Alternatives to High-GWP Hydrofluorocarbons

Dr Suely Carvalho
Dr Stephen O. Andersen
Duncan Brack
Dr Nancy J. Sherman

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Contributions from: *Dr Shamila Nair-Bedouelle* (United Nations Environment Programme—UNEP), *Donnalyn Charles* (Saint Lucia Ministry of Sustainable Development, Energy and Science and Technology), Dr Vaibhav Chaturvedi (Council on Energy, Environment and Water—CEEW), Dr Ezra Clark (UNEP), James Curlin (UNEP), *Dr Arunabha Ghosh* (CEEW), *Steve Gorman* (Consultant), *Dr Jianxin Hu* (Peking University), *Dr Oswaldo dos Santos Lucon* (São Paulo State Environmental Secretariat), *Alan Miller* (Consultant), *Dr C. Shelley Norman* (Johns Hopkins University), *Sateeaved Seebaluck* (Government of Mauritius), *Mikkel Morten Aaman Sorensen* (Danish Environmental Protection Agency), *Kristen N. Taddonio* United States Department of Energy (US DOE), *Mike Thompson* (Ingersoll Rand), *Dr Guus J.M. Velders* (National Institute for Public Health and the Environment) and *Durwood Zaelke* (Institute for Governance & Sustainable Development—IGSD).[1]

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[1] The views expressed in this report are those of the authors and team members and not necessarily the views of the organizations where they are employed. Affiliation is for identification only.

Contents

0 Executive Summary

This assessment report aims to give a concise and accessible picture of the current availability of alternatives to high-global warming potential (GWP) hydrofluorocarbons (HFCs) in their main uses, with elaboration of their efficacy, cost-effectiveness, safety, environmental impacts and technical performance, as well as their applicability at high ambient temperatures, with the goal of better informing decision making about the future of HFCs in a fast-evolving market and regulatory context.

This report builds on the findings of the Chatham House/Institute for Governance & Sustainable Development (IGSD) Workshop and Report (Andersen, Brack, and Depledge, 2014) and the IGSD Primer on Hydrofluorocarbons (Zaelke and Borgford-Parnell, 2014) and is a continuous work in progress, which will be updated frequently; corrections and additions are welcome.[2]

A wide choice of alternatives to HFCs are now available, with more under development, but many of these are very new. Not surprisingly, many Article 5 Parties (A5 Parties) have expressed concerns over factors such as availability, cost-effectiveness, safety, applicability in high-ambient-temperature environments, and maintenance requirements particularly because, in many cases, these countries are just beginning the process of phasing out hydrochlorofluorocarbons (HCFCs).

This report summarises: 1) the latest state of knowledge of the availability and characteristics of current alternatives to HFCs in the key sectors, 2) a discussion of barriers to their uptake and how the barriers can be overcome, 3) the crucial issue of the energy efficiency of HFC-using systems and their alternatives and 4) the potential for accessing financial support for the replacement of HFCs.

The objective is to provide information that will allow decision makers, and particularly ozone officers, to tackle the growing global threat to the Earth's (atmosphere).

The Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) has organizations in place to assess science, environmental effects, and technology; to educate the public and policy-makers; to build regulatory capacity and train service technicians; and to select, finance, and implement next-generation alternatives to most remaining uses of HCFCs and HFCs.

The case studies presented in the report show that high-GWP HFCs can be and are being successfully replaced in a wide range of uses in both A5 and non-A5 Parties. Given the progress of the introduction of energy-efficient lower-GWP HFC alternatives and the gradual spread of national and regional regulations and voluntary industry commitments, more and more countries committed to mitigating climate change will need to address the question of how to phase down the use of HFCs, regardless of whether the Montreal Protocol is amended to control HFCs.

Opportunities exist for both A5 and non-A5 Parties to reduce high-GWP HFCs used to manufacture new refrigeration, air conditioning, fire protection, aerosol, and miscellaneous products at the same time as HCFCs are phased out. Once the production of new products depending on high-GWP HFCs is halted, use can be limited to servicing existing equipment. The cost of retrofitting or replacing existing equipment may be too high to be cost-effective in the short term, although energy savings and increased reliability can offset enough cost to make replacement of obsolete equipment worthwhile.

The report finds that in product manufacturing, technology is already available to phase down high-GWP HFCs in most applications in the foam, domestic, commercial and industrial refrigeration, and solvents sectors.

Many technologies exist to replace high-GWP alternatives in stationary air conditioning, especially in the commercial and industrial sector. However, domestic air conditioning may present challenges that require immediate attention. It is expected that A5 parties will want to demonstrate the

[2] Contact Dr. Nancy Sherman, Director of Technical Assessment (nsherman@IGSD.org).

feasibility and ascertain local costs of new hydrofluoroolefins (HFOs) and blends, and, in the case of flammable solutions, A5 countries would need to first set new standards and train technicians, even for small air conditioning charges. Some countries, including China, India, Indonesia, and Japan, are championing the safe use of flammable hydrocarbon (HC)-290 and HFC-32 refrigerants in room air conditioners (A/Cs).

0.1 Specific alternatives to high-GWP HFCs suitable for A5 Parties

A5 Parties—if adequately financed for the added first cost, training and safety requirements (and, in some cases, the ongoing added cost of servicing)—have a wide choice of immediately available technologies that can eliminate, with few exceptions, high-GWP HFCs in MACs, domestic and commercial refrigeration, building air conditioning chillers, and thermal insulating foam. A5 Parties will want to implement next-generation choices that achieve high energy efficiency and reliability at local ambient temperatures.

A5 Parties can be market leaders in the safe use of flammable solutions by setting appropriate safety standards and properly training technicians, while non-A5 Parties may be followers because existing standards prohibiting all flammable refrigerants are entrenched in standards organizations where change comes only slowly (though clearly, appropriate safety standards are needed in every market).

A5 Parties, including China and India, with the ability to train and enforce safe practices in the manufacture, installation, service and disposal of room air A/Cs using flammable refrigerants, and with the technical and administrative ability to put safety regulations in place rapidly, can move quickly to replace room A/Cs containing HCFC-22 and HFC-410A with room A/Cs manufactured with HC-290, HFC-32, and HFC/HFO blends. Because HC-290 and HFC-32 refrigerants are flammable, installation should only occur in cases where the charge is large enough to cool the room on the hottest days, but small enough to be safe if discharged into the occupied room.

The vast majority of A5 Parties do not manufacture HCFCs or HFCs or products containing these substances. For these Parties, high-GWP HFCs are mostly contained in new imported equipment or are used for servicing new and existing equipment. The opportunity exists to import only energy-efficient low-GWP products; thereby avoiding the infrastructure and training that would otherwise be necessary to support already obsolete high-GWP HFC technology. Actions such as prior informed consent, environmental trade barriers and strong customs controls and regulations may be necessary to prevent the dumping in A5 Parties of obsolete high-GWP HFC products that require expensive new infrastructure.

A5 Parties can make a second transition and replace HFC-134a in the manufacture of new MACS with HFO-1234yf, the cost of which is marginal when compared with the cost of the car, or can wait for HFC-152a or carbon dioxide (CO_2) systems to be commercialized and proven energy efficient and reliable. Because HFO-1234yf systems can be recharged at service with HFC-134a, the full life-cycle climate benefits are only realized if vehicle owners, service technicians, and government authorities insist that the systems be recharged only with HFO-1234yf. It is not currently technically feasible to retrofit automobiles with HFC-134a systems to use HFO-1234yf.

0.2 Specific alternatives to high-GWP HFCs suitable for non-A5 Parties

Non-A5 Parties—with the advantages of easily-available financing and well-trained, equipped and disciplined service sectors—have a wide choice of immediately available technology that can eliminate, with few exceptions, high-GWP HFCs in motor vehicle air conditioning (MACs), domestic and commercial refrigeration, building air conditioning chillers, and thermal insulating foam. The European Union (EU) HFC phase-down schedule is indicative of the reductions all non-A5 regions can take.

Although the additional cost of HFO-1234yf vehicle air conditioning is small compared to the cost of new automobiles, it may be fair and reasonable to provide incentives such as rebates or sales tax reductions at the time of purchase or to secure agreements from chemical suppliers and automobile manufactures to provide extended warranties for A/C service.

