by a factor of 1.7 between 2015 and 2020 and by a factor 1.45 between 2020 and 2025, expressed in ktonnes CO<sub>2</sub> eq. (this corresponds more or less to the same growth in refrigerant demand in tonnes);

- One might conclude that the proposed MIT-5 manufacturing conversion is not expected to be too demanding and that institutional and industrial capacities should be able to deal with the conversion in this timeframe, if not before. This, of course, assumes the gradual acceptance of alternatives for all sub-sectors before 2025, which seems to be definitely possible taking into account the pace of acceptance for many alternatives anticipated at present.

**Table 6-13: Refrigerant demand for (refrigerant) ODS alternatives in the BAU, MIT-3, MIT-4 and MIT-5 scenarios for various periods in Article 5 Parties (n.b., in Mt CO<sub>2</sub>-eq.); the total concerns the total refrigerant demand over the period 2020-2050**

Period	2020-2030	2031-2040	2041-2050	Total
A5 BAU	16016	26321	37874	80211
A5 MIT-3	6349	4202	5257	15808
A5 MIT-4	9762	5798	5540	21100
A5 MIT-5	12069	6696	5719	24484

**Table 6-14: Refrigerant demand for (refrigerant) ODS alternatives in the BAU, MIT-3, MIT-4 and MIT-5 scenarios for the periods 2020-2030, 2020-2040 and 2020-2050 in Article 5 Parties (n.b., in Mt CO<sub>2</sub>-eq.); in brackets the saving for the various MIT scenarios compared to BAU in that period is given**

Period	2020-2030	2020-2040	2020-2050
A5 BAU	16016	42337	80211
A5 MIT-3	6349 (0,604)	10551 (0,751)	15808 (0,803)
A5 MIT-4	9762 (0,390)	15560 (0,632)	21100 (0,737)
A5 MIT-5	12069 (0,246)	18765 (0,557)	24484 (0,695)

(As already presented in the XXVI/9 report (UNEP, 2015)) Table 6-13 (and 6-14) show the following (rounded) integrated total refrigerant demand for the three scenarios for the period 2020-2030 in Mt CO<sub>2</sub>-eq.:

**BAU:** 16,000 Mt CO<sub>2</sub>-eq.  
**MIT-3:** 6,400 Mt CO<sub>2</sub>-eq.  
**MIT-4:** 9,800 Mt CO<sub>2</sub>-eq.  
**MIT-5:** 12,000 Mt CO<sub>2</sub>-eq.

The MIT-3 reduction from BAU of 9,500 Mt CO<sub>2</sub>-eq. represents a saving of 60%. In the case of the MIT-4 scenario, with a reduction of about 6200 Mt CO<sub>2</sub>-eq. compared to BAU, there is a saving of almost 40% from BAU. The MIT-5 reduction of 4,000 Mt CO<sub>2</sub>-eq. represents a smaller saving of 25% from BAU for this 2020-2030 period.

Values change calculated for the three scenarios in Mt CO<sub>2</sub>-eq. through 2050:

**BAU:** 80,200 Mt CO<sub>2</sub>-eq.  
**MIT-3:** 15,800 Mt CO<sub>2</sub>-eq.  
**MIT-4:** 21,000 Mt CO<sub>2</sub>-eq.  
**MIT-5:** 24,500 Mt CO<sub>2</sub>-eq.

The MIT-3 reduction from BAU represents a saving of 80%. In the case of the MIT-4 scenario there is a savings of about 75% while the MIT-5 reduction of 56,000 Mt CO<sub>2</sub>-eq. compared to BAU represents a savings of 70% from BAU. There are still differences between the various MIT scenarios. However, the BAU demand for the entire period 2020-2050 becomes so large that the differences in reduction between the various mitigation scenarios MIT-3, -4 and -5 become less relevant.

A more reasonable estimate of the savings that can be realised via the various MIT scenarios may be the consideration of the period 2020-2040;

<b>BAU:</b>	<i>42,300 Mt CO<sub>2</sub>-eq.</i>	
<b>MIT-3:</b>	<i>10,600 Mt CO<sub>2</sub>-eq.</i>	<i>75% saving compared to BAU</i>
<b>MIT-4:</b>	<i>15,600 Mt CO<sub>2</sub>-eq.</i>	<i>63% saving compared to BAU</i>
<b>MIT-5:</b>	<i>18,800 Mt CO<sub>2</sub>-eq.</i>	<i>56% saving compared to BAU.</i>

Another way to look at this is to analyse the trends in demand that are observed, as follows:

- Peak values determined for the refrigerant demand increase with a later start of conversion. The peak value for MIT-3 in 2020 is about 820 Mt CO<sub>2</sub>-eq. The peak value for MIT-4 in the year 2023, with conversion of stationary AC starting in 2025, is 25% higher (at 1025 Mt CO<sub>2</sub>-eq.), whereas the peak value for demand for MIT-5 in the year 2025 is 62% higher than the one for MIT-3 (at 1330 Mt CO<sub>2</sub>-eq.).
- For MIT-3, the average decline over a period of ten years after the peak year is 5.3% per year (from 820 down to 390 Mt CO<sub>2</sub>-eq. in 2030), for MIT-4 it is 4.5% per year (from 1025 down to 570 Mt CO<sub>2</sub>-eq. in 2033) and for MIT-5 it is 5.5% per year (from 1330 down to 605 Mt CO<sub>2</sub>-eq.). If the freeze year (which coincides with the peak year) is chosen as the starting point, an average annual reduction of 5% in total demand (manufacturing and servicing) seems feasible for all types of scenarios. These values all apply to a manufacturing conversion period of six years.
- For each separate Article 5 country the peak (freeze) values will still be in the same years for the various MIT scenarios considered, however, annual reduction percentages achievable thereafter may be significantly different per country.

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## 7

## List of acronyms and abbreviations

AHRI	Air Conditioning, Heating and Refrigeration Institute
AREP	Alternative Refrigerants Evaluation Program
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASTM	American Society for Testing and Materials
CEN	European Committee for Standardisation
CFC	Chlorofluorocarbon
CO <sub>2</sub>	Carbon Dioxide
COP	Coefficient of Performance
EPA	US Environmental Protection Agency
EU	European Union
GWP	Global Warming Potential
HC	Hydrocarbon
HCC	Hydrochlorocarbon
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HCO	Oxygenated hydrocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HTOC	Halons Technical Options Committee
IIR	International Institute for Refrigeration
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LCA	Life Cycle Analysis
LCCP	Life Cycle Climate Performance
MBH	Thousand BTUs per Hour
ODP	Ozone Depletion Potential
ODS	Ozone Depleting Substance
OEL	Occupational Exposure Limit
R/AC	Refrigeration and Air Conditioning (also RAC&HP)
RTOC	Refrigeration, AC and Heat Pumps Technical Options Committee
SNAP	Significant New Alternatives Policy
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



## **Annex 1 - Summary of Informal Discussion on the TEAP Decision XXVII/4 Task Force Report for OEWG-37**

Parties provided comments on this report and suggestions for TEAP's second report under Decision XXVII/4 in an informal discussion session with TEAP, Thursday 7 April, 1-2.30 p.m. The comments and suggestions are summarized below. All these comments will be taken into consideration by the TEAP XXVII/4 Task Force within the timeline remaining to the Task Force to complete its second report for submission to OEWG-38.

### **Update on refrigerants**

- The report should include updates and information on not-in-kind (NIK) technologies.
- Further consideration should also be provided with regards to safety with the aim of advancing technologies to meet the current safety standards in relation to the new alternatives. With regard to servicing, the report should address whether use of the alternatives including flammables would require specialized training, including under HAT conditions.
- A request was made for addressing criteria from paragraph 1(a) of the previous Decision XXVI/9, including addressing whether alternatives are “environmentally sound” in order to avoid having to revisit in the future decisions that are made today in selecting alternatives. Additionally, the term “environmentally sound” could be further elaborated.

### **Testing of alternatives under high ambient temperature (HAT) conditions**

- A Party that had proposed language for considering a HAT exemption in the contact group meeting offered to share the information to TEAP on the criteria and data used; the party also noted that it would welcome other alternative approaches.
- The section in the report that discussed the results of the alternatives testing under HAT conditions were actually positive, and this positive outcome along with any negative outcomes of the testing should be better reflected in the executive summary of the report. However, the executive summary of the report should also indicate that certain elements were not included in the alternatives testing such as risk assessment.
- The cost element should be reflected in a contextual manner to include the cost of in-kind replacement, full or partial system redesign.
- A couple of Parties suggested that it would be helpful if the report could include an overview of the status of the various alternatives based on the testing - not in additional discussion within the report but perhaps in a table format so key information would be in one place.
- A Party asked for HAT considerations to include some additional uses including in industrial equipment, chillers, and other sub-sectors such as transport air conditioning; additional uses mentioned were cooling of mines in South Africa and propane-driven technologies in Australia.

### **Scenarios**

- A Party identified that some idea of the magnitudes of the present banks of HFCs would be helpful.
- A request was made on whether the TEAP reported annual production of HFCs could be provided by countries.
- A Party suggested that the report should clarify that only certain HFCs were included in the production figures.
- With regard to the BAU, not all existing regulations were used so TEAP was requested to investigate whether the report could further consider these in addition to

a number of corporate commitments and changes in national procurement regulations.

- A Party requested whether the report could show a BAU scenario without any regulatory actions incorporated.
- Further clarification is needed on the estimated growth rates that were used compared to refrigerant demand growth.
- A request was made as to whether the impacts of a longer manufacturing conversion period of 18 years could be calculated and incorporated.
- The previous XXVI/9 report included estimated costs and emissions reductions for the various mitigation scenarios; a request was made to include these costs and benefits into this XXVII/4 report.
- A party requested whether the scenarios could show the demand on a regional basis.

## Annex 2 - Background information about refrigeration in the fishing industry

### A2.1 The fishing industry

The total number of fishing vessels in the world in 2010 is estimated at about 4.36 million, which is similar to previous estimates. Of these, 3.23 million vessels (74%) are considered to operate in marine waters, with the remaining 1.13 million vessels operating in inland waters. Overall, Asia and the Pacific have the largest fleet, comprising 3.18 million vessels and accounting for 73% of the world total, followed by Africa (11%), Latin America and the Caribbean (8%), North America (3%), Europe (3%) and rest of world (2%). Globally, 60% of all fishing vessels were engine-powered in 2010, but although 69% of vessels operating in marine waters were motorised, the figure was only 36% for inland waters. For the fleet operating in marine waters, there were also large variations among regions, with non-motorised vessels accounting for less than 7% of the total in Europe and the Near East, but up to 61% in Africa (UN, 2010).

As shown in Figure A2-1, almost 80% of the motorised fishing vessels in the world are less than 12m in overall length (LOA). Such vessels dominate in all regions, but markedly so in Africa, the Near East, and Latin America and the Caribbean. About 2% of all motorised fishing vessels correspond to industrialised fishing vessels of 24 m and larger (with a gross tonnage (GT) of roughly more than 100 GT or 100 Gross Register Tonnage (GRT)) and that fraction was larger in the Pacific and Oceania region, Europe, and North America.

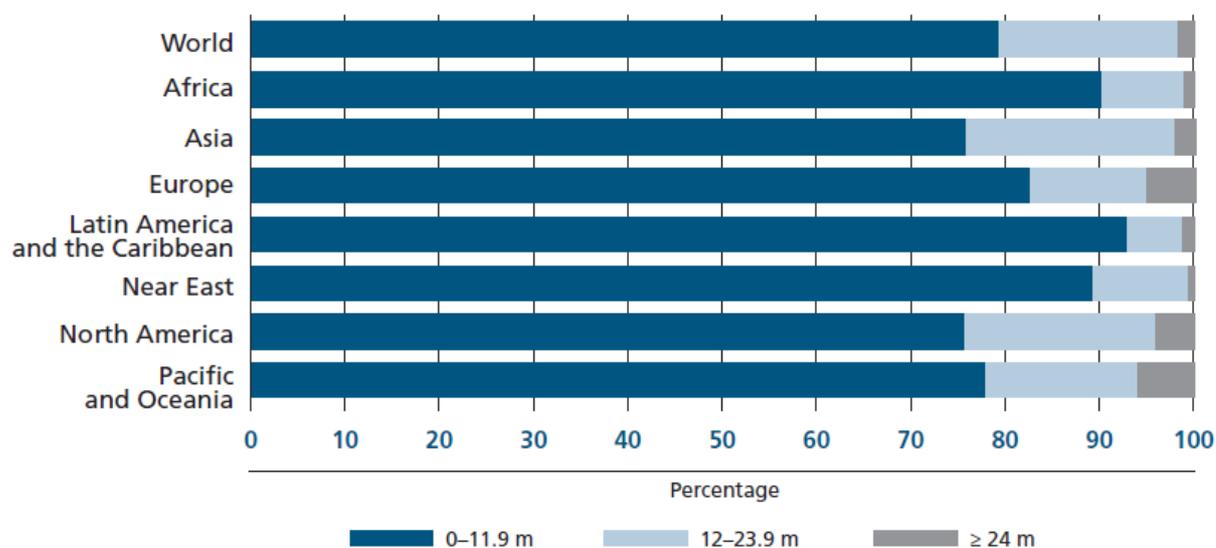


Figure A2-1 Ship Length (FAO, 2014)

#### A2.1.1 Pacific fishing vessels

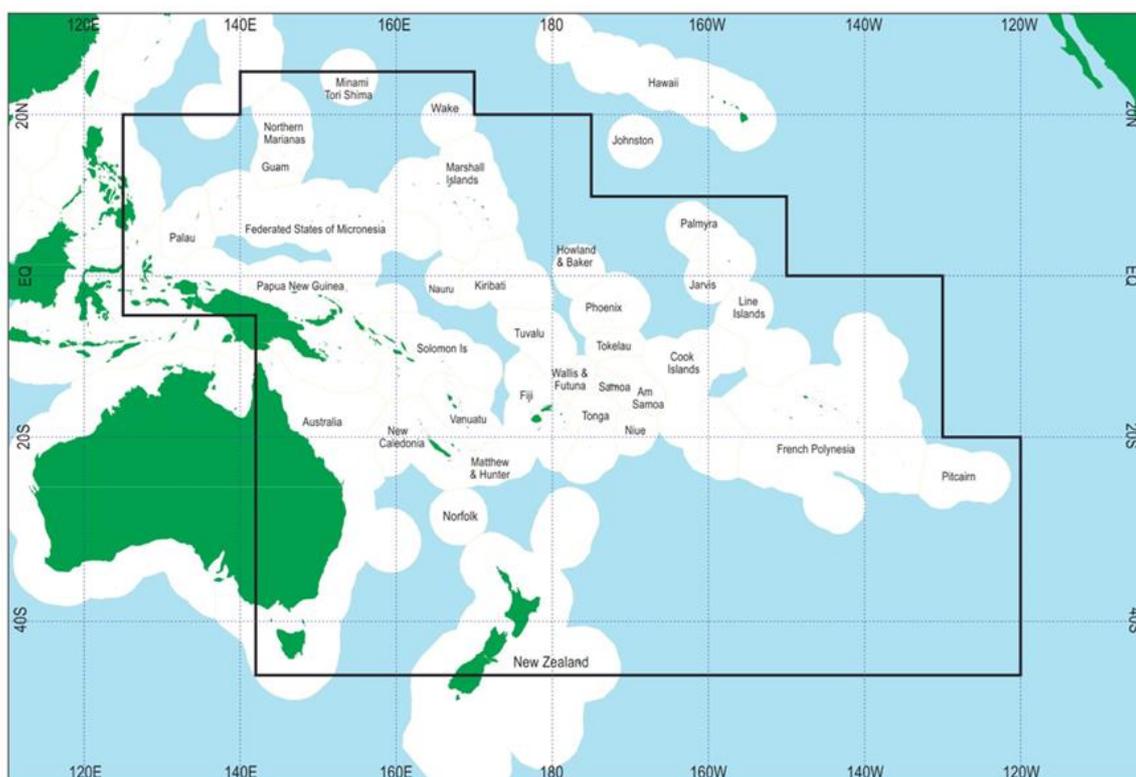
The area described as the Pacific Islands is shown in the Figure A2-2 below.