0.3 Flexible manufacturing facilities allow rapid future transition

Room A/C manufacturers in both A5 and non-A5 Parties can design their facilities to safely use a wide range of possible future refrigerants by anticipating that next-generation refrigerants will be either more flammable and/or require higher operating pressures than HCFC-22. For example, room A/C manufacturers in A5 Parties that choose to convert initially from HCFC-22 to HFC-410A, due to strict Montreal Protocol compliance needs, and then later make a second transition to lower-GWP options, can insist that the Multilateral Fund (MLF) finance appliance filling facilities and refrigerant storage areas to be suitable for all of the foreseeable technical options. Chemical manufacturers and safety authorities can cooperate with OzonAction, the MLF and Montreal Protocol implementing agencies to specify the factory designs.

0.4 Stringent environmental screening and safety precautions

Parties will want to choose technology that has satisfied stringent environmental screening for toxicity and acceptable atmospheric fate and will want to implement appropriate safety precautions for flammable and/or toxic substances. It will be prudent to check the technologies listed as acceptable by the US Environmental Protection Agency (EPA) Significant New Alternatives Policy Program (SNAP) and the EU's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation. It will be prudent to implement only technology proven safe, energy efficient, and affordable in case studies and reports of demonstration projects published by reputable independent organizations such as the Climate and Clean Air Coalition (CCAC) to Reduce Short-lived Climate Pollutants, the MLF and its implementing and bilateral agencies, UNEP, and the Montreal Protocol Technology and Economic Assessment Panel (TEAP) and its Technical Options Committees (TOCs). Parties and companies may consider contacting the experts listed on the case studies to ask if superior alternatives have emerged and to request advice on suppliers, installations, and service.

0.5 Best proof of technical and economic feasibility and market acceptance

Some of the best technical and economic information on alternatives and substitutes to high-GWP HFCs will come from projects undertaken for Parties by the MLF and its implementing and bilateral agencies where the actual costs, including those for refrigerant and foam blowing substances, will be transparently listed and where experience with the new technology will be faithfully and honestly shared through the networks.

0.6 Financial solutions

With additional funding to expeditiously restructure the HCFC phase-out to enable a leapfrogging of high-GWP HFCs, A5 Parties could have wider choices in foams, refrigeration, air conditioning, and other uses. National, regional, and international regulations, industry leadership, voluntary agreements, and technical innovation are driving change. The research and development pipeline is full and new alternatives are rapidly being commercialized.

However, costs beyond those normally financed by the MLF would be incurred, and therefore, additional funds will be necessary to build capacity, to train technicians to maintain and service products that contain flammable alternatives, to set new standards to allow for the introduction of new technology, to cover the operational costs of the new technologies (HFOs and blends), and to strengthen networks linking chemical companies, appliance manufacturers, technicians, and end-users. It will also be necessary to demonstrate and report the performance of next-generation technology when applied to A5 Parties, particularly in locations with long seasons of high ambient temperatures.

The simplest solution to financing ‘agreed incremental costs’ is replenishment of the MLF to take on 1) the added cost of leapfrogging high-GWP HFCs in the phase-out of HCFCs; 2) the added cost of a second transition from HFCs in applications like MACs that already use HFCs; and 3) the added cost of a two-stage transition, first from HCFCs to HFCs and then from HFCs to next-generation technology in applications where implementing HFCs is too far along to turn back. Parties could decide to make financing available immediately for A5 Parties choosing to go beyond compliance.

A second solution is to establish an expanded source of financing from non-A5 contributions as grants, provided the MLF Executive Committee welcomes and approves this co-financing and eases any administrative requirements that would prevent A5 Parties and enterprises from adopting measures justified by the climate, clean air, and natural resource benefits of higher energy efficiency.

A third solution is for A5 Parties to separately seek financing from sources other than the MLF for the HFC phase-down and energy efficiency improvements and to coordinate that funding with the HCFC phase-out schedule. However, the national ozone units in most A5 Parties are accustomed to having a ‘one-stop window’ for international financing that relates to ozone depletion, and are not well prepared (given, in general, their lack of knowledge of other financing institution or mechanisms) to access funds from the international financial institutions or funds that support energy-efficiency investments and clean energy projects, which are described in the full report. Some A5 parties have shown a preference to use government and private sector finance at the national level for the non-eligible portion of Montreal Protocol projects, rather than seek co-finance from international climate and aid organizations.

Unlike the ozone-depleting substance (ODS) phase-out, where transition costs were mostly in the manufacturing sector, products such as MACs built with the current choice of HFO-1234yf refrigerant, will increase the cost of new air-conditioned cars and the cost of service over the lifetime of the vehicle. It should also be borne in mind that some technologies are already cost effective for MLF finance, while other technologies have not yet achieved economies of scale or competitive cost.

1 Introduction

Before 1930, air conditioning was rare, and refrigeration was accomplished using naturally harvested and ice manufactured with refrigerants that were all flammable, toxic or both. After the invention of chlorofluorocarbons (CFCs) in 1928, most refrigeration and air conditioning applications transitioned from toxic and flammable refrigerants to CFCs and HCFCs, with some continuing use of ammonia for food processing, cold storage, ice making and ice rinks.

After the entry into force of the 1987 Montreal Protocol, approximately 85 per cent of the products that would have been made with or containing ODSs transitioned to not-in-kind (NIK) options, including natural refrigerants (primarily hydrocarbons, ammonia, and CO_2), with about 15 per cent choosing fluorocarbon (HFC) substitutes. Today, non-A5 Parties that previously chose to transition from ODSs to HFC refrigerants are transitioning to HFOs, natural refrigerants, and NIK alternatives (e.g. electromagnetic refrigeration, non-refrigerated (natural) food preservation, and landscaping and architecture that provides comfort without air conditioning).[3]

During the industrial revolution until the 1940s, asbestos was the predominant insulation material for both industrial and residential insulation. In the 1940s and 1950s, mineral wool overtook asbestos in sales and, in the 1970s, the rediscovery of the harmful health effects of asbestos and an increased concern over energy scarcity shifted sales to other forms of insulation, including fibreglass and foam, which was invented in 1948 but previously had been too expensive to compete.[4] Now there is a shift to safe natural insulation and to foam made with natural foam-blowing agents such as CO_2 and hydrocarbons.

HFCs are manufactured chemicals used as substitutes for ODSs in applications such as refrigeration and air conditioning, foams, solvents, fire protection and aerosol products. The current phase-out of ODSs under the Montreal Protocol, together with the growing global demand for air conditioning and refrigeration, especially in emerging economies, is accelerating the production, use and emissions for HFCs. Unlike the CFCs and HCFCs which they often replace, HFCs do not deplete the ozone layer, but some are very powerful greenhouse gases (GHGs), trapping up to thousands of times more heat in the atmosphere per unit of mass than CO_2. Their rapid rate of increase has the potential to contribute significantly to climate change.

The Vienna Convention and its Montreal Protocol control the *production and consumption* of ozone-depleting substances (except N_2O)[5], while the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol control *emissions* of GHGs including ozone-depleting N_2O.[6] Once produced, *emissions* of ODSs are not controlled by the Montreal Protocol or the Kyoto Protocol. Each treaty is responsible for *accounting and reporting* of their controlled substances. Over the last few years, proposals have been put forward for HFC production and consumption to be controlled under the Montreal Protocol as a complement to HFC emission controls and GHG reporting under the Kyoto Protocol.

The Montreal Protocol is widely acknowledged to be the world's most effective environmental treaty. Under its controls, 98 per cent of the production and consumption of ODSs have been phased out. The ozone layer is projected to recover to its pre-Antarctic ozone hole state over the next 50 or so years and to its pre-industrial state in about 500 years.[7] At the same time, the Montreal Protocol has also made

[3] Andersen, S. O., M. L. Halberstadt, & N. Borgford-Parnell (2013) *Stratospheric Ozone, Global Warming, and the Principle of Unintended Consequences—An Ongoing Science and Policy Success Story*, Journal of the Air & Waste Management Association (AWMA), Critical Review.
[4] Bozsaky, D. (2010) *The historical development of thermal insulation materials*, Periodica Polytechnica Architecture 41(2):49-56, doi: 10.3311/pp.ar.2010-2.02. *See also* Dow Chemical, *Building Insulation: The Historical Pursuit of Survival, Comfort, and Efficiency*, http://www.dowconstructionchemicals.com/na/en/feature-info/fast-facts0111.htm.
[5] Substances controlled by the Montreal Protocol include CFCs, halons, HCFCs, methyl chloroform, hydrobromofluorocarbons (HBFCs), bromochloromethane, and methyl bromide.
[6] Substances controlled by the Kyoto Protocol include carbon dioxide (CO_2) and five non-CO_2 greenhouse gases: HFCs, N_2O, methane (CH_4), sulphur hexafluoride (SF_6) and perfluorocarbons (PFCs).
[7] Velders G. J. M, Ravishankara A. R., Miller M. K., Molina M. J., Alcamo J., Daniel J. S., Fahey D. W., Montzka S. A., & Reimann S. (2012) *Preserving Montreal Protocol Climate Benefits by Limiting HFCs*, SCI. 335:922-923.

a major contribution to slowing the rate of global warming because almost all ODSs, including CFCs and HCFCs, are powerful GHGs, typically far more powerful even than HFCs. For example, replacing CFC-12 (IPCC Assessment Report (AR5) $GWP_{100\text{-}yr}$ = 10,200)[8] with its typical substitute HFC-134a (AR5 $GWP_{100\text{-}yr}$ = 1,300) reduces the warming impact from refrigerant emissions by almost 800 per cent.

Unfortunately, the rapidly increasing scale of new HFC refrigerant and foam-blowing demand may cancel the overall climate benefits of the CFC and HCFC phase-outs and casts a significant shadow over the Montreal Protocol's climate protection success story. Meanwhile, effective action to tackle climate change is becoming ever more urgent as accumulated GHGs in the atmosphere increase global temperature rise beyond the internationally agreed target of two degrees Celsius.

The climate benefits of the Montreal Protocol could be significantly offset by projected emissions of HFCs used to replace ODSs

The Montreal Protocol and its amendments and adjustments have made large contributions toward reducing global greenhouse gas emissions. In 2010, the decrease of annual ODS emissions under the Montreal Protocol is estimated to be about 10 gigatonnes of avoided CO_2-equivalent emissions per year, which is about five times larger than the annual emissions reduction target for the first commitment period (2008 - 2012) of the Kyoto Protocol (from the Executive Summary of the *Scientific Assessment of Ozone Depletion: 2010*).

- The sum of the hydrofluorocarbons (HFCs) currently used as ODS replacements makes a small contribution of about 0.5 gigatonnes CO_2-equivalent emissions per year. These emissions are currently growing at a rate of about 10 - 15 percent per year in developed countries where refrigeration and air conditioning is expanding in use and 7 percent per year in developed countries where ownership is already high. Without controls, HFC emissions are projected to continue to grow.
- If the current mix of these substances is unchanged, increasing demand could result in HFC emissions of up to 8.8 gigatonnes CO_2-equivalent per year by 2050, nearly as high as the peak emission of CFCs of about 9.5 gigatonnes CO_2-equivalent per year in the late 1980s (This is equivalent to about 45 percent of the fossil fuel and cement emissions of CO_2 in the late 1980s).
- Replacements of the current mix of high-Global Warming Potential (GWP) HFCs with low-GWP compounds or not-in-kind technologies would essentially avoid these CO_2-equivalent emissions.

*GWP-weighted emissions, also known as CO_2-equivalent emissions, are defined as the amount of gas emitted multiplied by its 100-year Global Warming Potential (GWP).

Source: *Montreal Protocol Scientific Assessment Panel: 2014* (Assessment for Decision-Makers), WMO Global Ozone Research and Monitoring Project—Report No. 56, 10 September 2014, Geneva.

To date, HFCs account for less than 1 per cent of the total contribution to global warming. However, production and emissions of HFCs are rising nationally and globally at a rate of up to 10 - 15 per cent per year, which would be a serious new climate threat if unabated, adding up to 0.5°C of warming by 2100.[9] HFCs and other fluorinated GHGs, which include sulphur hexafluoride (SF_6)

[8] This paper uses the latest estimates of global warming potential (GWP) from the Intergovernmental Panel on Climate Change Fifth Assessment Report—indicated as 'AR5" in the text. GWP is a measure of climate forcing over a specified time period relative to the reference chemical carbon dioxide, which is assigned the value of 1.

[9] Xu Y., D. Zaelke, G. J. M. Velders, & V. Ramanathan (2013) *The Role of HFCs in Mitigating 21st Century Climate Change*, Atmos. Chem. Phys. 13: 6083-89; *see also* Hare B., M. Scheaffer, M. Rocha, J. Rogelj, N. Hokne, K. Blok, K. van der Leun, & N. Harrision (2012) Closing the 2020 Emissions Gap: Issues, options and strategies, Climate Analytics; *and* Ramanathan V. *&* Y. Xu (2010) *The Copenhagen Accord for Limiting Global Warming: Criteria, Constraints, and Available Avenues*, Proc. Nat'l Acad. Sci. USA 107: 8055–62 (the Ramanathan and Xu study was the first to model the climate benefit of HFC mitigation in combination with SLCPs, CO_2 and other long-lived greenhouse gases).

and perfluorocarbons (PFCs), are already the fastest growing climate pollutants in many countries, including Australia, China, the EU, India and the US.[10] Without fast action, HFC forcing will increase as much as thirty-fold by 2050, from a forcing of 0.012 W/m2 to as much as 0.40 W/m2.[11]

The significant environmental impact of rising HFC emissions resulting from the ODS phase-out and high rates of growth in air conditioning and refrigeration products has prompted calls for the introduction of production and consumption controls for these substances under the Montreal Protocol, even though they are not ODSs. Emissions of HFCs presently fall only under the purview of the 1992 UNFCCC and are explicitly listed under its 1997 Kyoto Protocol. They are not, however, subject to any specific requirements under the climate regime and are unlikely to be in the near future.

A Global Response to HFCs Through Fair and Effective Climate and Ozone Policies, a paper published by Chatham House in July 2014, provides a comprehensive overview of the topics and arguments around this issue.[12] One of the key questions to address is the immediate and near-future availability of substitutes for HFCs—not just the existence of substitutes, but their efficacy, price and cost-effectiveness, safety, environmental impacts, technical performance and applicability at high ambient temperatures.

Participants at the Chatham House workshop in April 2014 and the Chatham House / IGSD side event during the July 2014 meeting of the Montreal Protocol Open-Ended Working Group (OEWG) discussed a series of steps necessary to simultaneously implement an HCFC phase-out and an HFC phase-down in A5 Parties,[13] including:

- Immediate MLF financing of integrated HCFC phase-out and HFC phase-down management plans;
- Openness to allowing essential-use exemptions (EUEs) or other flexibility mechanisms for the temporary use of HCFCs in order to avoid high-GWP HFCs;
- MLF and bilateral demonstration projects to confirm the technical performance and cost of alternatives;
- A fresh look at, and appropriate restructuring of, MLF guidelines to restore the original philosophy of full financing of agreed incremental costs, including prices of any alternatives protected by process and application patents; and
- A commitment by non-A5 Parties to finance whatever costs are necessary to accomplish the A5 HCFC phase-out and HFC phase-down, including an increase in the 2015 - 2018 replenishment of the MLF to finance increased energy efficiency and the avoidance of HFCs.

A key issue underlying all of these steps, however, is the availability of alternatives to HFCs. The Montreal Protocol TEAP has produced reports on alternatives to high-GWP ODS alternatives since 1999, including a TEAP Task Force and a joint workshop with the Intergovernmental Panel on Climate Change (IPCC) in 1999 and a Special Report with the IPCC in 2005. These reports have generated considerable discussion among the Parties and affected industries. In addition, many industry associations, as well as regional and national governments, have undertaken comprehensive assessments of technical alternatives to high-GWP HFCs. The result is a large volume of material, often written in technical language and relatively inaccessible to the non-technical reader.

[10] The EDGAR database presents detailed HFC emissions from available sources: http://edgar.jrc.ec.europa.eu/overview.php?v=42FT2010.

[11] Velders G. J. M, A. R. Ravishankara, M. K. Miller, M. J. Molina, J. Alcamo, J. S. Daniel, D. W. Fahey, S. A. Montzka, & S. Reimann (2012) *Preserving Montreal Protocol Climate Benefits by Limiting HFCs*, SCI. 335:922-923.

[12] Andersen, S. O., D. Brack, & J. Depledge (2014), *A Global Response to HFCs Through Fair and Effective Climate and Ozone Policies* (Chatham House).

[13] Under the Montreal Protocol, 'Article 5 Parties' are Parties to the Protocol that in 1987 (when the Protocol was signed) were listed as 'developing' by the United Nations and consumed less than 0.3 kilograms of CFC per capita. Since 1987, the Parties to the Montreal Protocol have listed some additional Parties under Article 5. Countries defined in 1987 as non-Article 5 Parties include developed countries, and developing countries consuming more than 0.3 kilograms of CFC per capita.