Marine Fisheries is the single largest industry and source of income for many Pacific Island Countries (PICs) (Awira, 2014). Economic benefit derived from this sector is sourced through a direct involvement of PICs in fishing, fish processing and through the licensing arrangement between PICs and foreign fishing nations. Many different nations operate fishing vessels in the PIC region and refrigeration is essential in all stages of the fisheries industry: from catching to processing to the consumer. Although PICs are complying with their obligations under the Montreal Protocol on the phasing out of HCFCs, this sector is still an elusive area.

The demand and market supply routes of refrigerants and refrigerant servicing in the marine fishing sector is not known for PICs and perhaps for other regions.

The management of Ozone Depleting Substances (ODS) in the fishing sector has to be intimately aligned with the complex nature and magnitude of this industry including that of clarifying the responsibility of flag states and vessels owners in the context of sustainable development. As of June 2014 the number of vessels registered under the Pacific Islands Forum Fisheries Agency (FFA), Good Standing Register stands at a total of 1,332 vessels (FFA database 2014) including bunkers, fish carriers, long liners, mother ships, pole and liners and purse seiners. Out of this total, the vessels with cold storage capabilities that have a direct link to the consumption of refrigerants with ozone depleting properties are long liners, purse seiners, fish carriers and pole and line fishing vessels.

One may ask why there are so many vessels operating in the region vying for the same four species of tuna? The answer is that the tuna fishery in the waters of the FFA member countries is the largest in the world and there is a need to generate and maximise economic benefit from fishery resources for PICs, as for some this is the only resource they have. Ten years ago, income from fisheries access was around US\$ 40 million but now PICs are getting somewhere around US\$ 250 million in fishing revenue and other direct benefits. This shows an increase of over 500% which can be attributed to the management measures put into place by FFA and the Tuna Commission as well as the introduction of the Parties of the Nauru Agreement vessel day scheme in 2007. In 2013 the total catch of tuna resources from the Western and Central Pacific - Commission Area (WCP-CA) was 2.61 million tonnes and this is valued at US\$ 6.3 billion. Catch taken from waters of the FFA member countries is 1.56 million tonnes or 60% of the WCP-CA total and this is valued at US\$ 3.4 billion.



Source: SPC; the dark lines represent the SPC statistical area.

*Figure A2-2 Map showing Pacific Islands region (Gillet, 2011)*

With more than 1,000 vessels roaming the Pacific Ocean from various nationalities fishing for tuna, there is an urgent need to have mechanisms to monitor and control the consumption of

all refrigerants used on fishing vessels to ensure that PICs meet their obligations under the Montreal Protocol and the International Maritime Organization's (IMO) agreement on the prevention of air pollution from ships which is covered under MARPOL 73/78 Annex VI. FFA Members do not have this capacity, nor do they have the financial, human or institutional resources. Monitoring, reporting and enhanced enforcement of refrigerant supplies to fishing vessels is also recommended. Often the fishing vessels enter and received supplies at designated fish depots. The level and adequacy of customs controls at these ports need to be studied.

Effective enforcement of supplies to vessels can also support control requirements on illegal, unreported and unregulated (IUU) fishing. Previously published IUU loss estimates for the Western and Central Pacific region are somewhere in the region of US\$ 750 million to US\$ 1.5 billion a year. Where IUU involves vessels not already licensed in the fishery, it can be assumed that for IUU there will also be a high demand for refrigerants and that they may be traded illegally to meet the demand of illegal fishers. This also extends the subject of application of for example Decision XIX/12: Preventing illegal trade in ozone-depleting substances.

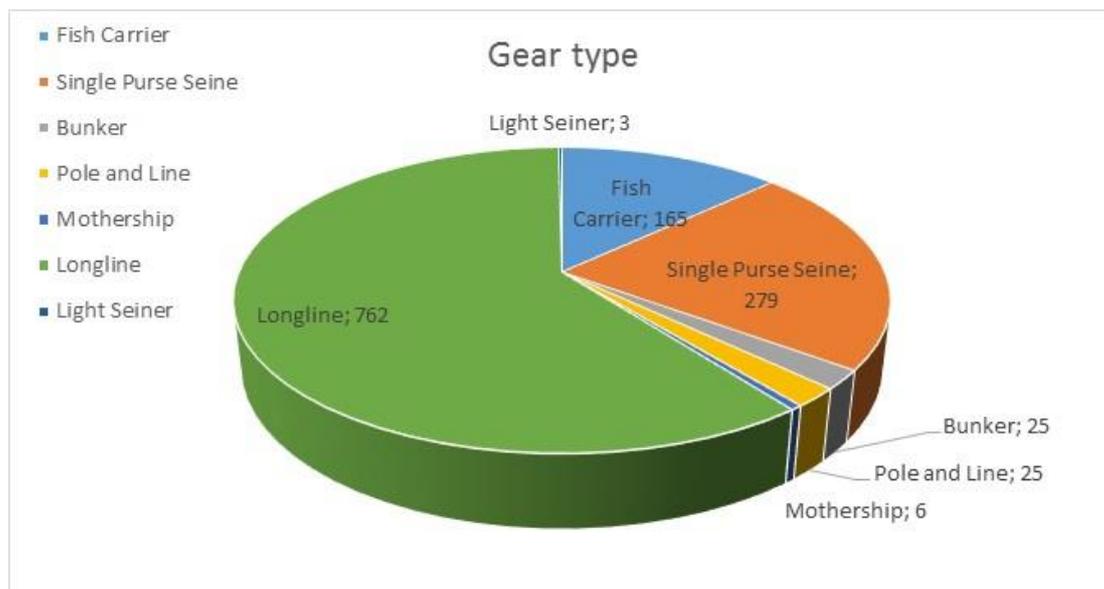
The distribution of ship types is shown in Figure A2-3.

Main fishing methods are Purse Seine and Long Line. Out of 1270 ships, 77% were flagged with outside the area and only 23% were FFA flagged (Awira, 2015)

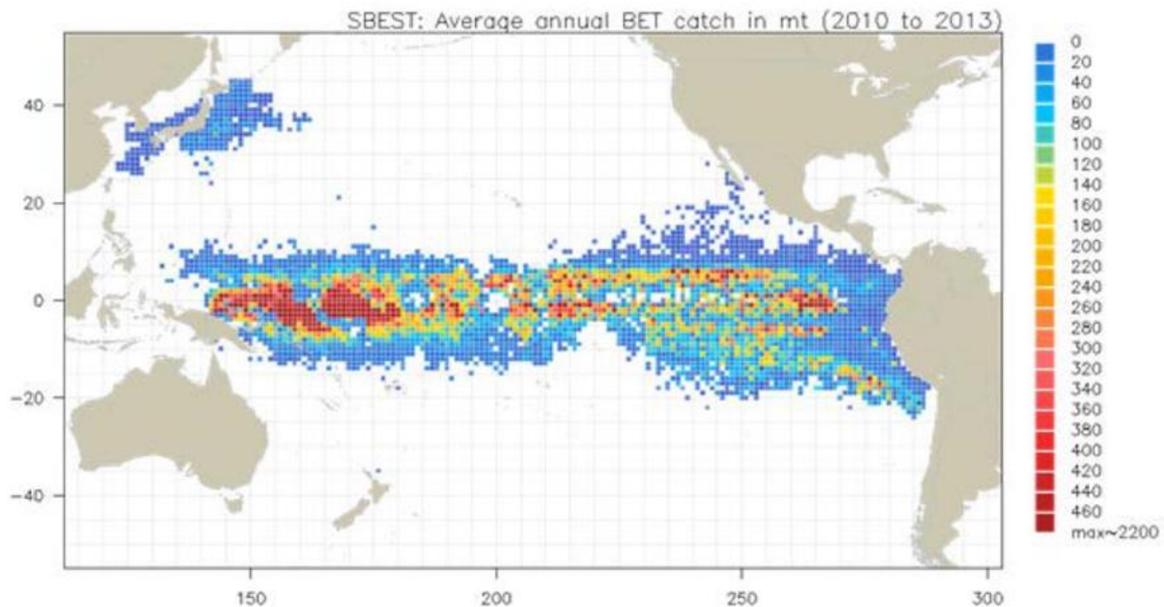
The biggest part of the Pacific Purse Seine, Bigeye Tuna are caught around the equator +/-10° degrees (see Figure A2-4). This means that a significant distance has to be travelled and that the fish have to be kept refrigerated or alive until landing to avoid spoilage (Honolulu, 2015).

A variety of methods are used for freezing tuna including air blast cooling or immersion in brine. Plate freezers are not generally used for larger fish due to the difficulty of getting them to fit between the plates.

One of the requirements for freezing the fish is related to parasite kill in the fish. According to European Union regulations, freezing fish at -20°C for 24 hours kills parasites. The U.S. Food and Drug Administration (FDA) recommends freezing at -35°C for 15 hours, or at -20°C for 7 days.



**Figure A23-3 Ship types in Pacific Islands Countries (Awira, 2015)**



**Figure A2-4 Distribution of tuna catch**

Not all fish is for export and much is used in the local economy. Industrial-scale shrimp fisheries, for instance, only occur in Papua New Guinea.

Costal fishing is very important for the local economy and nutrition, but in the global market it is only a small part of the total production. In any case these smaller boats usually use ice whereas the larger ships have mechanically refrigerated holds.

Coastal fishing in the region can be placed mostly into the following categories:

- *Small-scale commercial fishing*, (also referred to as “artisanal”) which can be further broadly sub-divided into those supplying domestic markets, and those producing export commodities.
- *Subsistence fisheries*, which support rural economies and are extremely important to the region’s nutrition and food security (Gillet, 2011)

The cold chain is not a concept implemented globally. The food spoilage in this part of the world is relatively high, in part due to the high ambient temperatures. There are numerous other techniques for storing non canned fish such as smoking, drying, brining and dry salting which do not involve refrigeration.

### **A2.1.2 The EU fishery fleet**

Considering that more than 70% of fishing fleet operating in the Pacific Islands is flagged outside the area (Awira, 2015), a look to the situation of other fleets is worthwhile. As an example of how the fishing fleets of non-Article 5 Parties are organised, the European Union (EU) fishery fleet situation is described here.

The EU fleet is very diverse, with the vast majority of boats being no more than 12 metres long, with a small number of vessels exceeding 40 metres in length.

Reducing fleet capacity is an essential tool for achieving a sustainable exploitation of fisheries resources. That is why the EU’s fishing fleet capacity has declined steadily since the early 1990s, in terms of both tonnage (an indicator of fish-holding capacity) and engine power (an indicator of the power available for fishing gear). The size of the EU-28 fishing fleet has dropped to about 86’500 vessels in 2013 compared to 104’000 vessels for the EU-15 in 1995, although it increased by 7.2 % between 2012 and 2013, following Croatia’s EU

accession. The EU's fishing fleet in 2013 had a combined capacity of 1.7 million gross tonnes and a total engine power of 6.6 million kW.

Almost one fifth (18.3%) of the EU-28's fishing fleet is registered in Greece. Generally however, these Greek vessels are small, with an average size of 4.9 gross tonnes (much less than the EU-28 average of 19.2 gross tonnes) and an average engine power of 28.9 kilowatts in 2013 (compared with an EU-28 average of 76.0 kW). In terms of capacity, Spain, France, Italy and the United Kingdom had the largest fishing fleets, accounting for 54.2 % of gross tonnage and 55.8 % of engine power in 2013 (EUROSTAT, 2014).

## **A2.2 Refrigeration within the fishing industry**

### **A2.2.1 Refrigeration on board**

In order to avoid spoilage and increase shelf-life, fish must be kept refrigerated as soon as they are caught.

If the fish are caught for local use, ice is the best suited refrigeration medium, as it can be used without any machinery on board ships and provides cold storage. Ice is very well suited for fish, as i) it provides the quick cooling after harvesting, needed for good quality, ii) its temperature is just right for short term conservation, and iii) though melt water can affect the quality of other goods, it does not alter the quality of fish, which are protected by skin and scales.

If not consumed fresh, fish is processed for conservation. This yields the different products that can be found on markets: canned, frozen, freeze dried or cured. Industrial processing of fish can be done on board factory ships or in land based plants. In all cases the process is similar to other kinds of food processing, with just some peculiarities which will be pointed out later on (de Larminat, 2015).

Table A2-1 summarizes the type of conservation method for the fish depending on the type of catch and on the type of vessel used for the catch.

*Table A2-1 Type of fish conservation used depending on the catch (de Larminat, 2015)*

Catches	Conservation method
local	ice
mid-distance	brine freezing/RSW
long-distance	deep freezing

The smallest ships have no refrigeration at all aboard. When a little larger, they load up flake ice every morning from the harbour. The catch is then iced as it comes on-board and held cold with the ice. Larger ships have Refrigerated Sea Water (RSW) tanks and produce ice on-board. Only the largest vessels have complete factory installations with blast freezers, plate freezers, RSW tanks and ice-machines.

In recent decades, major innovations in refrigeration, ice-making, packaging and transportation to ensure product integrity have also allowed an expansion of fish distributed in fresh, chilled and frozen forms. Developing countries have experienced a growth in the share of fish production utilised as frozen products (24% of fish for human consumption in 2012, up from 20% in 2002 and 13% in 1992).

However, many countries, especially those with less-developed economies, still lack adequate infrastructure and services including hygienic landing centres, electricity, potable water,

roads, ice, ice plants, cold rooms and refrigerated transport. These factors, associated with tropical temperatures, result in high post-harvest losses and quality deterioration, with subsequent risks for consumers' health. In addition, fish marketing is also more difficult owing to often limited and congested market infrastructure and facilities. Due to these deficiencies, together with well-established consumer habits, fish in developing countries is commercialised mainly live or fresh soon after landing or harvesting, or it is processed using traditional preservation methods, e.g. salting, drying and smoking. These methods remain prevalent in many countries, in particular in Africa and Asia, which show higher proportions of cured fish compared with other continents (FAO, 2014).

#### **A2.2.2 *Ice plants and Refrigerated Sea Water (RSW)***

The ice plant is a complete installation for the production and storage of ice, including the icemaker itself together with the associated refrigeration machinery, harvesting and storage equipment, and infrastructure.

Other than by description of the ice produced, there is no simple way to classify the different types of ice makers; hence we have block, slice, plate, tube, slush ice and so on.

Typically, ice plants are vapour compression refrigerating plants able to produce up to 10 tons per hour with evaporating temperatures ranging from -10°C to -30°C.

Ice can also be produced from sea water: when seawater is frozen slowly, freshwater ice crystals are initially frozen out of the mixture. The whole solution will not be frozen until the temperature has reached -22°C, the eutectic point (the eutectic point is a physical constant for a mixture of given substances). At higher freezing rates, the ice crystals will be salt-contaminated from the very beginning but this salt will eventually migrate to the outer surface and separate during storage. As the crystals are made mainly of fresh water, the residual liquid will contain an ever increasing concentration of salt as the temperature is reduced. The special structure of seawater ice gives it different properties from freshwater ice. Seawater ice is rather soft and flexible and, at normal subcooled ice temperatures of -5 to -10°C, it will not keep the form of flakes; in fact, at -5°C, seawater ice will look rather wet. For this reason, seawater ice is usually produced at lower temperatures than freshwater ice, and often this adjustment has to be made to the ice maker. Otherwise the plant required is basically the same.

A number of ice plants are suitable for operation at sea with little modification to their design and they may use either fresh or seawater supplies. Many vessels which process their catch at sea have ice makers installed for cooling the fish during processing. Since they are often at sea for many months at a time, it would be unreasonable for them to carry ice from a shore-based plant. Some fishing vessels have ice plants installed where it may not be economical to have a permanent shore-based plant; for example, because demand for ice is only seasonal due to the type of fishery.

Other fishing vessels operate their own ice plant because of difficulties in getting regular supplies without incurring unacceptable delays in port

There are other ways of chilling fish besides using ice. For example, they can be immersed in chilled water or cold air can be blown over them. Sea water, cooled by mechanical means, RSW or by the addition of ice, Chilled Sea Water (CSW), is a suitable alternative means of rapidly chilling large quantities of whole small fish, especially on board a fishing vessel. (Graham, 1992)

#### **A2.2.3 *Freezer trawlers***

Freezing facilities are generally only installed on larger stern trawlers; these are 65m to 80m in length and have a freezing capacity of between 30 and 60t each day and a cold storage capacity of 300 to 800t.

Once the fish are aboard it is important to process and freeze them before rigor mortis sets in which, if it occurs, will result in a degradation of quality. The onset depends on time and temperature.

The first operation is to gut the fish. If they are not gutted, when the fish are thawed they produce bloodstained fillets with off flavours. It is possible to freeze them with guts but only after bleeding which solves some flavour issues but can lead to other spoilage problems.

If fish are gutted, then they still need to be bled for about 15-30 minutes and then washed before being frozen in chilled seawater. If this is not done, the blood is forced into the flesh by the freezing process, resulting in staining. Also, if the time before gutting is in excess of six hours, the blood becomes thicker and harder to wash away.

White fish should be frozen as quickly as possible but if there are limitations to freezing capacity, it is possible to store cod in ice for 3 days, haddock 2 days and hake just 1 day without serious deterioration in quality.

The layout of each factory deck on a freezer trawler, favoured in the Atlantic, will vary depending on its shape and also whether filleting takes place or white fish are frozen. However, the basic configuration will remain the same: a hatch to supply caught fish, a pound to store the fish, a gutting area, a washing area, freezing equipment and a cold store.

A freezer trawler is usually fitted out with a number of vertical plate freezers. Vertical plate freezers are hollow plates made up of sections of extruded alloy and are connected via flexible hoses to the refrigerant supply header. The cooling liquid, refrigerant or heat transfer fluid, is circulated by a pump; there is also a system for heating in order to release the plates once the fish are frozen.

Fish are packed between the plates head to tail, without gaps, any gaps make freezing slower and make fish susceptible to breakage.

Large fish should not be forced between the plates but placed into an air blast freezer. The freezing time will be dependent on the air temperature and velocity.

Plate freezers should be loaded in rotation or the freezing time will be longer due to cooling capacity limitations. If they are loaded at the same time, initially the plant demand will be very high but when the freezing is nearly complete the cooling plant will have little load.

Freezing times should never be cut short: if the blocks are removed too early they may appear hard but the middle of the fish will be soft. When they are placed in the cold store, they are likely to stick together and, worse, the store temperature will rise and the fish freeze slowly with a consequent reduction in quality. Another negative aspect is that if the fish stick together they are liable to being broken when removed.

Once the fish are frozen they are transferred to the cold store via a hoist. The cold storage temperature on trawlers is normally -40°C. (Awira, 2015)

#### ***A2.2.4 Ultra-low temperature freezing***

Even if it represents a niche within the fishing industry, the catch to be forwarded to sashimi and sushi markets deserves a mention here because it poses a technological challenge to the refrigeration industry: tunas to be consumed as sashimi or sushi must in fact be brought down to at least -60°C, after removing gills and guts, to maintain the quality grade needed for raw consumption. (The Pacific Community)

The technological challenge lies in the fact that most of the systems and refrigerants used in traditional freezing plants are not able to go down to -60°C, so particular refrigeration systems and/or refrigerants have to be implemented to achieve this goal.

Tuna is quickly bled, processed and frozen before rigor mortis sets in which is why it is said to be "fresher than fresh". Approximately 80% of tuna sold in the Japanese market is in this

category and commands a high price. Only certain fish are suitable for sushi. Only if “they have the special look and glow in the eyes” are they are sent to the -60°C blast freezer. Much of the remainder goes for canned tuna production.

Varieties of fish other than tuna are also sold for sushi, and are frozen at very low temperatures before consumption (Pachai, 2013). Such treatment ensures the flavor and texture of the flesh stays at its best. However, not all fish are suitable and are also dependent on seasonal variations. In some cases such low-temperature freezing causes physiological disorders to develop within the fish. Therefore an in-depth knowledge is essential for the correct processing for the species being caught.

## **A2.3 Refrigerants currently used**

### ***A2.3.1 Refrigerants used on board***

From the field experience and estimates, it is known that in 2016 about 70% of the fleet still used HCFC-22 as their main refrigerant; this is a global phenomenon and includes all seagoing vessels. Ammonia (R-717) is the second refrigerant of choice. An EU report (Faber, 2009) shows that this is also the case in Europe.

A number of different refrigerants were used on board ships in the past including ammonia. Examples of these were CFC-12, R-502 and in some cases CFC-13, this is of significance when bearing in mind the age of some of the fishing vessels (30 years old). HCFC-22 came after the above refrigerants.

Low temperature air blast coolers are either cascade or two-stage sub-atmospheric systems. Cascade systems are likely to use R-23 in their low stage.

From reported data (Awira, 2015), it is known that refrigerant charges are estimated to be about 230 to 250 metric tonnes of HCFC-22 for fish carriers, long line and purse seiner vessels chartered and flagged in FFA member Countries.

The same report states that the total HCFC refill for flagged and chartered vessels amounts to 714 metric tonnes, while the Montreal Protocol HCFC baseline (consumption) for the 14 Pacific Islands Countries amounts to 271.69 metric tonnes.

### ***A2.3.2 Refrigerants used on land operations***

In land based industrial systems for food processing, including the fishing industry, R-717 is already the dominant refrigerant in non-Article 5 Parties while HCF-C-22 is the refrigerant mostly used by Article 5 Parties, both for process cooling and large ice plants. (de Larminat, 2015).

In recent years, non-Article 5 Parties have seen an increasing use of R-404A, especially in small and medium systems including those used for producing ice.

### ***A3.3.3 Refrigerant leakage***

In the maritime sector, the emission factor due to leakage in air conditioning and refrigeration systems with direct expansion are very high, estimated at 40% of the charge per year. Even when indirect systems are utilised, a loss of 20% per year is common. This is due to a combination of the age, the technology and the constant vibration and racking that a ship endures (FRDC, 2013)

As already mentioned, many vessels have licenses to operate in Article 5 Parties even though their flag is not Article 5. It is then not uncommon that the systems are refilled with refrigerant originating from an Article 5 Party. This refrigerant should be reported as export and import in the flag country and not, as currently occurs, as used by the Article 5 Party. For European flagged ships it would basically be illegal to top up the charge even if operating in an Article 5 Party.

#### **A2.3.4 High ambient temperatures (HAT)**

The issue of High Ambient Temperatures (46-52°C) is less likely to apply to fishing vessels and land based fisheries as refrigeration systems are generally cooled by sea water. Therefore, this is not very often a problem in open sea, but can become an issue in more slow moving rivers and lakes and potentially in ports where the water temperature can increase. For the refrigeration system it means that you can reach the limits of the operational envelope with the risk of the safety valve opening blowing out the refrigerant. This is mainly a problem if the ship is designed for colder water and is migrated to warmer waters for any reason. It is primarily a design topic more than a refrigeration issue.

High ambient temperatures are only significant as fish have inherently a high bacterial loading and can spoil quickly if not subject to the correct storage conditions.

#### **A2.4 Low-GWP alternatives to ODS refrigerants**

The most important information that can be drawn from the background analysis of the fishing industry is that, currently, the existing fishing fleet is dominated by HCFC-22 and R-717.

R-717 is a non ODS substance with a low GWP and is perfectly satisfactory for continued use, once the safety issues are taken into account (R-717 is a B2L fluid according to ASHRAE 34 standard).

HCFC-22 is an ODS and must be phased-out. Substitution of HCFC-22, considering its ubiquitous presence throughout the industry, is the real challenge facing the fishing industry.

Considering also that 70% of the global fishing fleet is based in Asia/Pacific, this challenge becomes even more important for Asia/Pacific Parties and specifically for Pacific islands, whose economy is heavily dependent on their fishing industry.

Table A2-2 provides the main characteristic of all the refrigerants that can play an interesting role in HCFC-22 substitution.

##### **A2.4.1 Alternatives to HCFC-22**

Traditionally, trawlers operate with direct expansion and have relatively high refrigerant charges and high leakage rates; this makes the choice for the transition from HCFC-22 a difficult one.

An obvious retrofit replacement for HCFC-22 is R-404A which is a very popular and widely used blend. However, due to its high GWP value, it is now being phased out in Europe by 2020, as well as in certain sub-sectors in the USA; in other regions R-404A is under pressure. Analysing the options left after the HCFC phase-out and considering that high GWP is an issue as well, one presently stands with a limited number of potential alternatives even without considering the cost implications. A non-exhaustive list of potential alternative refrigerants is shown in Table A2-2 (UNEP, 2014, UNEP, 2016).

The (unsaturated - olefin type) HFO refrigerants are not suitable to replace HCFC-22 or R-404A for low temperatures. More promising are those refrigerant mixtures obtained by blending HFC and HFO in suitable proportions to make them a low-GWP fluid and, at the same time have the properties needed for a refrigerant in this application.

Ammonia (R-717) is very competitive but requires a refrigeration plant change and cannot be considered as a retrofit.

As the situation of HCFC-22 substitutes showing low-GWP properties is rapidly and positively evolving towards the development of suitable alternatives for most of the terrestrial applications (UNEP, 2015, UNEP, 2016), one can expect that those alternatives will be suitable also for on board applications of the fishing industry.

When evaluating the substitution of HCFC-22 for on board refrigeration, the decision must take into account several variables; in principle it is possible to distinguish among the following cases:

**Table A2-2 Potential HCFC-22 alternatives, their GWPs and safety class**

Refrigerant	Normal Boiling Point (°C)	GWP 100 years	Safety Class
<b>HCFC-22</b>	-40.8	1810	A1
<b>HFC-23</b>	-82,0	12500	A1
<b>R-404A</b>	-46.6/-45.8	4200	A1
<b>R-407A</b>	-45.2/-38.7	2100	A1
<b>R-407C</b>	-43.8/-36.6	1700	A1
<b>R-407F</b>	-46.1/-39.7	1800	A1
<b>R-428A</b>	-48.3/-47.5	3700	A1
<b>R-448A</b>	-45.9/-39.8	1300	A1
<b>R-449A</b>	-46.0/-39.9	1300	A1
<b>R-507A</b>	-47.1	4300	A1
<b>R-717 (NH<sub>3</sub>)</b>	-33.3	0	B2L
<b>R-744 (CO<sub>2</sub>)</b>	-78*	1	A1

\*Sublimation point in atmosphere of CO<sub>2</sub>. Triple point is -56.2°C@5.2 bar.

\*\* Even if it classified of lower-toxicity (A1) it can present human health hazards when operating in enclosed spaces such as vessels: such risks have to be prevented with specific safety measures (it should be noted though, that these risks are present also with HCFC,HFC, HFO and HCFO refrigerants).

- If the entire vessel is approaching the end of its operating life and is going to be retired soon, then no refrigeration plant upgrade is worthwhile. Before going to the scrapyards, proper recover of remaining refrigerant is the most important operation to be scheduled for the refrigeration plant.
- If the ship has a long life ahead but the refrigeration plant needs a major overhaul, then the change of refrigerant is a reasonable operation to be implemented. The new refrigerant has to be chosen with care. Change of refrigerant may involve a complete refurbishment of the refrigeration plant: converting an halocarbon plant to ammonia, for example, will require disposing of all copper-nickel equipment and substitution with steel (often with stainless steel because of sea water).
- If the HCFC-22 equipped refrigeration plant is relatively young (less than 10-15 years) then retrofitting it with a drop-in solution can be the right option. Rapidly evolving situations in the development of low-GWP HFO/HFC blends makes it highly probable that in a few years a satisfactory solution also for this specific problem could be at hand.
- For new ships, several options are available nowadays: all of them are environmentally benign in terms of ozone depletion and climate change and are also economically feasible.

In the following a number of feasible options for the main applications of fishing vessels refrigeration will be described and critically analysed. At the end of the paragraph a summary table (FRDC, 2013) is provided to allow for comparisons. A separate paragraph will then be devoted to Ultra-low temperature applications, which require particular technology.

#### **A2.4.2 Option 1 – Non-halocarbon refrigerants (R-717 and R-744)**

Ammonia (R-717) and carbon dioxide (R-744) (so called “natural” refrigerants) are fit, from a thermodynamic point of view, for the refrigeration plants aboard fishing vessels.

Ammonia is lower flammable and toxic: its application requires considerable safety requirements (sensors and alarms, ammonia concentration meters, extensive signage, training, breathing apparatus etc.) and the systems must be run by skilled personnel. Carbon dioxide is non-flammable, colourless, odourless and tasteless. Even if it classified of lower-toxicity (safety classification A1 according to ASHRAE standard 34) it can present human health hazards when operating in enclosed spaces such as vessels: such risks have to be prevented with specific safety measures (it should be noted though, that these risks are present also with HCFC and HFC refrigerants) (FRDC, 2013).

When the safety issues can be properly addressed and skilled personnel is available, then a R-717 plant can be the right choice, from both technical and economical points of view.

When safety may become an issue, the main priority is to reduce the mass of R-717 charged in the plant: confining ammonia only in one machine room, for example, can reduce the safety requirements considerably. This can be done by adopting a NH<sub>3</sub>/CO<sub>2</sub> (R-717/R-744) cascade system: ammonia is the high-temperature fluid and carbon dioxide is the low-temperature fluid. The high-temperature side of the plant is confined to the machine room while the low temperature fluid is sent to all the plant terminals throughout the ship (Kawamura, 2015).