This paper aims to give a concise and accessible picture of the current availability of alternatives to high-GWP HFCs in their main uses, with the goal of better informing the debate over the future of HFCs. The paper consolidates, updates, and sharpens the findings of earlier assessments. Several case studies are included that describe how select A5 and non-A5 Parties are already successfully avoiding and/or phasing down high-GWP HFCs.

The report builds on the excellent work of the TEAP and its TOCs and task forces, as well as on assessments developed in support of MLF HCFC phase-out projects, and voluntary and regulatory initiatives and bilateral agreements in Australia, California, China, Denmark, the EU, India, the US, and elsewhere. Some of the information comes from publically available reports of the MLF's Implementing Agencies, many of which also have responsibility and expertise in energy efficiency and climate protection. In addition to assessment documents, we have relied on the most recent information from technical conferences, including workshops organised over the last several years on the sidelines of the OEWG and meetings of the Parties (MOPs). Annex 5 lists the eight recent assessments that have proved most valuable to this report; footnotes document the sources of the findings on technical and economic feasibility.

This paper is a continuous work in progress; we aim to update it over time to add the latest information on emerging technologies. Corrections and additions should be sent to Dr Nancy Sherman, Director of Technical Assessment, IGSD (nsherman@IGSD.org).

2 Regional and National Approaches to Phasing Down HFCs

Although effective international controls do not yet apply to HFC production, consumption or emissions, a number of countries and regions have already adopted domestic commitments and regulations to reduce the production, use and/or emissions of HFCs, and many industry associations and corporations are implementing voluntary policies to avoid and eliminate these chemicals.

In Spring 2014, for example, the new EU Fluorinated Gases (F-Gas) Regulation entered into force, and will apply fully from 1 January 2015. This replaced the 2006 regulation, which targeted only containment, including the control of leaks, proper servicing of equipment, and recovery of the gases at the end of the equipment's life. The new regulation will phase down 79 per cent of GWP-weighted HFC use by 2030, from the baseline 2009 - 12 levels, with interim reduction steps starting in 2015. The use of HFCs with a GWP greater than 150 will be banned in new equipment in a number of sectors, including commercial refrigeration (with some exceptions) and foams. From 2020, very high-GWP HFCs will no longer be allowed to service and maintain certain refrigeration equipment. The regulation also stipulates that importers and producers within the EU will have to provide evidence that HFC-23, produced as a by-product in the production of HCFC-22, is either destroyed or recovered for subsequent use.

In addition, the EU Directive on MACs (the MAC Directive), adopted in 2006, prohibits the use of F-gases with a GWP of more than 150 in 'new types' of automobiles sold in the EU from 2011 and in all new automobiles sold in the EU from 2017.[14] Taken together, EU policies on fluorinated gases (including HFCs) are projected to reduce 1.5 Gt CO_2-eq emissions by 2030, and more than 5 Gt CO_2-eq by 2050, compared with a business-as-usual (BAU) scenario.

The limits set in the EU regulation as presented in Table 2.1 illustrate currently feasible GWP targets with timetables that were negotiated with industry and established by law. For example, the table shows that only refrigerants with GWP<150 are allowed for the manufacture of refrigerators and freezers by 2015, for motor vehicles by 2017, aerosol products by 2018, extruded polystyrene foam by 2020, stationary commercial refrigeration by 2022 (with exceptions) and most foam products by 2025. Room A/C refrigerants will have a GWP limit of less than 750 by 2025.

[14] Under EU regulations, 'new type' vehicles generally have a new 'platform' or are otherwise significantly redesigned. Costs of environmental compliance are lower when significant technology upgrades are synchronized.

Table 2.1: EU GWP Timelines

	GWP<150	GWP<750	GWP<2500	No GWP limit
Household refrigerators and freezers	2015			
Motor vehicle air conditioning	2017			
Convenience technical aerosol products	2018			
Extruded polystyrene	2020			
Stationary commercial refrigeration	2022*		2020	
Room air conditioning		2025		
Foam products**	2025			
Exempted foam/MDI and other essential medical and technical aerosol products				No deadlines

* The GWP limit for commercial refrigeration is only for rack systems >40kW with exceptions for low-temperature refrigeration and for HFC with GWP < 1500 for the primary loop of cascade systems.

** Some foam products are currently indefinitely exempt.

In the US, the Climate Action Plan announced by President Barack Obama in June 2013 set out a number of measures to address HFCs. It is estimated that eliminating certain HFCs could provide 23 per cent of the emissions reductions needed to achieve the US 2020 GHG reduction goal of 17 per cent below 2005 emissions.[15] The Action Plan includes the use of the EPA SNAP regulation, established to evaluate and regulate alternatives and substitutes to ODSs. The SNAP programme publishes lists of acceptable and unacceptable substitutes; new rules are expanding the list of low-GWP alternatives, while other rules are revoking approval of specific HFCs for particular end uses, changing the listing from acceptable to unacceptable.

In addition, the US Corporate Average Fuel Economy (CAFE) standards encourage automobile manufacturers and importers to replace HFC-134a in MACs by allowing companies to earn credits toward fuel efficiency standards by replacing HFC-134a with low-GWP alternatives in MACs. The EPA also runs the GreenChill partnership with food retailers to reduce refrigerant emissions and their impact on the ozone layer and climate change. In addition, the US government is aiming to purchase cleaner alternatives to HFCs whenever feasible and to transition over time to equipment that uses safer and more sustainable alternatives.

Regulations banning use, prohibiting venting, and taxing HFCs or promoting alternatives to HFCs are also in place in many other countries, including Austria, Belize, Burkina Faso, Canada, Colombia, Denmark, Egypt, France, Germany, Italy, Macedonia, Montenegro, Netherlands, New Zealand, Norway, Poland, Serbia, Slovenia, Sweden, Switzerland, United Kingdom, and Yemen.[16] For example:

- Austria: ban on almost all HFC uses in new equipment; fiscal incentives for HFC-free alternatives.
- Canada: federal and provincial regulations prohibit the release of HFCs from refrigeration and air conditioning equipment. The regulations are supported by a Refrigeration Code of Practice that outlines best practices to minimize and eliminate emissions in the cooling sectors.

[15] Bianco N., F. Litz, K. Meek, & R. Gasper (2013), Can the U.S. Get There from Here?: Using Existing Federal Laws and State Action to Reduce Greenhouse Gas Emissions, World Resources Institute, 3–4.

[16] United States (2014) Submissions by Parties on the Implementation of Decision XIX/6, UNEP/OzL.Pro.WG.1/34/INF/4/Add.2. 30 June: http://conf.montreal-protocol.org/meeting/oewg/oewg-34/presession/Background%20Documents%20are%20available%20in%20English%20only/OEWG-34-INF4-Add2.pdf.

A new government/industry consultation will soon begin on how best to strengthen HFC management and phase-down of production and consumption.

- Denmark: ban on almost all HFC uses; containment (leak/emission prevention); tax on HFCs; promotion of HFC-free alternatives.
- Japan: phase-down of HFCs, promotion of low-GWP equipment and products, improved containment in commercial equipment, and registration and approval of fillers and recyclers.
- Norway: tax/refund scheme for HFCs.
- Serbia: import and export licensing and reporting for HFCs (GWP >150); ban on sale of certain equipment/products that rely on F-gases; containment and mandatory gas recovery; record-keeping.
- Switzerland: ban on many HFC uses; emission reduction measures for remaining HFC uses; disincentives for new uses of HFCs; promotion of HFC-free alternatives; reports on HFC imports.

Recent years have also seen an increasing trend of major companies and industry associations adopting voluntary commitments to environmentally sustainable sourcing and behaviour. In 2010, for example, the Consumer Goods Forum (CGF), a global industry network of more than 400 retailers, manufacturers and service providers, adopted a commitment for its member companies to start, by 2015, phasing out HFCs in refrigeration. The CGF also agreed to work on public policy and regulatory barriers, in particular in the US, to facilitate the collection of performance metrics and methodologies to create 'one source of truth' for HFC-free technologies, and to demonstrate progress among its member companies, with the aim of encouraging others.[17]

There are many examples of individual companies—including AEON, Carrefour, Coca-Cola, Danfoss, Heineken, Nestlé, and Unilever—adopting commitments not to use HFCs in new equipment and to phase out the use of HFCs in existing equipment. On 16 September 2014 (International Ozone Day), a dozen US and multinational companies made a variety of pledges to phase down and replace HFCs and to commercialize alternatives and substitutes.