One of the first NH<sub>3</sub>/CO<sub>2</sub> (R-717/R-744) cascade systems was presented in 2003 at the IIAR conference (Nielsen, 2003). The paper describes a 75m long purse seiner with a freezing capacity of 210 tons of fish per day. The system consists of 11 vertical plate freezers, a vertical flake ice freezer, and CO<sub>2</sub> air-coolers for 3 cargo holds.

A cascade system is very efficient for low temperature operations (down to -48°C). It is also cost effective, as compressors and piping are small if compared to those needed for other fluids. Moreover, sending to the plant terminals R-744 instead than R-717 reduces the risks due to flammability and toxicity (de Larminat, 2015).

Also on board ships, the use of R-744 as the sole refrigerant can be a technically feasible option. Recently a trawler using only R-744 as a working fluid has been built and put into operation (Hafner, 2016). Systems using only R-744 as a refrigerant could potentially have a challenge to maintain the high energy efficiency when sea water temperatures are high. It is however expected that ejector-assisted systems can be utilised to overcome this challenge, in the same way as the ongoing development within commercial refrigeration systems using R-744 as refrigerant. Some such systems are already installed and under testing.

One of the advantages of the lower evaporation temperature (-48°C) obtained with R-744 as a refrigerant is a quicker freezing time and less damage to the fish at the surface due to softening of the surface during defrosting of the plate freezers. These benefits in fish quality are very much appreciated and therefore many ships are now converted to this solution especially in Europe, but now also in the US.

Hydrocarbons are also technically feasible refrigerants for on-board refrigeration, but the strict safety concerns and large refrigerant charge required make the practical application of flammable refrigerants aboard vessels unlikely.

The use of R-717 or R-744 in one of the three plant options analysed here is viable also in terms of overall climate change impact: when considering both the direct and indirect GHG emissions involved with the use of such plant alternatives (through TEWI, Total Equivalent Warming Impact) the assessment gives an impact reduction with respect to the existing situation (FRDC, 2013).

In any case, R-717 cannot be considered a viable solution for the replacement or retrofit of refrigeration plants on existing vessels without rebuilding. On the contrary, its choice is probably the right one when new ships are involved. R-744, on the contrary, can be a viable solutions both for new ships and for plant refurbishment in existing vessels, as some recent experiences have demonstrated (Hafner, 2016)

Just for sake of reference, the cost of an on-board R-717/R-744 cascade plant is estimated at 500k AUS\$ for a new ship whose cost is 2.5M AUS\$ or more (FRDC, 2013). In the markets where these plants are sold, the cost is on the same level as for HFC plants.

	Financial considerations		Technology risk (Complexity and performance)	Regulatory and environmental risk (10 years horizon)
	Capital investment	Operating expenses		
<b><i>Option 1 – Non-halocarbon refrigerants</i></b>				
R-717 system	Medium	Medium	High	Nil
	Requires new ship with separate machine room or rebuilding	Potential improvement in efficiency. Require competence, but inexpensive refrigerant	Highly complex relative to on-board capabilities. Additional safety risk of ammonia (lower flammable and toxic). Training required in new markets	No environmental policy risk throughout expected life of equipment.
R-717/R-744 cascade system	Medium	Medium	High	Nil
	Requires new ship with separate machine room or rebuilding	Potential improvement in efficiency. High maintenance cost due to complexity. Require competence, but inexpensive refrigerant	Highly complex relative to on-board capabilities. Additional safety risk of ammonia (lower flammable and toxic), Training required in new markets	No environmental policy risk throughout expected life of equipment.
R-744 system	Medium	Medium	Medium	Nil
	Suitable for existing vessels with replacement of system	Potential improvement in efficiency at the expenses of complexity. Require competence, but inexpensive refrigerant	Some complexity relative to on-board capabilities. Training required in new markets	No environmental policy risk throughout expected life of equipment.

#### ***A2.4.3 Option 2 – Refrigerant replacement with plant adjustments***

For systems with more than 10 to 15 years' service life, it will generally not be feasible to perform just a refrigerant drop-in retrofit. Experience shows that compressors and other parts tend to break down shortly after a refrigerant retrofit. Replacement installations are therefore safer and more reliable. Reliability is usually one of the biggest concerns to ship owners as loss of cooling can be costly.

The most fundamental conversion is when the total system is converted to a NH<sub>3</sub>/CO<sub>2</sub> solution. This type of conversion requires a major overhaul, because the safety conditions change when ammonia is involved. Also material compatibility is different when transiting from halocarbon refrigerants to ammonia.

A conversion from HCFC-22 to R-744 is a possible option as well, even if it requires a plant replacement.

Experience from the markets where these conversions to R-717 and R-744 have been done is that they can be done to the same cost as for a conversion to HFC.

A conversion to a haocarbon refrigerant could be feasible. As a matter of fact, the conversion from HCFC-22 to R-507A is investigated in (FRDC, 2013). This conversion would require the change of some components and other adjustments in the refrigeration systems in order to improve the efficiency and, necessarily, would require measures for leak containment. A conversion of this type is estimated to cost in the range of 250k to 280k AUS\$ for the Northern Prawn Fishery fleet. But, R-507A (together with its companion R-404A) is not a low-GWP HFC (actually, its GWP is 4300 (UNEP, 2014)) and it cannot be considered a viable substitute anymore.

According to (UNEP, 2016) R-404A and R-507A are now being substituted for commercial refrigeration applications by blends such as R-448A and R-449A, which contain some HFOs and whose GWP is <1500. As is well known, the situation is evolving rapidly so it is not possible, at this stage, to name a refrigerant that will certainly be the definitive low-GWP substitute for R-507A or R-404A.

It may be reasonable, nevertheless, to expect in the medium term a solution that will make feasible the above-suggested type of conversion. The economics of the operation will, of course, depend on the cost of the new refrigerant. Most likely, the possible alternatives will be flammable in category A2 or A2L, thus requiring adequate safety considerations and precautions.

	Financial considerations		Technology risk (Complexity and performance)	Regulatory and environmental risk (10 years horizon)
	Capital investment	Operating expenses		
	Medium	Unknown	Unknown	Unknown
<b><i>Option 2 – Refrigerant replacement with plant adjustments</i></b>				
Conventional refrigeration plant system operating with low-GWP HFC blend	Suitable for existing vessels with change of components and adjustments	Cost of refrigerants at present unknown flammability must be addressed	No significant change in type of technology and components	Environmental policy risk throughout expected life of equipment unknown at present

#### ***A2.4.4 Option 3 – Refrigerant drop-in***

For systems with less than 10 to 15 years' service life, then a refrigerant drop-in retrofit becomes a feasible option, provided there is such a drop-in. At present, actually, there is no low-GWP HFC available on the market that can be used as drop-in for on-board systems.

Some low-GWP HFC alternatives to HCFC-22 are proposed by the chemical industry as a drop-in for land-based applications (UNEP, 2015, UNEP 2016). When these alternatives become commercially available, they could be used also as HCFC-22 substitutes for on board applications. Considering the rapidly evolving situation in the development of low-GWP HFCs it may be probable that in a few years-time a satisfactory solution will also be available for this specific problem.

One aspect to be considered in cases concerning a step-by-step transition from HCFC-22 to HCF (both high-GWP and low-GWP) is how to meet regulatory requirement of product importers, especially when non-flagged vessels are involved.

	Financial considerations		Technology risk (Complexity and performance)	Regulatory and environmental risk (10 years horizon)
	Capital investment	Operating expenses		
	Unknown	Unknown	Unknown	Unknown
<b>Option 3 – Refrigerant drop-in</b>				
Conventional refrigeration plant system operating with low-GWP HFC blend	Requires improvement of refrigerant containment	Cost of refrigerants at present unknown flammability must be addressed	No significant change in type of technology and components	Environmental policy risk throughout expected life of equipment unknown at present

#### A2.4.5 Option 4 – Maintaining HCFC-22

Considering the current problems in finding proper solutions for the retrofit of on-board systems equipped with HCFC-22, one reasonable option could be keeping it in the system for a further few years, until the end of the system or ship life.

The time horizon for this type of option should be no more than 4-5 years and the target should be those on-board plants with more than 10-15 years' service life.

Maintaining HCFC-22 would require the contextual execution of the following operations: i) comprehensive upgrade for improved refrigerant containment, ii) increased focus on preventive maintenance regime, iii) securing sufficient stock of gas to be held in reserve, iv) planning for an inevitable capital equipment replacement program at the end of the period to a newly released low-GWP fluid to be assessed closer to the equipment replacement date. The literature source estimates the costs for this option at 30k-50k AUS\$ plus the cost of gas reserves (FRDC, 2013).

Also for this option, one aspect to be considered is how to meet regulatory requirement of product importers, especially when non-flagged vessels are involved.

	Financial considerations		Technology risk (Complexity and performance)	Regulatory and environmental risk (10 years horizon)
	Capital investment	Operating expenses		
	Low	High	Low	Very high
<b>Option 4 – Maintaining HCFC-22</b>				
Existing plant, operating with HCFC-22, with improved containment Short term solution (max 4-5 years) May not be practical for all vessels	Requires improvement of refrigerant containment	HCFC-22 price expected to increase	No change in technology Availability of HCFC-22 will decrease	HFC-22 phase-out in advanced stages

#### A2.4.6 Ultra-low temperature solutions

Blast freezers for low temperature operations (-60°C and below) needed for sushi or sashimi grade tuna must use a cascade or two-stage compressor.

Table A2-3 (UNEP, 2014, UNEP, 2016) shows the situation of available refrigerants for cascade systems to be used on board ships.

*Table A2-3 Refrigerants used on board ship in cascade systems*

Refrigerant	Normal Boiling Point (°C)	Cascade stage	GWP 100 years
<b>HCFC-22</b>	-41	1	1780
<b>R-404A</b>	-46.6/-45.8	1	4200
<b>R-407F</b>	-46.1/-39.7	1	1800
<b>R-507A</b>	-47.1	1	4300
<b>R-717</b>	-33.3	1	0
<b>HFC-23</b>	-82	2	12500
<b>R-508A</b>	-87.4	2	12000
<b>R-508B</b>	-87.4	2	12000
<b>R-744</b>	-56.2*	2	1
<b>HC-170</b>	-89	2	5.5

\*CO<sub>2</sub> triple point is -56.2°C @ 5.2 bar

There are no viable low-GWP HFC alternatives to R-23, R-508A and R-508B, which are the refrigerants currently used in the low-temperature stage in cascade systems.

The new (unsaturated HFC) HFO compounds do not offer any low temperature solutions.

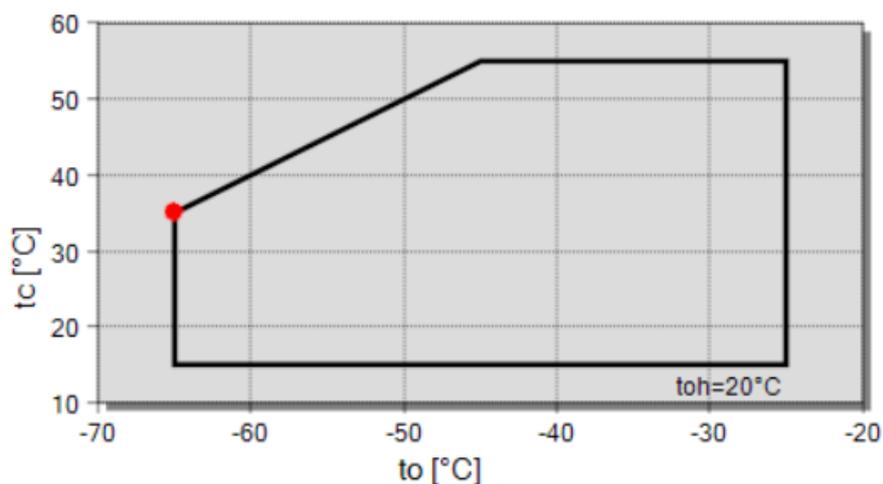
A possible alternative could technically be HC-170 (ethane, flammable, class A3), but its A3 flammability makes it unfeasible for on board systems.

A viable low-GWP alternative with evaporation down to -55°C, but requiring an equipment exchange, is an R-717/R-744 cascade system.

Another option could be a cascade system using NH<sub>3</sub> in the high stage and HFC-32 in the low stage (the normal Boiling Point for HFC-32 is -52.0°C). The disadvantage is that the system will go to negative pressure at -70°C. This is a potential risk because air that enters can cause the refrigerant to explode.

It is possible to use a two-stage compressor to achieve low temperature blast freezing. The lowest evaporating temperature is -65°C @ +35°C condensing temperature. Evaporation will then happen at a sub-atmospheric pressure. Below is shown the possible operating envelop for such a system operating with R-407F. Also R-410A could be used in a two-stage compressor system.

In the medium term, a very interesting solution for the Ultra-Low temperature freezing can be the air-cycle (also known as Joule-Brayton reverse cycle). This is a non-vapour compression technology and fits better in the Not-In-Kind section, where it will be described and evaluated.



**Figure A2-5 Limits for two stage compressor operating on R-407F**

#### **A2.4.7 Land based equipment**

Land based equipment for the fishing industry faces the same transition problems faced by other industrial refrigeration applications. Information on how to handle transition can be retrieved in the most recent reports produced by RTOC and TEAP Task Forces (UNEP, 2014, UNEP 2015, UNEP, 2016).

One peculiar characteristic of fishing industry land based installations is that all of them are inevitably connected to a water stream (sea, lake, river), which can be used as a machine coolant. This fact makes fishing industry less sensitive to high ambient temperatures (HAT) even when located in Parties with high ambient temperature conditions.

#### **A2.4.8 Not-In-Kind technologies**

Provided that with the definition of “Not-In-Kind technologies” one refers to those refrigeration techniques which do not use vapour compression reverse cycle, there are some interesting options under study that deserve to be analysed to check if there is any possibility for their application within the fishing industry in the short term.

For very low temperatures, air (R-729) can be used as a working fluid in the so called air cycle, or Joule-Brayton reverse cycle. It was first proposed for ice making in 1844 by Dr. John Gorrie. The cycle was used for some years and then abandoned for absorption systems and later for compression systems.

The main reason for not using air was that the efficiency at the working conditions of most of refrigeration applications is far lower than the vapour compression efficiency. With modern motors and technologies, however, the air cycle can be a good solution when temperatures below  $-55^{\circ}\text{C}$  are to be reached, especially if the refrigerant has to be non-flammable. Some interesting attempts of air cycle applications at low temperatures are available in the literature (Gigiel, 2006, Machida, 2011, Giannetti, 2015). To be available at a commercial level the technology needs more development work and therefore it can be a feasible option only in the medium to long term.

Absorption systems could also be a viable alternative to vapour compression, down to temperatures of  $-55^{\circ}\text{C}$ . Systems could use the water (R-718)/ammonia (R-717) pair where water acts as solvent and ammonia as refrigerant. The same safety problems encountered with the application of vapour compression ammonia systems are to be faced here. Technology is mature and consolidated: the main problem with the absorption systems is the size and space needed on-board and the sensitivity to roll and pitch of a ship.

An important challenge for on board applications comes from the fact that driving energy is waste heat from engine and therefore there is a possible lack of cooling capacity if the ship's engine is not working e.g. in harbour (Fernandez, 1998)

A lot of research in magnetic cooling is ongoing. The capacities with improving technology are increasing. It is a bit early in the development cycle to determine whether or not the cooling capacity will be sufficient and at the temperature differences needed on board modern fishing ships.

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### Annex 3 - EU (F-gas, MAC Directive), USA (EPA SNAP Program) and Japan Regulatory Prohibitions (Ch. 6)

	European Union			United States			Japan		
Typical Historical Zero-ODP Option	Applications and Products	GWP Max Limit, F-gas Prohibited	Effective Date of Prohibition	Applications and Products	Unacceptable examples (GWP)	Date of Prohibition	Designated Products	Target GWP	Target Year
<b>Mobile Air Conditioning</b>									
HFC-134a	Mobile Air Conditioners	150	2013 (new types); 2017 (all)	Light-Duty Motor Vehicle Air Conditioners		MY 2021 (~1/6/2020)	Mobile Air Conditioners		2023
<b>Stationary Air Conditioning and Refrigeration</b>									
HFC-134a, HC-600a	Domestic refrigerators & freezers	150	2015	<i>Household refrigerators and freezers (Proposed)</i>		2021			
HFC-134a, R-404A	Commercial refrigerators and freezers (hermetically sealed systems)	2500	2020	Stand-alone Low-Temperature	R-404A (3922)	2020			
HFC-134a, R-404A				<i>Refrigerated Food Processing and Dispensing (Proposed)</i>		2021			
HFC-134a		150	2022	Stand-alone Medium-Temperature	HFC-134a (1430)	2019 (<0.64 kW); 2020 (rest)			
HFC-134a				Vending Machines	HFC-134a (1430)	2019			

	European Union			United States			Japan		
Typical Historical Zero-ODP Option	Applications and Products	GWP Max Limit, F-gas Prohibited	Effective Date of Prohibition	Applications and Products	Unacceptable examples (GWP)	Date of Prohibition	Designated Products	Target GWP	Target Year
R-404A, R-407A, R-507	Retail Food/ Supermarkets (Multipack centralized commercial refrigeration systems with a capacity 40kW or more)	150	2022	Retail food refrigeration (supermarket systems)	R-404A (3922), R-507A (3985)	2017	Condensing Unit and Refrigerating Unit (for separate type showcases, etc.)	1500	2025
R-404A	Retail Food/ Supermarkets (primary circuit of cascade systems)	1500	2022						
R-717	<i>Cold Storage</i>			<i>Cold Storage Warehouses (Proposed)</i>	<i>R-404A (3922), R-407A (2107), R-410A (2088), R-507 (3985)</i>	2023	Cold Storage Warehouses (>50,000 m <sup>3</sup> )	100	2019
HFC-134a	<i>Chillers</i>			<i>Centrifugal Chillers (Proposed)</i>	<i>HFC-134a (1430)</i>	2024	Commercial Air Conditioning (for offices and stores)	750	2020
HFC-134a, R-407C				<i>Positive Displacement</i>	<i>HFC-134a (1430), R-407C (1744),</i>	2024			

	European Union			United States			Japan		
Typical Historical Zero-ODP Option	Applications and Products	GWP Max Limit, F-gas Prohibited	Effective Date of Prohibition	Applications and Products	Unacceptable examples (GWP)	Date of Prohibition	Designated Products	Target GWP	Target Year
R-410A				<i>Chillers (Proposed)</i>	<i>R-410A (2088)</i>		[chillers, rooftop units, larger split systems]		
R-410A	Rooftop Units, Larger Split Systems								
R-410A	Movable room air conditioning appliances (e.g. portable air conditioners, window units)	150	2020				Room Air Conditioning	750	2018
R-410A	Single split air conditioning systems containing < 3 kg of F-gases	750	2025						
<b>Fire Protection</b>									
HFC-227ea, CO <sub>2</sub> , Water,	Fire protection systems & fire	HFC-23	2016						

Typical Historical Zero-ODP Option	European Union			United States			Japan		
	Applications and Products	GWP Max Limit, F-gas Prohibited	Effective Date of Prohibition	Applications and Products	Unacceptable examples (GWP)	Date of Prohibition	Designated Products	Target GWP	Target Year
Dry Powder	extinguishers			<i>Total flooding systems using C<sub>3</sub>F<sub>8</sub> or C<sub>4</sub>F<sub>10</sub> (Proposed)</i>	<i>PFC-218 (8830); PFC-3-1-10 (8860)</i>	2018			
<b>Foams</b>									
HCs, HFC-134a	Tire Inflators	SF6, all HFCs	4/7/2007	Tire Inflators	HFC-134a (1430)	20/7/2016			
HFC-134a, HFC-152a	Consumer product aerosols for entertainment and decorative purposes	150	4/7/2009	Consumer aerosols, with some exceptions for technical and medical aerosols	HFC-134a (1430)	2016	Dust Blowers	10	2019
HFC-134a, HFC-227ea (MDIs)	Technical aerosols (unless required to meet national safety standards or medical applications)	150	2018						

	European Union			United States			Japan		
Typical Historical Zero-ODP Option	Applications and Products	GWP Max Limit, F-gas Prohibited	Effective Date of Prohibition	Applications and Products	Unacceptable examples (GWP)	Date of Prohibition	Designated Products	Target GWP	Target Year
HFC-134a, HFC-245fa, HFC-365mfc	XPS Foams with HFCs	150	2023	Polystyrene Extruded Boardstock and Billet (XPS)	HFC-134a (1430)	2021			
HCs, HFC-134a	One-component foams	150	4/7/2008	Polyisocyanurate Laminated Boardstock,	HFC-134a (1430), HFC-245fa (1030), HFC-365mfc (794)	2017-2020	Urethane Foam (house construction materials)	100	2020
HCs, HFC-134a, HFC-245fa, HFC-365mfc	Other Foams with HFCs	150	2020	Polystyrene Extruded Sheet, Phenolic Insulation Board and Bunstock, Polyolefin, and several types of Polyurethane foams					
HFC-134a, HFC-245fa, HFC-365mfc	Other Foams (Rigid PU Spray Foam)	150	2020	<i>Rigid PU Spray Foam (Proposed)</i>	HFC-134a (1430), HFC-245fa (1030), HFC-365mfc (794)	2020-2021			

Notes:

- GWPs are AR4 values (IPCC, 2007)
- Prohibition dates January 1<sup>st</sup> unless otherwise noted and shown as day/month/year.
- Proposed USA prohibitions in *italics*; dates assume as proposed with a final rule published 1/1/2017.
- Exceptions include, *inter alia*, US mobile AC for export to markets lacking service infrastructure, EU stationary refrigeration products below -50 C, USA chillers for military vessels and human-rated spacecraft, EU foams where required to meet national safety standards, USA foams until 1/1/2022 (existing) or 1/1/2025 (proposed) for space- and aeronautics–related applications, and Japan exceptions to designated products.



## Annex 4 - Updated Tables for total, new manufacturing, and servicing demand

Below updated tables until 2050 (compared to 2030 in the XXVI/9 TF report) are given for the total demand, new manufacturing and servicing demand (data used for the scenario graphs in chapter 6):

- for non-Article 5 and Article 5 Parties
- for the major R/AC sub-sectors
- for the BAU, MIT-3 and MIT-5 scenarios:
  
- *Table A4-1: Demand in tonnes for new manufacturing plus servicing (total demand) for non-Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-2: Demand in tonnes for new manufacturing only for non-Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-3: Demand in tonnes for servicing only for non-Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-4: Demand in ktonnes CO<sub>2</sub>-eq. for new manufacturing plus servicing (total demand) for non-Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-5: Demand in ktonnes CO<sub>2</sub>-eq. for new manufacturing only for non-Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-6: Demand in ktonnes CO<sub>2</sub>-eq. for servicing only for non-Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-7: Demand in tonnes for servicing and new manufacturing (total demand) for Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-8: Demand in tonnes for new manufacturing only for Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table: A4-9: Demand in tonnes for servicing only for Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-10: Demand in ktonnes CO<sub>2</sub>-eq. for new manufacturing plus servicing (total demand) for Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-11: Demand in ktonnes CO<sub>2</sub>-eq. for new manufacturing only for Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios*
  
- *Table A4-12: Demand in ktonnes CO<sub>2</sub>-eq. for servicing only for Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios*

**Table A4-1: Demand in tonnes for new manufacturing plus servicing (total demand) for non-Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios**

In tonnes (new manufacturing plus servicing)			2010	2015	2020	2025	2030	2035	2040	2045	2050
nA5 BAU	Domestic	HFC-134a	1876	1451	957	954	862	999	1158	1342	1556
		HC-600a	362	415	545	786	1156	1340	1553	1801	2087
	Commercial	HFC-134a	2256	2373	2400	2395	2104	2013	2334	2705	3136
		R-404A + R-507	15305	16093	11907	7478	5667	5457	6326	7334	8502
		Low GWP	0	0	4373	9213	13988	18396	21326	24723	28661
	Industrial	HFC-134a	1041	1113	1148	1188	1233	1343	1484	1661	1875
		R-404A + R-507	603	743	491	378	218	193	213	203	178
		R-22	1323	675	455	306	206	139	0	0	0
		Low GWP	6649	8898	11269	13764	16735	19994	23621	27625	32207
	Transport	HFC-134a	222	213	302	371	483	585	679	787	912
		R-404A + R-507	1176	1540	917	833	705	626	588	543	491
		Low GWP	0	0	557	756	1014	1314	1662	2065	2532
	SAC	HFC-134a	4032	4468	1422	994	226	0	0	0	0
		R-410A	39385	77354	94230	114001	131319	151966	176170	204229	236758
		R-407C	11195	26802	26172	30349	31368	32918	34890	37176	39826
		Low GWP	0	0	8770	13597	19034	25337	32644	41115	50935
	MAC	HFC-134a	69670	68359	48425	38118	27509	24564	28477	33013	38271
		Low GWP	0	0	18218	32849	49939	63812	73975	85758	99417
nA5 MIT-3	Domestic	HFC-134a	1876	1451	2	1	1	0	0	0	0
		HC-600a	362	415	1500	1739	2017	2338	2710	3142	3642
	Commercial	HFC-134a	2256	2373	2400	2395	2104	2013	2334	2705	3136
		R-404A + R-507	15305	16093	10320	4207	759	0	0	0	0
		Low GWP	0	0	5962	12483	18896	23854	27653	32057	37163
	Industrial	HFC-134a	1041	1113	1148	1188	1233	1343	1484	1661	1875
		R-404A + R-507	603	743	322	219	121	88	100	76	36
		Low GWP	6649	8898	11438	13923	16831	20099	23736	27752	32348
		HFC-134a	222	213	302	371	483	585	679	787	912
	Transport	R-404A + R-507	1176	1540	730	484	162	0	0	0	0
		Low GWP	0	0	744	1105	1558	1940	2249	2608	3023
		HFC-134a	4032	4468	1422	994	226	0	0	0	0
	SAC	R-410A	39385	77354	22337	15831	4127	0	0	0	0
		R-407C	11195	26802	13904	11080	4215	0	0	0	0
		Low GWP	0	0	92513	129552	170632	210221	243704	282520	327518
		HFC-134a	69670	68359	41871	25932	8755	0	0	0	0
	MAC	Low GWP	0	0	24772	45035	68704	88376	102452	118770	137687
		HFC-134a	1876	1451	957	1	1	1	1	0	0
nA5 MIT-5	Domestic	HC-600a	362	415	545	1739	2016	2338	2710	3142	3642
		HFC-134a	2256	2373	2400	2395	2104	2013	2334	2705	3136
	Commercial	R-404A + R-507	15305	16093	11907	4983	1535	57	0	0	0
		Low GWP	0	0	4690	12483	18896	23854	27653	32057	37163
		HFC-134a	1041	1113	1148	1188	1233	1343	1484	1661	1875
	Industrial	R-404A + R-507	603	743	491	277	159	126	162	156	123
		Low GWP	6649	8898	11269	13885	16793	20061	23674	27672	32262
		HFC-134a	222	213	302	371	483	585	679	787	912
		R-404A + R-507	1176	1540	872	531	209	23	0	0	0
	Transport	Low GWP	0	0	602	1058	1511	1917	2249	2608	3023
		HFC-134a	4032	4468	1422	994	226	0	0	0	0
		R-410A	39385	77354	94230	26474	14768	1761	0	0	0
	SAC	R-407C	11195	26802	26172	14906	8041	2012	0	0	0
		Low GWP	0	0	8770	115904	156984	203045	243704	282520	327518
		HFC-134a	69670	68359	48425	29702	12514	1943	0	0	0
		Low GWP	0	0	18218	41265	64934	86433	102452	118770	137687

**Table A4-2: Demand in tonnes for new manufacturing only for non-Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios**

In tonnes (new manufacturing)			2010	2015	2020	2025	2030	2035	2040	2045	2050	
nA5 BAU	Domestic	HFC-134a	1872	1449	955	953	861	998	1157	1341	1554	
		HC-600a	362	415	545	786	1155	1339	1553	1800	2087	
	Commercial	HFC-134a	2027	1786	665	771	894	1036	1201	1393	1614	
		R-404A + R-507	7006	3028	2262	1787	2072	2402	2784	3228	3742	
		Low GWP	0	0	3248	4600	5332	6182	7166	8308	9631	
	Industrial	HFC-134a	327	397	418	439	461	535	620	719	833	
		R-404A + R-507	345	420	153	97	16	19	22	26	30	
		R-22	320	0	0	0	0	0	0	0	0	
		Low GWP	2412	3884	5013	5938	7027	8146	9444	10948	12692	
	Transport	HFC-134a	45	57	142	164	191	221	256	297	344	
		R-404A + R-507	578	738	89	131	152	176	204	236	274	
		Low GWP	0	0	482	531	616	714	827	959	1112	
	SAC	HFC-134a	3387	3118	0	0	0	0	0	0	0	
		R-410A	34160	61755	68084	78927	91499	106072	122966	142552	165257	
		R-407C	7513	16313	10791	12350	14317	16597	19241	22306	25858	
		Low GWP	0	0	7209	8516	9873	11445	13268	15382	17831	
	MAC	HFC-134a	17728	17622	4573	5430	6295	7297	8460	9807	11369	
		Low GWP	0	0	12279	14105	16352	18956	21976	25476	29533	
	nA5 MIT-3	Domestic	HFC-134a	1872	1449	0	0	0	0	0	0	0
			HC-600a	362	415	1500	1739	2016	2337	2709	3141	3641
Commercial		HFC-134a	2027	1786	665	771	894	1036	1201	1393	1614	
		R-404A + R-507	7006	3028	990	0	0	0	0	0	0	
		Low GWP	0	0	4520	6387	7404	8584	9951	11536	13373	
Industrial		HFC-134a	327	397	418	439	461	535	620	719	833	
		R-404A + R-507	345	420	4	0	0	0	0	0	0	
		Low GWP	2412	3884	5162	6035	7044	8165	9466	10974	12721	
Transport		HFC-134a	45	57	142	164	191	221	256	297	344	
		R-404A + R-507	578	738	0	0	0	0	0	0	0	
		Low GWP	0	0	601	662	767	890	1031	1195	1386	
SAC		HFC-134a	3387	3118	0	0	0	0	0	0	0	
		R-410A	34160	61755	1268	0	0	0	0	0	0	
		R-407C	7513	16313	335	0	0	0	0	0	0	
		Low GWP	0	0	84480	99794	115688	134115	155476	180239	208946	
MAC		HFC-134a	17728	17622	0	0	0	0	0	0	0	
		Low GWP	0	0	17005	19535	22647	26254	30435	35283	40902	
nA5 MIT-5		Domestic	HFC-134a	1872	1449	955	0	0	0	0	0	0
			HC-600a	362	415	545	1739	2016	2337	2709	3141	3641
		Commercial	HFC-134a	2027	1786	665	771	894	1036	1201	1393	1614
	R-404A + R-507		7006	3028	2262	0	0	0	0	0	0	
	Low GWP		0	0	3248	6387	7404	8584	9951	11536	13373	
	Industrial	HFC-134a	327	397	418	439	461	535	620	719	833	
		R-404A + R-507	345	420	153	0	0	0	0	0	0	
		Low GWP	2412	3884	5013	6035	7044	8165	9466	10974	12721	
	Transport	HFC-134a	45	57	142	164	191	221	256	297	344	
		R-404A + R-507	578	738	89	0	0	0	0	0	0	
		Low GWP	0	0	482	662	767	890	1031	1195	1386	
	SAC	HFC-134a	3387	3118	0	0	0	0	0	0	0	
		R-410A	34160	61755	68084	0	0	0	0	0	0	
		R-407C	7513	16313	10791	0	0	0	0	0	0	
		Low GWP	0	0	7209	99794	115688	134115	155476	180239	208946	
	MAC	HFC-134a	17728	17622	4573	0	0	0	0	0	0	
		Low GWP	0	0	12279	19535	22647	26254	30435	35283	40902	