In September 2014, at the UN Secretary-General Ban Ki moon's Climate Summit, many countries and companies announced further pledges to reduce use and emissions of HFCs and 33 state partners of the CCAC were joined by numerous companies and organizations including the California Air Resources Board (ARB), the World Meteorological Organization, and Refrigerants Naturally! in pledging to 'promote public procurement of climate-friendly low-global GWP alternatives whenever feasible and gradually transition to equipment that uses more sustainable alternatives to high-HFCs.'[18]

The broader international arena is also seeing increasing support for the accelerated reduction of HFCs. At the 'Rio + 20' UN Conference on Sustainable Development, more than one hundred heads of state adopted the conference declaration, *The Future We Want*, recognizing the climate threat from HFCs and calling for the gradual phase-down of their production and consumption;

[17] Consumer Goods Forum, Refrigeration, http://sustainability.mycgforum.com/refrigeration.html (last visited 3 November 2014); *and* Refrigerants, Naturally!, http://www.refrigerantsnaturally.com/ (last visited 3 November 2014).

[18] CCAC, *UN Climate Summit commitments to reduce short-lived climate pollutants, and their impacts*, http://www.unep.org/ccac/Events/UNClimateSummit2014/ActionStatementSupport/tabid/794296/Default.aspx (last visited 3 November 2014). The full text of the pledge states: 'We, the supporters of this Joint Statement, support an amendment to phase down the production and consumption of hydrofluorocarbons (HFC) under the Montreal Protocol, while emissions accounting and reporting remains under the United Nations Framework Convention on Climate Change (UNFCCC) and we will work with others to begin formal negotiations in 2014. We will take action to promote public procurement of climate-friendly low-global warming potential (GWP) alternatives whenever feasible and gradually transition to equipment that uses more sustainable alternatives to high-GWP HFCs. We welcome complementary private sector-led efforts, including a Global Cold Food Chain Council to reduce the use and emissions of high-GWP HFCs and enhance energy efficiency in the cold food chain while minimizing food spoilage, and a Global Refrigerant Management Initiative on HFCs in servicing with a goal of reducing global emissions by 30 - 50 percent within 10 years.'

the UN General Assembly adopted the declaration by resolution in September 2012.[19] At the G20 St Petersburg Leaders' Summit in 2013, member countries agreed to use '…the expertise and the institutions of the Montreal Protocol to phase down the production and consumption of HFCs, based on the examination of economically viable and technically feasible alternatives' and to 'continue to include HFCs within the scope of UNFCCC and its Kyoto Protocol for accounting and reporting of emissions.'[20]

There are also recent bilateral agreements between the US and China and the US and India that support action on HFCs using the institutions of the Montreal Protocol while simultaneously cooperating on technology that can avoid and replace HFCs.

The combined effect of these diplomatic, market, and regulatory measures is to encourage the rapid development and commercialization of alternatives to HFCs, and to reduce or close off consumer markets to HFCs and HFC-containing equipment—a matter of significance to major exporters of this technology even if HFC use is not controlled in the countries where equipment made with or containing HFCs is manufactured.

Environmental and technical non-governmental organizations (NGOs) are actively supporting the HFC phase-down with catalogues, case studies, and policy advice. For example, Chatham House has published a guide to HFC amendment and regulatory design;[21] the Environmental Investigations Agency (EIA) with Shecco has produced a comprehensive catalogue of natural refrigerant alternatives;[22] the CEEW, IGSD, NRDC and The Energy and Resources Institute (TERI) have published the business case for an HFC phase-down in India;[23] UNEP and the European Commission (DG Climate Action) have published a guide to removing A5 Party barriers to low-GWP refrigerants;[24] and The Climate and Clean Air Coalition (CCAC) has published case studies of low-GWP HC, CO_2, and HFO alternatives in Commercial Refrigeration.[25] Furthermore, TEAP and its TOCs are receiving increasingly clear instructions to better assess sustainable alternatives to ODSs that have lower-GWP and higher energy efficiency.

3 Available Alternatives

This section summarises recent information on the availability of alternatives to high-GWP HFCs in large consumption sectors.

TEAP reports are the starting point for any assessment of alternatives to ODSs and HFCs. It is expected that all assessments of alternatives to high-GWP HFCs will come to similar conclusions, particularly because there is significant overlap in the membership of the assessment teams. However, it is increasingly important to catalogue and assess the latest information directly from the marketplace on a real-time basis. Furthermore, when TEAP started its work in 1988, most of

[19] United Nations (2012) Resolution adopted by the General Assembly: The Future We Want, A/res/66/288 ('222. We recognize that the phase-out of ozone-depleting substances is resulting in a rapid increase in the use and release of high global-warming potential hydrofluorocarbons to the environment. We support a gradual phase-down in the consumption and production of hydrofluorocarbons.').

[20] G-20 (2013) Leaders' Declaration, para. 101.

[21] Andersen, S. O., D. Brack, & J. Depledge (2014), *A Global Response to HFCs Through Fair and Effective Climate and Ozone Policies* (Chatham House).

[22] EIA (Environmental Investigation Agency) & Shecco (2014) Putting the Freeze on HFCs: A Global Digest of Available Climate-Friendly Refrigeration and Air-Conditioning Technologies, Washington DC & London, July.

[23] Stephen O. A., P. S. Chidambaram, B. Deol, D. Doniger, A. Ghosh, A. Jaiswal, R. Palakshappa, J. Schmidt, & G. Sethi (2013) Cooling India with Less Warming: The Business Case for Phasing Down HFCs in Room and Vehicle Air Conditioning, Council on Energy, Environment & Water (CEEW), the Institute for Governance & Sustainable Development (IGSD), the Natural Resources Defense Council (NRDC), and The Energy and Resources Institute (TERI) in cooperation with the Confederation of Indian Industry (CII).

[24] UNEP & EC (2010) Barriers to the Use of Low-GWP Refrigeration in Developing Countries & Opportunities to Overcome These, ISBN 978-92-807-3124-8.

[25] CCAC (2014) Low-GWP Alternatives in Commercial Refrigeration: Propane, CO_2 and HFO Case Studies, UNEP publication DIT-1666PA.

the new technology was invented and first implemented in non-A5 Parties, but now the centres of engineering excellence are increasingly located in A5 Parties. In addition, A5 Parties are less encumbered by obsolete and out-dated standards, regulations and investments in already built systems that tend to slow the introduction of new technology, which allows A5 Parties to be first to innovate and implies an increasing need for South-South and South-North cooperation.

Moreover, TEAP has not been instructed to elaborate options to avoid ODSs and HFCs in areas such as architectural design that minimizes heating and cooling, insulating materials that are not foam, absorption refrigeration and air conditioning systems, district heating and cooling, and cooling systems based on cold seawater to replace HCFC- and HFC-based A/Cs. For example, the Maldives and Colombia are both undertaking district cooling projects co-financed by the MLF, the private sector and the CCAC.[26]

Taken together, available TEAP and other comprehensive assessments provide detailed information on most alternatives, with some exceptions, including that HFC-152a (AR5 $GWP_{100\text{-yr}}$ = 138) is generally neglected for MACs, methyl formate and methylal (both AR5 $GWP_{100\text{-yr}}$ = ~0) are generally neglected for foam, and the market penetration of HFC-32 in room A/Cs is generally underestimated.

Energy-efficient, low-GWP alternatives that are more costly often struggle to compete with business-as-usual HFC choices. However, national, regional, and international regulations and voluntary industry and consumer leadership play a critical role in the development of energy-efficient, low-GWP alternatives by banning some chemicals and setting standards for others that create effective market incentives. This is illustrated by the 1987 Montreal Protocol, which started with a modest ambition of just 20 per cent reduction in CFCs by July 1993, and 50 per cent by July 1998 and a freeze in halons three years after the Protocol's entry into force. The Protocol was then strengthened with amendments that added controlled substances and adjustments that accelerated the phase-out as new technology was developed and commercialized in response to the Protocol's schedules and ambitious country and industry goals.