**Table A4-3: Demand in tonnes for servicing only for non-Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios**

In tonnes (servicing)			2010	2015	2020	2025	2030	2035	2040	2045	2050	
nA5 BAU	Domestic	HFC-134a	4	2	2	1	1	1	1	1	1	2
		HC-600a	0	0	0	0	1	1	0	1	1	0
	Commercial	HFC-134a	229	587	1735	1624	1210	977	1133	1312	1522	
		R-404A + R-507	8299	13065	9645	5691	3595	3055	3542	4106	4760	
		Low GWP	0	0	1125	4613	8656	12214	14160	16415	19030	
		HFC-134a	714	716	730	749	772	808	864	942	1042	
	Industrial	R-404A + R-507	258	323	338	281	202	174	191	177	148	
		R-22	1003	675	455	306	206	139	0	0	0	
		Low GWP	4237	5014	6256	7826	9708	11848	14177	16677	19515	
	Transport	HFC-134a	177	156	160	207	292	364	423	490	568	
		R-404A + R-507	598	802	828	702	553	450	384	307	217	
		Low GWP	0	0	75	225	398	600	835	1106	1420	
		HFC-134a	645	1350	1422	994	226	0	0	0	0	
	SAC	R-410A	5225	15599	26146	35074	39820	45894	53204	61677	71501	
		R-407C	3682	10489	15381	17999	17051	16321	15649	14870	13968	
		Low GWP	0	0	1561	5081	9161	13892	19376	25733	33104	
	MAC	HFC-134a	51942	50737	43852	32688	21214	17267	20017	23206	26902	
		Low GWP	0	0	5939	18744	33587	44856	51999	60282	69884	
nA5 MIT-3	Domestic	HFC-134a	4	2	2	1	1	0	0	0	0	
		HC-600a	0	0	0	0	1	1	1	1	1	
	Commercial	HFC-134a	229	587	1735	1624	1210	977	1133	1312	1522	
		R-404A + R-507	8299	13065	9330	4207	759	0	0	0	0	
		Low GWP	0	0	1442	6096	11492	15270	17702	20521	23790	
		HFC-134a	714	716	730	749	772	808	864	942	1042	
	Industrial	R-404A + R-507	258	323	318	219	121	88	100	76	36	
		Low GWP	4237	5014	6276	7888	9787	11934	14270	16778	19627	
		HFC-134a	177	156	160	207	292	364	423	490	568	
	Transport	R-404A + R-507	598	802	730	484	162	0	0	0	0	
		Low GWP	0	0	143	443	791	1050	1218	1413	1637	
		HFC-134a	645	1350	1422	994	226	0	0	0	0	
	SAC	R-410A	5225	15599	21069	15831	4127	0	0	0	0	
		R-407C	3682	10489	13569	11080	4215	0	0	0	0	
		Low GWP	0	0	8033	29758	54944	76106	88228	102281	118572	
	MAC	HFC-134a	51942	50737	41871	25932	8755	0	0	0	0	
		Low GWP	0	0	7767	25500	46057	62122	72017	83487	96785	
	nA5 MIT-5	Domestic	HFC-134a	4	2	2	1	1	1	1	0	0
HC-600a			0	0	0	0	0	1	1	1	1	
Commercial		HFC-134a	229	587	1735	1624	1210	977	1133	1312	1522	
		R-404A + R-507	8299	13065	9645	4983	1535	57	0	0	0	
		Low GWP	0	0	1442	6096	11492	15270	17702	20521	23790	
		HFC-134a	714	716	730	749	772	808	864	942	1042	
Industrial		R-404A + R-507	258	323	338	277	159	126	162	156	123	
		Low GWP	4237	5014	6256	7850	9749	11896	14208	16698	19541	
		HFC-134a	177	156	160	207	292	364	423	490	568	
Transport		R-404A + R-507	598	802	783	531	209	23	0	0	0	
		Low GWP	0	0	120	396	744	1027	1218	1413	1637	
		HFC-134a	645	1350	1422	994	226	0	0	0	0	
SAC		R-410A	5225	15599	26146	26474	14768	1761	0	0	0	
		R-407C	3682	10489	15381	14906	8041	2012	0	0	0	
		Low GWP	0	0	1561	16110	41296	68930	88228	102281	118572	
MAC		HFC-134a	51942	50737	43852	29702	12514	1943	0	0	0	
		Low GWP	0	0	5939	21730	42287	60179	72017	83487	96785	

**Table A4-4: Demand in ktonnes CO<sub>2</sub>-eq for new manufacturing plus servicing (total demand) for non-Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios**

In ktonnes CO <sub>2</sub> equivalents (new manufacturing plus servicing)			2010	2015	2020	2025	2030	2035	2040	2045	2050	
nA5 BAU	Domestic	HFC-134a	2438	1887	1244	1240	1120	1298	1505	1745	2022	
		HC-600a	7	8	11	16	23	27	31	36	42	
	Commercial	HFC-134a	2933	3084	3120	3113	2735	2617	3034	3517	4077	
		R-404A + R-507	60388	63498	46975	29512	22379	21555	24988	28968	33582	
		Low GWP	0	0	1312	2764	4196	5519	6398	7417	8598	
		HFC-134a	1353	1447	1492	1544	1603	1746	1930	2159	2437	
	Industrial	R-404A + R-507	2375	2926	1935	1491	858	761	849	800	700	
		Low GWP	1	2	103	99	63	55	38	35	41	
		HFC-134a	289	277	393	483	629	761	882	1023	1186	
	Transport	R-404A + R-507	4634	6066	3614	3283	2780	2468	2316	2140	1936	
		Low GWP	0	0	167	227	304	394	498	619	759	
		HFC-134a	5241	5808	1848	1293	294	0	0	0	0	
	SAC	R-410A	75619	148520	180922	218882	252133	291774	338246	392120	454575	
		R-407C	18135	43419	42399	49165	50816	53328	56522	60225	64518	
		Low GWP	0	0	1315	2040	2855	3801	4897	6167	7640	
		HFC-134a	90571	88867	62952	49554	35762	31934	37020	42916	49752	
	MAC	Low GWP	0	0	18	33	50	64	74	86	99	
		HFC-134a	2438	1887	2	2	1	0	0	0	0	
nA5 MIT-3	Domestic	HC-600a	7	8	30	35	40	47	54	63	73	
		HFC-134a	2933	3084	3120	3113	2735	2617	3034	3517	4077	
	Commercial	R-404A + R-507	60388	63498	40703	16597	2999	0	0	0	0	
		Low GWP	0	0	1788	3745	5669	7156	8296	9617	11149	
		HFC-134a	1353	1447	1492	1544	1603	1746	1930	2159	2437	
		R-404A + R-507	2375	2926	1267	862	478	347	393	298	143	
	Industrial	Low GWP	1	2	154	146	92	86	72	74	83	
		HFC-134a	289	277	393	483	629	761	882	1023	1186	
		R-404A + R-507	4634	6066	2876	1908	638	0	0	0	0	
	Transport	Low GWP	0	0	223	331	467	582	675	782	907	
		HFC-134a	5241	5808	1848	1293	294	0	0	0	0	
		R-410A	75619	148520	42886	30396	7923	0	0	0	0	
	SAC	R-407C	18135	43419	22525	17949	6828	0	0	0	0	
		Low GWP	0	0	27754	38866	51190	63066	73111	84756	98255	
		HFC-134a	90571	88867	54432	33712	11367	0	0	0	0	
		Low GWP	0	0	25	45	69	88	102	119	138	
	nA5 MIT-5	Domestic	HFC-134a	2438	1887	1244	2	1	1	1	0	0
			HC-600a	7	8	11	35	40	47	54	63	73
Commercial		HFC-134a	2933	3084	3120	3113	2735	2617	3034	3517	4077	
		R-404A + R-507	60388	63498	46975	19659	6060	227	0	0	0	
		Low GWP	0	0	1407	3745	5669	7156	8296	9617	11149	
		HFC-134a	1353	1447	1492	1544	1603	1746	1930	2159	2437	
Industrial		R-404A + R-507	2375	2926	1935	1012	627	496	638	613	483	
		Low GWP	1	2	103	135	81	75	54	50	58	
		HFC-134a	289	277	393	483	629	761	882	1023	1186	
Transport		R-404A + R-507	4634	6066	3437	2092	822	92	0	0	0	
		Low GWP	0	0	180	317	453	575	675	782	907	
		HFC-134a	5241	5808	1848	1293	294	0	0	0	0	
SAC		R-410A	75619	148520	180922	50829	28354	9915	0	0	0	
		R-407C	18135	43419	42399	24148	13027	3260	0	0	0	
		Low GWP	0	0	2631	34771	47095	60914	73111	84756	98255	
		HFC-134a	90571	88867	62952	38613	16269	2526	0	0	0	
MAC		Low GWP	0	0	18	41	65	86	102	119	138	
		HFC-134a	2438	1887	2	2	1	0	0	0	0	

**Table A4-5: Demand in ktonnes CO<sub>2</sub>-eq. for new manufacturing only for non-Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios**

In ktonnes CO2 equivalents (new manufacturing)			2010	2015	2020	2025	2030	2035	2040	2045	2050
nA5 BAU	Domestic	HFC-134a	2434	1883	1241	1238	1119	1297	1503	1743	2021
		HC-600a	7	8	11	16	23	27	31	36	42
	Commercial	HFC-134a	2635	2321	865	1002	1162	1347	1562	1810	2099
		R-404A + R-507	27645	11962	8932	7063	8187	9491	11003	12756	14787
		Low GWP	0	0	974	1380	1600	1855	2150	2492	2889
	Industrial	HFC-134a	424	516	543	570	600	695	806	934	1083
		R-404A + R-507	1359	1653	604	383	65	75	87	101	117
		Low GWP	1	1	88	58	11	13	15	18	21
	Transport	HFC-134a	58	74	184	214	248	287	333	386	448
		R-404A + R-507	2278	2907	350	516	598	693	803	931	1079
		Low GWP	0	0	145	159	185	214	248	288	334
	SAC	HFC-134a	4403	4053	0	0	0	0	0	0	0
		R-410A	65586	118570	130720	151541	175677	203658	236095	273699	317293
		R-407C	12171	26428	17481	20007	23194	26888	31170	36135	41890
		Low GWP	0	0	1081	1277	1481	1717	1990	2307	2675
	MAC	HFC-134a	23046	22908	5944	7059	8183	9486	10997	12749	14780
		Low GWP	0	0	12	14	16	19	22	25	30
	nA5 MIT-3	Domestic	HFC-134a	2434	1883	0	0	0	0	0	0
HC-600a			7	8	30	35	40	47	54	63	73
Commercial		HFC-134a	2635	2321	865	1002	1162	1347	1562	1810	2099
		R-404A + R-507	27645	11962	3906	0	0	0	0	0	0
		Low GWP	0	0	1356	1916	2221	2575	2985	3461	4012
Industrial		HFC-134a	424	516	543	570	600	695	806	934	1083
		R-404A + R-507	1359	1653	17	0	0	0	0	0	0
		Low GWP	1	1	132	87	16	19	22	26	30
Transport		HFC-134a	58	74	184	214	248	287	333	386	448
		R-404A + R-507	2278	2907	0	0	0	0	0	0	0
		Low GWP	0	0	180	199	230	267	309	359	416
SAC		HFC-134a	4403	4053	0	0	0	0	0	0	0
		R-410A	65586	118570	2434	0	0	0	0	0	0
		R-407C	12171	26428	543	0	0	0	0	0	0
		Low GWP	0	0	25344	29938	34707	40234	46643	54072	62684
MAC		HFC-134a	23046	22908	0	0	0	0	0	0	0
		Low GWP	0	0	17	20	23	26	30	35	41
nA5 MIT-5		Domestic	HFC-134a	2434	1883	1241	0	0	0	0	0
	HC-600a		7	8	11	35	40	47	54	63	73
	Commercial	HFC-134a	2635	2321	865	1002	1162	1347	1562	1810	2099
		R-404A + R-507	27645	11962	8932	0	0	0	0	0	0
		Low GWP	0	0	974	1916	2221	2575	2985	3461	4012
	Industrial	HFC-134a	424	516	543	570	600	695	806	934	1083
		R-404A + R-507	1359	1653	604	0	0	0	0	0	0
		Low GWP	1	1	88	87	16	19	22	26	30
	Transport	HFC-134a	58	74	184	214	248	287	333	386	448
		R-404A + R-507	2278	2907	350	0	0	0	0	0	0
		Low GWP	0	0	145	199	230	267	309	359	416
	SAC	HFC-134a	4403	4053	0	0	0	0	0	0	0
		R-410A	65586	118570	130720	0	0	0	0	0	0
		R-407C	12171	26428	17481	0	0	0	0	0	0
		Low GWP	0	0	2163	29938	34707	40234	46643	54072	62684
	MAC	HFC-134a	23046	22908	5944	0	0	0	0	0	0
		Low GWP	0	0	12	20	23	26	30	35	41

**Table A4-6: Demand in ktonnes CO<sub>2</sub>-eq. for servicing only for non-Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios**

In ktonnes CO <sub>2</sub> equivalents (servicing)			2010	2015	2020	2025	2030	2035	2040	2045	2050
nA5 BAU	Domestic	HFC-134a	4	4	3	2	1	1	2	2	1
		HC-600a	0	0	0	0	0	0	0	0	0
	Commercial	HFC-134a	298	763	2255	2111	1573	1270	1472	1707	1978
		R-404A + R-507	32743	51536	38043	22449	14192	12064	13985	16212	18795
		Low GWP	0	0	338	1384	2596	3664	4248	4925	5709
	Industrial	HFC-134a	929	931	949	974	1003	1051	1124	1225	1354
		R-404A + R-507	1016	1273	1331	1108	793	686	762	699	583
		Low GWP	0	1	15	41	52	42	23	17	20
	Transport	HFC-134a	231	203	209	269	381	474	549	637	738
		R-404A + R-507	2356	3159	3264	2767	2182	1775	1513	1209	857
		Low GWP	0	0	22	68	119	180	250	331	425
	SAC	HFC-134a	838	1755	1848	1293	294	0	0	0	0
		R-410A	10033	29950	50202	67341	76456	88116	102151	118421	137282
		R-407C	5964	16991	24918	29158	27622	26440	25352	24090	22628
		Low GWP	0	0	234	763	1374	2084	2907	3860	4965
	MAC	HFC-134a	67525	65959	57008	42495	27579	22448	26023	30167	34972
		Low GWP	0	0	6	19	34	45	52	61	69
	nA5 MIT-3	Domestic	HFC-134a	4	4	2	2	1	0	0	0
HC-600a			0	0	0	0	0	0	0	0	0
Commercial		HFC-134a	298	763	2255	2111	1573	1270	1472	1707	1978
		R-404A + R-507	32743	51536	36797	16597	2999	0	0	0	0
		Low GWP	0	0	432	1829	3448	4581	5311	6156	7137
Industrial		HFC-134a	929	931	949	974	1003	1051	1124	1225	1354
		R-404A + R-507	1016	1273	1250	862	478	347	393	298	143
		Low GWP	0	1	22	59	76	67	50	48	53
Transport		HFC-134a	231	203	209	269	381	474	549	637	738
		R-404A + R-507	2356	3159	2876	1908	638	0	0	0	0
		Low GWP	0	0	43	132	237	315	366	423	491
SAC		HFC-134a	838	1755	1848	1293	294	0	0	0	0
		R-410A	10033	29950	40452	30396	7923	0	0	0	0
		R-407C	5964	16991	21982	17949	6828	0	0	0	0
		Low GWP	0	0	2410	8928	16483	22832	26468	30684	35571
MAC		HFC-134a	67525	65959	54432	33712	11367	0	0	0	0
		Low GWP	0	0	8	25	46	62	72	84	97
nA5 MIT-5		Domestic	HFC-134a	4	4	3	2	1	1	1	0
	HC-600a		0	0	0	0	0	0	0	0	0
	Commercial	HFC-134a	298	763	2255	2111	1573	1270	1472	1707	1978
		R-404A + R-507	32743	51536	38043	19659	6060	227	0	0	0
		Low GWP	0	0	433	1829	3448	4581	5311	6156	7137
	Industrial	HFC-134a	929	931	949	974	1003	1051	1124	1225	1354
		R-404A + R-507	1016	1273	1331	1012	627	496	638	613	483
		Low GWP	0	1	15	48	65	56	32	24	28
	Transport	HFC-134a	231	203	209	269	381	474	549	637	738
		R-404A + R-507	2356	3159	3087	2092	822	92	0	0	0
		Low GWP	0	0	35	118	223	308	366	423	491
	SAC	HFC-134a	838	1755	1848	1293	294	0	0	0	0
		R-410A	10033	29950	50202	50829	28354	9915	0	0	0
		R-407C	5964	16991	24918	24148	13027	3260	0	0	0
		Low GWP	0	0	468	4833	12388	20680	26468	30684	35571
	MAC	HFC-134a	67525	65959	57008	38613	16269	2526	0	0	0
		Low GWP	0	0	6	21	42	60	72	84	97

**Table A4-7: Demand in tonnes for servicing and new manufacturing (total demand) for Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios**

In tonnes (new manufacturing plus servicing)			2010	2015	2020	2025	2030	2035	2040	2045	2050
A5 BAU	Domestic	HFC-134a	12941	13329	15333	18242	21634	26893	33468	41682	51935
		HC-600a	3083	5747	10141	15684	23446	29496	36965	46197	57613
	Commercial	HFC-134a	2743	5089	9356	11910	15018	18781	23404	29166	36346
		R-404A + R-507	11343	31391	55505	97823	148283	198343	255658	320891	399889
		Low GWP	0	0	0	0	0	0	0	0	0
	Industrial	HFC-134a	720	1320	2255	3730	6074	8301	10829	13737	17118
		R-404A + R-507	599	3132	6266	10969	15212	20001	25495	31870	39332
		Low GWP	19347	23571	28991	36291	46469	56461	67842	81380	97596
	Transport	HFC-134a	544	1075	1982	2608	3104	3798	4521	5424	6697
		R-404A + R-507	1143	1881	2192	3135	4195	5235	6592	8316	10393
		Low GWP	0	0	0	0	0	0	0	0	0
	SAC	HFC-134a	1091	2315	4556	5849	7087	8173	8961	9609	10338
		R-410A	40975	106661	192770	284682	364845	427266	479588	524488	566180
		R-407C	16543	55278	101216	174433	285500	372998	457406	532391	587361
		Low GWP	0	0	0	0	0	0	0	0	0
MAC	HFC-134a	36354	51396	66680	84928	108190	138081	176230	224919	287060	
	Low GWP	0	0	0	0	0	0	0	0	0	
A5 MIT-3	Domestic	HFC-134a	12941	13329	12953	1296	549	333	94	0	0
		HC-600a	3083	5747	12521	32630	44531	56056	70339	87879	109548
	Commercial	HFC-134a	2743	5089	9356	11910	15018	18781	23404	29166	36346
		R-404A + R-507	11343	31391	50015	30001	9356	1285	0	0	0
		Low GWP	0	0	5490	67822	140098	197058	255658	320891	399889
	Industrial	HFC-134a	720	1320	2255	3730	6074	8301	10829	13737	17118
		R-404A + R-507	599	3132	5774	4392	2883	1131	1412	3306	5077
		Low GWP	19347	23571	29484	42868	58798	75331	91924	109944	131850
	Transport	HFC-134a	544	1075	1982	2608	3104	3798	4521	5424	6697
		R-404A + R-507	1143	1881	1976	1265	928	554	164	0	0
		Low GWP	0	0	216	1871	3267	4680	6428	8316	10393
	SAC	HFC-134a	1091	2315	4556	5849	7087	8173	8961	9609	10338
		R-410A	40975	106661	170273	65015	18972	13467	4267	0	0
		R-407C	16543	55278	92804	58029	20684	13059	4411	0	0
		Low GWP	0	0	30909	336071	610690	773737	928316	1056879	1153541
MAC	HFC-134a	36354	51396	59636	22153	6375	0	0	0	0	
	Low GWP	0	0	7044	62775	101815	138081	176230	224919	287060	
A5 MIT-5	Domestic	HFC-134a	12941	13329	15333	15442	1541	636	389	111	0
		HC-600a	3083	5747	10141	18484	43539	55752	70044	87768	109548
	Commercial	HFC-134a	2743	5089	9356	11910	15018	18781	23404	29166	36346
		R-404A + R-507	11343	31391	55505	88798	45752	23639	7810	0	0
		Low GWP	0	0	0	9024	102531	174704	247847	320891	399889
	Industrial	HFC-134a	720	1320	2255	3730	6074	8301	10829	13737	17118
		R-404A + R-507	599	3132	6266	10200	7134	5289	2973	3306	5077
		Low GWP	19347	23571	28991	37060	54546	71173	90363	109944	131850
	Transport	HFC-134a	544	1075	1982	2608	3104	3798	4521	5424	6697
		R-404A + R-507	1143	1881	2192	2860	1577	1066	662	209	0
		Low GWP	0	0	0	275	2618	4169	5930	8108	10393
	SAC	HFC-134a	1091	2315	4556	5849	7087	8173	8961	9609	10338
		R-410A	40975	106661	192770	254067	104162	83830	55193	16085	0
		R-407C	16543	55278	101216	160942	108166	30160	21180	7194	0
		Low GWP	0	0	0	44105	438017	686274	860621	1033601	1153541
MAC	HFC-134a	36354	51396	66680	76006	28027	4843	0	0	0	
	Low GWP	0	0	0	8922	80163	133238	176230	224919	287060	

**Table A4-8: Demand in tonnes for new manufacturing only for Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios**

In tonnes (new manufacturing)			2010	2015	2020	2025	2030	2035	2040	2045	2050
A5 BAU	Domestic	HFC-134a	11234	12812	14610	17323	20540	25597	31899	39751	49537
		HC-600a	2622	5557	9740	14957	22252	27730	34557	43064	53666
	Commercial	HFC-134a	2617	4779	8726	10874	13551	16887	21045	26225	32682
		R-404A + R-507	9216	20804	31030	52412	76790	95695	119253	148611	185196
		Low GWP	0	0	0	0	0	0	0	0	0
	Industrial	HFC-134a	406	650	1040	1663	2661	3191	3827	4590	5504
		R-404A + R-507	238	1613	2532	3972	4435	5319	6379	7649	9173
		Low GWP	3305	4242	5579	7566	10645	12766	15309	18358	22015
	Transport	HFC-134a	321	551	948	964	981	1223	1524	1899	2367
		R-404A + R-507	877	1241	1158	1660	2290	2853	3556	4431	5522
		Low GWP	0	0	0	0	0	0	0	0	0
	SAC	HFC-134a	862	1587	2923	3072	3229	3478	3747	4036	4348
		R-410A	34583	82577	134702	178540	206625	222594	239796	258329	278294
		R-407C	6107	26645	43128	69810	112998	121731	131139	141274	152192
		Low GWP	0	0	0	0	0	0	0	0	0
	MAC	HFC-134a	25061	32577	40822	52100	66495	84866	108313	138238	176430
		Low GWP	0	0	0	0	0	0	0	0	0
	A5 MIT-3	Domestic	HFC-134a	11234	12812	12238	580	0	0	0	0
HC-600a			2622	5557	12112	31700	42792	53327	66455	82815	103203
Commercial		HFC-134a	2617	4779	8726	10874	13551	16887	21045	26225	32682
		R-404A + R-507	9216	20804	26172	4495	0	0	0	0	0
		Low GWP	0	0	4858	47916	76790	95695	119253	148611	185196
Industrial		HFC-134a	406	650	1040	1663	2661	3191	3827	4590	5504
		R-404A + R-507	238	1613	2132	230	0	0	0	0	0
		Low GWP	3305	4242	5979	11308	15080	18085	21687	26007	31188
Transport		HFC-134a	321	551	948	964	981	1223	1524	1899	2367
		R-404A + R-507	877	1241	956	110	0	0	0	0	0
		Low GWP	0	0	203	1551	2290	2853	3556	4431	5522
SAC		HFC-134a	862	1587	2923	3072	3229	3478	3747	4036	4348
		R-410A	34583	82577	113983	10182	0	0	0	0	0
		R-407C	6107	26645	36495	3981	0	0	0	0	0
		Low GWP	0	0	27353	234187	319623	344324	370935	399603	430485
MAC		HFC-134a	25061	32577	34293	2481	0	0	0	0	0
		Low GWP	0	0	6529	49619	66495	84866	108313	138238	176430
A5 MIT-5		Domestic	HFC-134a	11234	12812	14610	14533	688	0	0	0
	HC-600a		2622	5557	9740	17747	42104	53327	66455	82815	103203
	Commercial	HFC-134a	2617	4779	8726	10874	13551	16887	21045	26225	32682
		R-404A + R-507	9216	20804	31030	44426	5149	0	0	0	0
		Low GWP	0	0	0	7986	71642	95695	119253	148611	185196
	Industrial	HFC-134a	406	650	1040	1663	2661	3191	3827	4590	5504
		R-404A + R-507	238	1613	2532	3348	0	0	0	0	0
		Low GWP	3305	4242	5579	8190	15080	18085	21687	26007	31188
	Transport	HFC-134a	321	551	948	964	981	1223	1524	1899	2367
		R-404A + R-507	877	1241	1158	1402	137	0	0	0	0
		Low GWP	0	0	0	258	2152	2853	3556	4431	5522
	SAC	HFC-134a	862	1587	2923	3072	3229	3478	3747	4036	4348
		R-410A	34583	82577	134702	150481	9255	0	0	0	0
		R-407C	6107	26645	43128	58838	5061	0	0	0	0
		Low GWP	0	0	0	39031	305306	344324	370935	399603	430485
	MAC	HFC-134a	25061	32577	40822	43830	3166	0	0	0	0
		Low GWP	0	0	0	8270	63328	84866	108313	138238	176430

**Table: A4-9 Demand in tonnes for servicing only for Article 5 Parties for the period 2010-2050 for the six major sub-sectors and for the BAU, MIT-3 and MIT-5 scenarios**

In tonnes (servicing)			2010	2015	2020	2025	2030	2035	2040	2045	2050
A5 BAU	Domestic	HFC-134a	1707	517	723	919	1094	1296	1569	1931	2398
		HC-600a	461	190	401	727	1194	1766	2408	3133	3947
	Commercial	HFC-134a	126	310	630	1036	1467	1894	2359	2941	3664
		R-404A + R-507	2127	10587	24475	45411	71493	102648	136405	172280	214693
		Low GWP	0	0	0	0	0	0	0	0	0
	Industrial	HFC-134a	314	670	1215	2067	3413	5110	7002	9147	11614
		R-404A + R-507	361	1519	3734	6997	10777	14682	19116	24221	30159
		Low GWP	16042	19329	23412	28725	35824	43695	52533	63022	75581
	Transport	HFC-134a	223	524	1034	1644	2123	2575	2997	3525	4330
		R-404A + R-507	266	640	1034	1475	1905	2382	3036	3885	4871
		Low GWP	0	0	0	0	0	0	0	0	0
	Industrial	HFC-134a	229	728	1633	2777	3858	4695	5214	5573	5990
		R-410A	6392	24084	58068	106142	158220	204672	239792	266159	287886
		R-407C	10436	28633	58088	104623	172502	251267	326267	391117	435169
		Low GWP	0	0	0	0	0	0	0	0	0
MAC		HFC-134a	11293	18819	25858	32828	41695	53215	67917	86681	110630
Low GWP	0	0	0	0	0	0	0	0	0	0	
A5 MIT-3	Domestic	HFC-134a	1707	517	715	716	549	333	94	0	0
		HC-600a	461	190	409	930	1739	2729	3884	5064	6345
	Commercial	HFC-134a	126	310	630	1036	1467	1894	2359	2941	3664
		R-404A + R-507	2127	10587	23843	25506	9356	1285	0	0	0
		Low GWP	0	0	632	19906	63308	101363	136405	172280	214693
	Industrial	HFC-134a	314	670	1215	2067	3413	5110	7002	9147	11614
		R-404A + R-507	361	1519	3642	4162	2883	1131	1412	3306	5077
		Low GWP	16042	19329	23505	31560	43718	57246	70237	83937	100662
	Transport	HFC-134a	223	556	1217	2073	2825	2825	2825	2825	2825
		R-404A + R-507	266	684	1159	962	0	0	0	0	0
		Low GWP	0	0	33	853	2535	2535	2535	2535	2535
	SAC	HFC-134a	229	728	1633	2777	3858	4695	5214	5573	5990
		R-410A	6392	24084	56290	54833	18972	13467	4267	0	0
		R-407C	10436	28633	56309	54048	20684	13059	4411	0	0
		Low GWP	0	0	3556	101884	291067	429413	557381	657276	723056
MAC		HFC-134a	11293	18819	25343	19672	6375	0	0	0	0
Low GWP	0	0	515	13156	35320	53215	67917	86681	110630		
A5 MIT-5	Domestic	HFC-134a	1707	517	723	909	853	636	389	111	0
		HC-600a	461	190	401	737	1435	2425	3589	4953	6345
	Commercial	HFC-134a	126	310	630	1036	1467	1894	2359	2941	3664
		R-404A + R-507	2127	10587	24475	44372	40603	23639	7810	0	0
		Low GWP	0	0	0	1038	30889	79009	128594	172280	214693
	Industrial	HFC-134a	314	670	1215	2067	3413	5110	7002	9147	11614
		R-404A + R-507	361	1519	3734	6852	7134	5289	2973	3306	5077
		Low GWP	16042	19329	23412	28870	39466	53088	68676	83937	100662
	Transport	HFC-134a	223	524	1034	1644	2123	2575	2997	3525	4330
		R-404A + R-507	266	640	1034	1458	1440	1066	662	209	0
		Low GWP	0	0	0	17	466	1316	2374	3677	4871
	Industrial	HFC-134a	229	728	1633	2777	3858	4695	5214	5573	5990
		R-410A	6392	24084	58068	103586	94907	83830	55193	16085	0
		R-407C	10436	28633	58088	102104	103105	30160	21180	7194	0
		Low GWP	0	0	0	5074	132711	341950	489686	633998	723056
MAC		HFC-134a	11293	18819	25858	32176	24861	4843	0	0	0
Low GWP	0	0	0	652	16835	48372	67917	86681	110630		