3.1 Foams

Most HCFC consumption in A5 Parties is for the manufacturing of foam, refrigeration, and air conditioning products and the servicing of refrigeration and air conditioning equipment, with only a small fraction of total consumption for other HCFC consumption sectors including solvents, aerosols, and fire protection. HCFCs are used as foam blowing or expansion agents, which reduce density and increase thermal and acoustical insulating properties of polymeric foam. HFCs used in the foam sector include HFC-245fa and HFC-365mfc (frequently blended with small quantities of HFC-227ea to reduce flammability, e.g. 87 per cent HFC-365mfc and 13 per cent HFC-227ea)[27]. These HFCs used in foam-blowing typically have higher GWPs than the chemicals they are replacing, such as HCFC-141b.

Alternatives are available that would allow A5 Parties to leapfrog high-GWP HFCs in foam and enable developed countries to phase down HFC foams. Fortunately, large enterprises in A5 Parties have co-financed the high cost of safety systems to take advantage of the lower operating cost of hydrocarbon technology – but unfortunately, small- and medium-sized enterprises (SMEs) in A5 Parties were not, and are not, always offered adequate financing for safety systems that take longer to pay back from savings due to lower foam chemical component costs.

Today, a wide selection of both flammable and non-flammable options are available, and others are currently being commercialized with low or even negligible GWP for most foam applications, with

[26] The CCAC was founded by the governments of Bangladesh, Canada, Ghana, Mexico, Sweden and the US, along with the United Nations Environment Programme (UNEP). It currently has 43 government partners and 53 non-state partners (scientific, trade, and environmental organizations, including IGSD). See more at: http://www.unep.org/ccac/About/History/tabid/130280/Default.aspx#sthash.Cn8LZp3s.dpuf.

[27] NOVEXPANS™ HFC 365mfc/HFC 227ea(87/13).), http://www.inventec.dehon.com/en/chemicals/expansion-des-mousses/18/novexpans-hfc-365mfc-hfc-227ea-87-13/90.html (last visited 3 November 2014).

the exceptions of some spray foam and some applications by SMEs. Safe use, competitive costs, and availability to A5 countries remain as barriers to be overcome.

A5 Parties

The phase-out of HCFC use in the foam sector is a priority of the MLF because the most commonly used chemical, HCFC-141b, has a relatively high ozone-depleting potential (ODP), cost of conversion is relatively low, and several feasible alternative technologies are widely available.

In order to facilitate alternative selection by A5 Parties, the MLF has invested US$18 million to 'demonstrate new and adjusted technologies in A5 countries' (UNEP 2014).[28] The final reports on demonstration projects presented by different MLF implementing agencies identified barriers that need to be overcome for technologies to be used by A5 countries.

As a result of the efforts of the MLF and foam systems suppliers, outstanding progress has been made in phasing out HCFCs while moving away from high-GWP HFCs, mainly in sectors where HFCs were expensive and performed poorly in energy efficiency. However, some foam investment experts point to a lack of adequate financing and technical proficiency to maintain equipment and systems for the safe introduction of flammable alternatives by SMEs. Furthermore, it has been reported that SMEs often cannot afford co-funding beyond the agreed eligible incremental costs paid by the MLF, which do not cover the full costs of transition. In some cases it may cost less to relocate SMEs away from inner-city neighbourhoods where safety measures are too expensive to implement.

Current chemicals used in foam manufacturing in A5 Parties

Before the discovery of stratospheric ozone depletion, fluorocarbons were widely used to produce foam because they are low-cost, non-flammable, achieve high insulating value, and produce a rigid physical structure. HCFCs were used as a transition substance to facilitate the CFC phase-out and in limited cases where they were technically needed. The consumption of HCFCs in the foam sector varies depending on the application. HCFC-141b and HCFC-22 are used in applications including polyurethane (PU) rigid foam (appliance thermal insulation) and PU integral skin foam, which has a low-density foamed core surrounded by a high-density skin and is used for shoe soles and structural applications, including automotive interiors and furniture parts. HCFC-141b is also used in PU board, PU spray foam, and PU in-situ/block and phenolic foam. HCFC-142b and HCFC-22 are used to make extruded polystyrene (XPS) foam board.

Alternatives

There are several zero-ODP alternatives available, including HFCs including as HFC-245fa, HFC-365mfc/227ca, HFC-134a, and HFC-152a. Blends of olefins and non-fluorinated solutions are being tested in all applications. In some cases, cost is the motivation to use blends. In other cases, blends perform better than any single solution by itself. However, except for HFC-152a, HFC foam-blowing agents have higher GWPs than the chemicals they are replacing, such as HCFC-141b.

[28] UNEP Multilateral Fund Secretariat (2014) Overview of Approved HCFC Demonstration Projects and Options for Additional Projects to Demonstrate Climate-Friendly and Energy-Efficient Alternative Technologies to HCFCs (Decision 71/51 (a)), UNEP/OzL.Pro/ExCom/72/40.

Table 3.1 Alternatives: foam

Foam Sector Application	HCFCs Scheduled for Phase-out	High-GWP HFCs Proposed for Phase-down	Sustainable Low-GWP HCs (flammable)	Sustainable Low-GWP HCOs (flammable until blended with foam ingredients)	Sustainable Olefins (lower flammability or not flammable)	Sustainable CO_2-based (not flammable)
PU appliances	HCFC-141b HCFC-22	HFC-245fa HFC-365mfc/227ea	cyclopentane cyclo- / iso-pentane	Methyl formate	HFO-1234ze HCFO-1233zd HFO-1336mzz AFA-1 (undisclosed chemistry)	CO_2 (water)
PU board	HCFC-141b		n-pentane cyclo- / iso-pentane	Cyclo/ isopentane		
PU panel	HCFC-141b		Pentane	Methyl formate		CO_2 (water)
PU spray	HCFC-141b			Methyl formate		CO_2 (water) Supercritical CO_2
PU in-situ/block	HCFC-141b		n-pentane cyclo-/ iso-pentane	Methyl formate		CO_2 (water)
PU integral skin	HCFC-141b HCFC-22	HFC-245fa HFC-134a	Pentane	Methyl formate Methylal		CO_2 (water)
XPS board	HCFC-142b HCFC-22	HFC-134a HFC-152a	Iso-butane	DME	HFO-1234ze	CO_2 CO_2/ethanol
Phenolic	HCFC-141b	HFC-245fa HFC-365mfc/227ea	n-pentane cyclo-/iso-pentane			

Source: Modified and updated from the TEAP Task Force Report responding to Decision XXIV/7 (TEAP, 2013)

Green = Wide Commercial Use

Orange = Emerging Commercial Use

Red = HCFCs scheduled for Montreal Protocol phase-out; High-GWP HFCs proposed for Montreal Protocol phase-down

Market penetration: flammable solutions

The flammable solutions in the foam sector are hydrocarbons (cyclo-pentane, n-pentane, iso-pentane, butane and iso-butane), methyl formate, and methylal. The MLF and large companies often co-finance safety systems allowing the use of these replacements, with the company's costs recovered through lower ingredient costs. A successful transition of SMEs requires sufficient financing to achieve cost-effectiveness and safe handling. One MLF demonstration project in Egypt shows ways to decrease the costs of hydrocarbon introduction by offering HC preblends or practicing direct HC injection.[29]

Each alternative must be selected to match the application. For example, foam made with methyl formate has suitable technical performance in many applications, but low-density rigid PU foam (lower than 35 kg/m^3) made with methyl formate has stability issues that can cause shrinkage (lack of dimensional stability). System houses typically counter this shrinkage by co-blowing low density PU foam with HFCs, which reduces the GWP advantage of methyl formate in this use. Therefore, co-blowing with HFOs is currently being investigated in a UNDP project. This kind of 'devil-in-the-details' is why the HCFC phase-out and potential HFC phase-down need expert technical guidance such as that provided by TEAP, MLF, implementing agencies, and technical partners.

Larger companies can pay for and safely handle flammable blowing/expansion agents. Conversion to hydrocarbon alternatives (cyclo-pentane) has occurred in foam insulating products, with success in the domestic refrigerator/freezer manufacturing sector.

It is important to mention that foam 'system houses' have been responsible for the successful increase in market penetration of flammable alternatives by acting as the information dissemination and technical assistance 'centres' to downstream companies, helping to achieve higher penetration of alternative technology in the polyurethane foam sector. System houses are able to handle flammable alternatives safely in a pure form and then develop and distribute fully formulated systems to downstream users, reducing safety risks. Examples are the role of the system houses in the market penetration of methyl-formate-based systems and methylal. The use of pre-blended hydrocarbons is also being considered in a few countries, including China and Mexico.

Methyl formate-based systems were introduced and commercialized by Foam Supplies Inc., and this process is patented in major markets, with other patents pending. Methyl formate has been licensed to the following enterprises: Australia Urethane Systems (Asia and the Pacific), British Oxygen Corporation (selected European Countries), Purcom Quimica South America, Expanded Incorporation (India), and Resichem (South Africa). Foam Supplies Inc. has agreed to non-exclusive licensing to foam system houses that participate in MLF-funded HCFC phase-out projects. Foam is manufactured using methyl formate-based systems in Australia, Brazil, Cameroon, Canada, China, Commonwealth of Independent States (CIS) countries, Colombia, Dominican Republic, Ecuador, Egypt, El Salvador, India, Indonesia, Jamaica, Mexico, New Zealand, Nigeria, Philippines, Russian Federation, Singapore, South Africa, South Korea, Turkey, Trinidad and Tobago, the US, and Vietnam (Foam Supplies – FSI, 2014).

Twelve countries with ongoing projects introducing methyl formate are funded by the MLF, with estimated phase-out of about 5,000 MT HCFCs (UNEP 2014).[30] In these countries, hundreds of downstream users of local system houses have selected methyl formate technology. Safety precautions, especially for SMEs, include the use of pre-blended ingredients formulated at system houses, use of corrosion-resistant components that come in contact with pure methyl formate, and/or requirements that methyl formate blends be less prone to corrosion (UNDP 2010).[31]

[29] United Nations Development Programme (UNDP) (2010) Methyl Formate as Blowing Agent in the Manufacture of Polyurethane Foam Systems An Assessment for the Application in MLF Projects, http://www.undp.org/content/dam/aplaws/publication/en/publications/environment-energy/www-ee-library/ozone/Demo%20projects/UNDP%20Methyl%20Formate%20Project.pdf.

[30] Ibid.

[31] United Nations Development Programme (UNDP) (2010) Methyl Formate as Blowing Agent in the Manufacture of Polyurethane Foam Systems An Assessment for the Application in MLF Projects.

UNDP has reported the use of methyl formate in Brazil by a few clients of system houses that opted for methylal. In Mexico, one system house is using it for shoe soles (Zadro) and others are using it in some applications in minor quantities. It is UNDP's understanding that the use of methylal outside Brazil and Mexico is very limited.[32]

Blends of olefins and non-fluorinated solutions are being widely tested in all categories to optimize cost and/or performance (e.g. thermal performance; physical properties of foams etc.). It is expected that this may provide an opportunity for use of low-GWP solutions at a lower cost than neat olefins or flammable products alone.

Where such system houses do not exist, SMEs may not be able to tackle technology conversion to flammable solutions due to safety issues (flammability). In spray foam applications, flammability barriers have yet to be overcome, particularly for SMEs. Already, some countries have postponed conversion of the foam sector (UNEP 2014).[33]

In summary, flammable and non-flammable options, including blends, are, or will soon be available with AR5 $GWP_{100\text{-}yr}$ less than 25 or even negligible for most applications, with the exceptions of some spray foam and some applications by SMEs.

The market penetration of existing and emerging alternatives to HFC foam will accelerate once barriers are resolved, including the availability of information on how to access the new technologies, information on availability and costs of the foam-blowing agent and its components in the local market, options and fair pricing of licenses and associated technology transfer fees, and information and technical assistance on how to safely handle flammable blowing agents and other foam chemical ingredients, including blends (UNEP 2014).[34]

Once these barriers are removed, it is likely that A5 Parties will still insist that new and emerging technologies be adjusted to their specific circumstances. In these circumstances, blends such as olefins with more water or some methyl formate might be very helpful to support conversion. It usually takes at least two to three years to prepare and implement a demonstration project. Therefore, MLF financing for elimination of HCFCs via HCFC Phase-out Management Plans (HPMPs) will need to be provided simultaneously with financing from other sources for fast action to reduce HFC usage in the foam sector, including incremental operating and capital costs and the cost of safety, over and above what currently is covered by MLF. Now that larger companies are converting, SMEs will require assistance, as they are unable or unwilling to co-finance the safe introduction of higher-cost emerging technologies, such as HFOs.

Market penetration: non-flammable solutions

CO_2 and several non-flammable next-generation alternatives are replacements for high-GWP HFCs. For example, the use of CO_2-based formulations in XPS foam and integral skin applications are most cost-effective in medium- and large-scale applications (UNEP 2014).[35] However, in other thermal-insulation foam applications, many limitations associated with CO_2 usage are found (high thermal conductivity, high density and poor aging, licensing constraints). Where CO_2 is used in the supercritical state, the main limitations can be overcome (UNEP 2014).[36]

Next generation non-flammable solutions are in different stages of development and marketing by major international chemical companies. These blowing or expansion agents include HFO-1233zd (AR5 $GWP_{100\text{-}yr}$ =1) and other HFOs and HFO mixtures, including HFO-1234ze(E) (AR5 $GWP_{100\text{-}yr}$ <1), HFO-1336mzz (AR5 $GWP_{100\text{-}yr}$ =2) and HFO-1233zd (previously Arkema's undisclosed

[32] Personal communication UNDP/MPU Sept 2014.
[33] UNEP (2014) Overview of Approved HCFC Demonstration Projects and Options for Additional Projects to Demonstrate Climate-Friendly and Energy-Efficient Alternative Technologies to HCFCs (Decision 71/51 (a)), UNEP/OzL.Pro/ExCom/72/40.
[34] Ibid.
[35] Ibid.
[36] Ibid.

chemistry called AFA-L1). HFO-1233zd is commercialized for foam in domestic appliances by Festivo (Finland), Haier (China), Medea (China), and Whirlpool (Mexico and US) and commercial appliances by Okamura (Japan) and Porkka (Finland).[37] These next generation HFOs will be available in 2015 or later, albeit at relatively high costs.

As olefins become commercially available, blends of olefins and non-fluorinated solutions will be optimized for use in A5 Parties. Blending will temper olefin costs while still providing necessary performance characteristics. For example, testing of pentane/olefin blends by major foam system houses and appliance manufacturers is well under way. The MLF has provided technical assistance to some local system houses in India, Malaysia, and Saudi Arabia to develop and introduce HFO formulations; for instance, HFO-1233zd is being developed/tested in Malaysia.

The option of blending HFOs and HCOs (oxygenated hydrocarbons such as methyl formate and methylal) to counter the flammability or stability of the latter in low density applications is already practiced in some applications with HFC/HCO blends. This chemical formulation strategy may produce superior physical properties, processing and low flammability of HFOs, combined with the cost-effectiveness of HCOs.

Successful results of MLF-funded and other demonstration projects at the company level are important in order to raise the confidence of other users. Global HFO availability and costs are uncertain, but costs are expected to be high.

3.2 Motor vehicle air conditioning

Current technology

Most four-wheel automobiles manufactured worldwide have air conditioning as standard equipment and, until the transition began in 2012, all used HFC-134a (AR5 $GWP_{100\text{-yr}}$ = 1300) and CFC-12 before that (AR5 $GWP_{100\text{-yr}}$ = 10,200). MACs consume between 3 to 20 per cent of motor fuel, depending on the length and severity of the cooling season; level of outdoor air pollution and improved sense of security that cause windows to be closed; automobile exterior and interior colours and glass area; drive cycle; and congestion. About one third to one half of national global GWP-weighted HFC emissions are from MACs (depending on the mix of HFC products in the market and the practices used in servicing).

Next generation technology

There are at least four low-GWP alternatives to HFC-134a (HFO-1234yf, HFC-152a, Mexichem AC6, and CO_2), but only HFO-1234yf systems have so far been commercialized. Research and development for CO_2 MACs was undertaken from about 1990 and for HFC-152a MACs from about 2002 until 2009, when global automakers selected HFO-1234yf. HFO-1234yf is suitable for commercialization in A5 Parties, depending on cost and access, which hinges somewhat on whether the ‘application patent’ giving monopoly pricing power to Honeywell will be allowed in various markets. At current HFO-1234yf pricing, lower cost HFC-152a is the available second choice to phase down HFC-134a in MACs. Higher introductory pricing of HFO-1234yf might be overcome by the purchasing clout of large automobile companies, or by competition from HFC-152a or AC6 systems. Once commercialized, CO_2 might also compete on cost and environmental performance.