**Table A4-10: Demand in ktonnes CO<sub>2</sub>eq. for new manufacturing plus servicing (total demand) for Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios**

In ktonnes CO <sub>2</sub> equivalents (new manufacturing plus servicing)			2010	2015	2020	2025	2030	2035	2040	2045	2050
A5 BAU	Domestic	HFC-134a	16823	17327	19933	23715	28125	34960	43509	54186	67516
		HC-600a	62	115	203	314	469	590	739	924	1152
	Commercial	HFC-134a	3566	6615	12162	15484	19524	24415	30425	37915	47250
		R-404A + R-507	44723	123759	218844	385658	584559	781886	1007810	1264957	1576367
		Low GWP	0	0	0	0	0	0	0	0	0
	Industrial	HFC-134a	937	1716	2931	4849	7896	10792	14078	17858	22253
		R-404A + R-507	2359	12341	24689	43217	59936	78802	100448	125566	154966
		Low GWP	1	1	3	5	9	11	13	16	19
	Transport	HFC-134a	707	1398	2577	3390	4035	4938	5877	7051	8706
		R-404A + R-507	4502	7411	8635	12354	16530	20625	25937	32766	40950
		Low GWP	0	0	0	0	0	0	0	0	0
	SAC	HFC-134a	1418	3009	5923	7603	9213	10624	11649	12492	13440
		R-410A	78671	204789	370118	546589	700502	820350	920809	1007017	1087066
		R-407C	26799	89550	163971	282581	462511	604256	740997	862474	951525
		Low GWP	0	0	0	0	0	0	0	0	0
	MAC	HFC-134a	47261	66815	86684	110406	140647	179505	229099	292395	373178
		Low GWP	0	0	0	0	0	0	0	0	0
	A5 MIT-3	Domestic	HFC-134a	16823	17327	16839	1685	714	432	122	0
HC-600a			62	115	250	653	891	1121	1407	1758	2191
Commercial		HFC-134a	3566	6615	12162	15484	19524	24415	30425	37915	47250
		R-404A + R-507	44723	123759	197206	118371	32484	5078	0	0	0
		Low GWP	0	0	1647	20347	42029	59117	76697	96267	119967
Industrial		HFC-134a	937	1716	2931	4849	7896	10792	14078	17858	22253
		R-404A + R-507	2359	12341	22749	17303	11359	4454	5564	13024	20005
		Low GWP	1	1	150	1078	3707	5672	7238	8585	10295
Transport		HFC-134a	707	1398	2577	3390	4035	4938	5877	7051	8706
		R-404A + R-507	4502	7411	7785	4984	3657	2184	646	0	0
		Low GWP	0	0	68	648	980	1404	1928	2495	3118
SAC		HFC-134a	1418	3009	5923	7603	9213	10624	11649	12492	13440
		R-410A	78671	204789	326924	124828	36425	25856	8192	0	0
		R-407C	26799	89550	150343	94007	33508	21156	7146	0	0
		Low GWP	0	0	9273	100821	183207	232121	278495	317064	346062
MAC		HFC-134a	47261	66815	77527	28799	8288	0	0	0	0
		Low GWP	0	0	7	63	102	138	176	225	287
A5 MIT-5		Domestic	HFC-134a	16823	17327	19933	20074	2003	827	506	144
	HC-600a		62	115	203	370	871	1115	1401	1755	2191
	Commercial	HFC-134a	3566	6615	12162	15484	19524	24415	30425	37915	47250
		R-404A + R-507	44723	123759	218844	350091	180501	93204	30793	0	0
		Low GWP	0	0	0	2707	30759	52411	74354	96267	119967
	Industrial	HFC-134a	937	1716	2931	4849	7896	10792	14078	17858	22253
		R-404A + R-507	2359	12341	24689	40190	28109	20839	11712	13024	20005
		Low GWP	1	1	3	235	2432	4424	6770	8585	10295
	Transport	HFC-134a	707	1398	2577	3390	4035	4938	5877	7051	8706
		R-404A + R-507	4502	7411	8635	11269	6214	4200	2610	822	0
		Low GWP	0	0	0	83	785	1251	1779	2432	3118
	SAC	HFC-134a	1418	3009	5923	7603	9213	10624	11649	12492	13440
		R-410A	78671	204789	370118	487808	199992	160953	105970	30882	0
		R-407C	26799	89550	163971	260727	175229	48859	34312	11654	0
		Low GWP	0	0	0	13232	131405	205882	258186	310080	346062
	MAC	HFC-134a	47261	66815	86684	98808	36435	6296	0	0	0
		Low GWP	0	0	0	9	80	133	176	225	287

**Table A4-11: Demand in ktonnes CO<sub>2</sub>-eq. for new manufacturing only for Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios**

In ktonnes CO <sub>2</sub> equivalents (new manufacturing)			2010	2015	2020	2025	2030	2035	2040	2045	2050	
A5 BAU	Domestic	HFC-134a	14993	16655	18993	22520	26702	33276	41468	51677	64399	
		HC-600a	52	111	195	299	445	555	691	861	1073	
	Commercial	HFC-134a	3402	6213	11344	14136	17617	21953	27358	34093	42486	
		R-404A + R-507	36328	81998	122316	206575	302644	377150	469997	585702	729891	
		Low GWP	0	0	0	0	0	0	0	0	0	
	Industrial	HFC-134a	528	845	1352	2162	3460	4149	4975	5966	7155	
		R-404A + R-507	937	6354	9976	15650	17476	20957	25131	30138	36141	
		Low GWP	0	1	1	2	4	5	6	8	9	
	Transport	HFC-134a	417	717	1232	1254	1276	1590	1981	2469	3077	
		R-404A + R-507	3455	4891	4564	6542	9022	11243	14010	17460	21758	
		Low GWP	0	0	0	0	0	0	0	0	0	
	SAC	HFC-134a	1121	2063	3800	3993	4197	4521	4871	5247	5653	
		R-410A	66400	158547	258628	342797	396720	427380	460409	495991	534324	
		R-407C	9893	43164	69868	113092	183057	197204	212445	228863	246551	
		Low GWP	0	0	0	0	0	0	0	0	0	
	MAC	HFC-134a	32579	42350	53069	67730	86443	110326	140807	179709	229359	
		Low GWP	0	0	0	0	0	0	0	0	0	
	A5 MIT-3	Domestic	HFC-134a	14604	16655	15910	754	0	0	0	0	0
			HC-600a	52	111	242	634	856	1067	1329	1656	2064
		Commercial	HFC-134a	3402	6213	11344	14136	17617	21953	27358	34093	42486
R-404A + R-507			36328	81998	103166	17714	0	0	0	0	0	
Low GWP			0	0	1457	14375	23037	28708	35776	44583	55559	
Industrial		HFC-134a	528	845	1352	2162	3460	4149	4975	5966	7155	
		R-404A + R-507	937	6354	8401	908	0	0	0	0	0	
		Low GWP	0	1	1221	1125	1335	1601	1920	2302	2761	
Transport		HFC-134a	417	717	1232	1254	1276	1590	1981	2469	3077	
		R-404A + R-507	3455	4891	3766	432	0	0	0	0	0	
		Low GWP	0	0	61	465	687	856	1067	1329	1657	
SAC		HFC-134a	1121	2063	3800	3993	4197	4521	4871	5247	5653	
		R-410A	66400	158547	218847	19549	0	0	0	0	0	
		R-407C	9893	43164	59121	6449	0	0	0	0	0	
		Low GWP	0	0	8206	70256	95887	103297	111281	119881	129146	
MAC		HFC-134a	32579	42350	44581	3225	0	0	0	0	0	
		Low GWP	0	0	7	50	66	85	108	138	176	
A5 MIT-5		Domestic	HFC-134a	14604	16655	18994	18893	894	0	0	0	0
			HC-600a	52	111	195	355	842	1067	1329	1656	2064
		Commercial	HFC-134a	3402	6213	11344	14136	17617	21953	27358	34093	42486
	R-404A + R-507		36328	81998	122316	175098	20289	0	0	0	0	
	Low GWP		0	0	0	2396	21493	28708	35776	44583	55559	
	Industrial	HFC-134a	528	845	1352	2162	3460	4149	4975	5966	7155	
		R-404A + R-507	937	6354	9976	13193	0	0	0	0	0	
		Low GWP	0	1	1	190	1335	1601	1920	2302	2761	
	Transport	HFC-134a	417	717	1232	1254	1276	1590	1981	2469	3077	
		R-404A + R-507	3455	4891	4564	5524	542	0	0	0	0	
		Low GWP	0	0	0	78	646	856	1067	1329	1657	
	SAC	HFC-134a	1121	2063	3800	3993	4197	4521	4871	5247	5653	
		R-410A	66400	158547	258628	288923	19076	0	0	0	0	
		R-407C	9893	43164	69868	95318	8802	0	0	0	0	
		Low GWP	0	0	0	11709	91276	103297	111281	119881	129146	
	MAC	HFC-134a	32579	42350	53069	56980	4116	0	0	0	0	
		Low GWP	0	0	0	8	63	85	108	138	176	

**Table A4-12: Demand in ktonnes CO<sub>2</sub>-eq. for servicing only for Article 5 Parties for the period 2010-2050 and for the six major sub-sectors for the BAU, MIT-3 and MIT-5 scenarios**

In ktonnes CO2 equivalents (servicing)			2010	2015	2020	2025	2030	2035	2040	2045	2050
A5 BAU	Domestic	HFC-134a	1830	672	940	1195	1423	1684	2041	2509	3117
		HC-600a	10	4	8	15	24	35	48	63	79
	Commercial	HFC-134a	164	402	818	1348	1907	2462	3067	3822	4764
		R-404A + R-507	8395	41761	96528	179083	281915	404736	537813	679255	846476
		Low GWP	0	0	0	0	0	0	0	0	0
	Industrial	HFC-134a	409	871	1579	2687	4436	6643	9103	11892	15098
		R-404A + R-507	1422	5987	14713	27567	42460	57845	75317	95428	118825
		Low GWP	1	0	2	3	5	6	7	8	10
	Transport	HFC-134a	290	681	1345	2136	2759	3348	3896	4582	5629
		R-404A + R-507	1047	2520	4071	5812	7508	9382	11927	15306	19192
		Low GWP	0	0	0	0	0	0	0	0	0
	SAC	HFC-134a	297	946	2123	3610	5016	6103	6778	7245	7787
		R-410A	12271	46242	111490	203792	303782	392970	460400	511026	552742
		R-407C	16906	46386	94103	169489	279454	407052	528552	633611	704974
		Low GWP	0	0	0	0	0	0	0	0	0
	MAC	HFC-134a	14682	24465	33615	42676	54204	69179	88292	112686	143819
		Low GWP	0	0	0	0	0	0	0	0	0
	A5 MIT-3	Domestic	HFC-134a	2219	672	929	931	714	432	122	0
HC-600a			10	4	8	19	35	54	78	102	127
Commercial		HFC-134a	164	402	818	1348	1907	2462	3067	3822	4764
		R-404A + R-507	8395	41761	94040	100657	32484	5078	0	0	0
		Low GWP	0	0	190	5972	18992	30409	40921	51684	64408
Industrial		HFC-134a	409	871	1579	2687	4436	6643	9103	11892	15098
		R-404A + R-507	1422	5987	14348	16395	11359	4454	5564	13024	20005
		Low GWP	1	0	-1071	-47	2372	4071	5318	6283	7534
Transport		HFC-134a	290	681	1345	2136	2759	3348	3896	4582	5629
		R-404A + R-507	1047	2520	4019	4552	3657	2184	646	0	0
		Low GWP	0	0	7	183	293	548	861	1166	1461
SAC		HFC-134a	297	946	2123	3610	5016	6103	6778	7245	7787
		R-410A	12271	46242	108077	105279	36425	25856	8192	0	0
		R-407C	16906	46386	91222	87558	33508	21156	7146	0	0
		Low GWP	0	0	1067	30565	87320	128824	167214	197183	216916
MAC		HFC-134a	14682	24465	32946	25574	8288	0	0	0	0
		Low GWP	0	0	0	13	36	53	68	87	111
A5 MIT-5		Domestic	HFC-134a	2219	672	939	1181	1109	827	506	144
	HC-600a		10	4	8	15	29	48	72	99	127
	Commercial	HFC-134a	164	402	818	1348	1907	2462	3067	3822	4764
		R-404A + R-507	8395	41761	96528	174993	160212	93204	30793	0	0
		Low GWP	0	0	0	311	9266	23703	38578	51684	64408
	Industrial	HFC-134a	409	871	1579	2687	4436	6643	9103	11892	15098
		R-404A + R-507	1422	5987	14713	26997	28109	20839	11712	13024	20005
		Low GWP	1	0	2	45	1097	2823	4850	6283	7534
	Transport	HFC-134a	290	681	1345	2136	2759	3348	3896	4582	5629
		R-404A + R-507	1047	2520	4071	5745	5672	4200	2610	822	0
		Low GWP	0	0	0	5	139	395	712	1103	1461
	SAC	HFC-134a	297	946	2123	3610	5016	6103	6778	7245	7787
		R-410A	12271	46242	111490	198885	180916	160953	105970	30882	0
		R-407C	16906	46386	94103	165409	166427	48859	34312	11654	0
		Low GWP	0	0	0	1523	40129	102585	146905	190199	216916
	MAC	HFC-134a	14682	24465	33615	41828	32319	6296	0	0	0
		Low GWP	0	0	0	1	17	48	68	87	111