HFO-1234yf

The transition to HFO-1234yf in the EU has begun in response to the MAC F-Gas Directive capping MAC refrigerant GWP at 150 by 2017 for all new cars; in the US in response to credits toward fuel efficiency standards and a proposal to remove HFC-134a from the list of MAC refrigerants under US EPA rules for approved uses of F-gases; and in Japan in response to their HFC-134a phase-down, which is likely to be harmonized with the EU and US schedules. HFO-1234yf is a slightly

[37] Personal communication with Honeywell.

flammable (ASHRAE A2L) refrigerant approved by the US SNAP Programme, the EU REACH) programme, and qualified by the International Standards Organisation (ISO) and SAE International for design, safety, and service standards. The atmospheric degradation of emissions of HFO-1234yf produces five times more trifluoroacetic acid (TFA) than the HFC-134a it replaces, which, at current projections, is not considered a threat to ecosystems (Henne et al, 2012).[38]

The incremental capital cost of manufacturing HFO-1234yf systems includes refrigerant charging stations designed for slightly flammable gases and the incremental per vehicle cost of one additional component (external heat exchanger), upgraded evaporator, new unique valves and the more expensive refrigerant. The incremental component cost per vehicle is about US$40 - 75 for vehicles with small (600 g) charge and US$75 - 100 for vehicles with larger (1.2kg) charge. Incremental ownership costs for fuel will be unchanged, but life-cycle service costs are expected to be similar or slightly higher, depending on the price of HFO-1234yf for service, leak rate, service procedures and accidents. Note that by the time the newest vehicles with HFO-1234yf need servicing (4 - 9 years from manufacture), the cost of the refrigerant may have fallen due to economies of scale and competition.

Honeywell holds a disputed 'application patent' for the use of HFO-1234yf in MACs, and Arkema, Asahi, Daikin, DuPont, Honeywell, Mexichem, and Solvay hold patents for the process of making HFO-1234yf. This HFO is currently manufactured in Jiangsu Province, China, and Chiba, Japan, with additional plants under construction in France, Japan, and the US.

CO_2

The car manufacturer Daimler has considered HFO-1234yf too flammable and has pledged to commercialize CO_2 systems, presumably by 2017, to correspond with the ban on HFC-134a in all new cars sold in the EU. CO_2 is a non-flammable high-pressure refrigerant that satisfies US EPA SNAP and EU REACH. SAE International standards are being developed. CO_2 systems also may need to satisfy international and national high-pressure gas standards originally developed to avoid boiler explosions.

The incremental vehicle costs of CO_2 systems include more expensive components designed for higher pressures, which would be partly offset by the low cost of the refrigerant. The incremental cost per vehicle is unknown, but expected to be significantly higher than for HFO-1234yf systems. The incremental ownership cost is also expected to be higher, particularly when operating in locations with high ambient temperature and cooling degree-days, with more expensive component replacement cost and more frequent servicing due to higher operating pressures.

The 1991 patent issued to the Norwegian Gustaf Lorentzen for the modern thermodynamic transcritical CO_2 cycle, which is the basis for CO_2 MACs, has expired. Existing patents for less significant components are not expected to increase the cost of CO_2 systems.

HFC-152a

HFC-152a is a flammable refrigerant that satisfies US EPA SNAP when used in a secondary-loop system or with other designs to prevent the refrigerant from leaking into passenger-occupied spaces. HFC-152a is approved under EU REACH, but SAE standards are not yet completed. Unlike HFC-134a, HFO-1234yf, and AC6 (described below), HFC-152a does not atmospherically degrade into TFA.

The incremental per-vehicle costs of HFC-152a systems include additional components (heat exchanger, coolant pump, and additional controls), which are partly offset by the lower cost of the refrigerant. The incremental cost per vehicle is likely less than US$0 - 30 per vehicle regardless of the size of the refrigerant charge. The incremental ownership cost will be much lower than HFO-1234yf systems due to fuel savings, low refrigerant cost, higher system energy efficiency, and the potential ability to use energy produced from deceleration for a portion of cooling.

[38] Henne S., D. E. Shallcross, S. Reimann, P. Xiao, D. Brunner, S. O'Doherty, & B. Buchmann (2012) *Future Emissions and Atmospheric Fate of HFC-1234yf from Mobile Air Conditioning in Europ*e, Environ. Sci. Technol. 46(3):1650-1658.

Manufacturing patents for HFC-152a have expired and existing secondary-loop patents by companies and individuals are not expected to increase the cost of HFC-152a systems.

Mexichem 'AC6' [39]

AC6 (R-445A) is a mildly flammable proprietary refrigerant blend of CO_2, HFC-134a, and HFO-1234ze (6 per cent/9 per cent/85 per cent by weight, respectively; yielding an AR5 GWP_{100yr} of ~130) proposed by Mexichem.

The advantage compared to HFO-1234yf is lower flammability and potentially higher cooling capacity,[40] but it has significant glide. AC6 has not yet satisfied US EPA SNAP or EU REACH, and SAE standards are not yet completed. However, favourable results in the SAE Cooperative Research Programme have resulted in a decision to move from phase I evaluation, which validated that AC6 has comparable cooling capacity and life-cycle climate performance (LCCP) and reduced flammability compared to HFO-1234yf, to phase II evaluation of selective leakage, compressor durability, materials compatibility, and manufacturing and service issues.[41]

The production of TFA from the atmospheric degradation of emissions of AC6 depends on the leakage rate of the portion of the blend that is HFC-134a. The incremental manufacturing and ownership cost of AC6 systems will depend on the cost of the new and recycled refrigerant, with all other costs comparable to HFO-1234yf systems. Ownership costs may be prohibitively high if refrigerant ingredients differentially leak from operating systems, causing a loss of cooling capacity or energy efficiency.

The price of newly manufactured AC6 likely will be less than HFO-1234yf, but the cost of refrigerant recovery and reuse may be higher if the blend cannot be accurately reformulated in service facilities and instead must be returned to the manufacturer for reprocessing.

Hydrocarbons

Hydrocarbons (HCs), which are highly flammable refrigerants, are considered by most safety authorities and vehicle manufacturers to be too flammable to use in MACs and are not approved for MACs by US EPA SNAP, but satisfy EU REACH. SAE International is not developing standards for hydrocarbons.

In many non-A5 Parties, retrofitting MACs to utilize HCs is illegal or discouraged; however, in some jurisdictions, notably in some Australian states, it is legal to retrofit CFC, HFC, and HFO MACs to hydrocarbons, which is immediately less expensive than using non-flammable, or less flammable, refrigerants.[42]

Technical and economic feasibility of reducing MAC HFC emissions

Properly charged MACs are more energy efficient and have longer equipment life than under-charged systems. Leak tightness depends on design, quality of parts, care during manufacture of components and factory assembly of systems, and service and end-of life practices. The best- and worst-in-class estimated emissions of new vehicles sold in the US in 2012 (the latest year with complete reporting) ranged from 5.9 to 21.9 grams per year for passenger cars, with similar ranges of estimated emissions for sport utility vehicles, vans, and trucks.[43] Best service practices and quality

[39] Corporate sponsors of the SAE International MAC Refrigerant Blend Cooperative Research Programme (MRB CRP) include: Behr, Bosch, Chrysler, Cinetic, Filling, Daimler, Denso, Doowon, General Motors, Halla, Visteon Climate Control, Hyundai, Jaguar Land Rover, Mexichem, Nissan, PSA, Renault, SAIC Motors, Sanden, Schrader International, TEXA, and Volvo Cars

[40] SAE International (2012) Development and Evaluation of AC5 And AC6 Refrigerants for MAC Applications: A White Paper produced by the SAE MRB Cooperative Research Programme.

[41] Peral-Antúnez, E. (2012) MAC REFRIGERANT BLEND Cooperative Research Programme: Update, 31 October, SAE International (12TMSS-0022).

[42] The government of Germany makes the case for CO_2 MACs in: Hoffmann, G. & W. Plehn (2010) Natural Refrigerants for Mobile Air Conditioning in Passenger Cars a Contribution to Climate Protection, German Federal Environment Agency (umweltbundesamt): http://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/4081.pdf.

[43] Minnesota (2008) Mobile Air Conditioner Leakage Rates; Disclosure, MN Stat § 216H.12 (2013)

replacement parts can reduce vehicle service and end-of-life emissions by at least 50 per cent.[44] The cost of improved MAC design and components is less than the added cost to vehicle owners for the more frequent repair and reduced mileage from under-charged MACs.

[44] SAE International (2007) Reducing Refrigerant Emissions at Service and Vehicle End of Life. Improved Mobile Air Conditioning (I-MAC) Cooperative Research Project, 30 June, http://www.epa.gov/cpd/mac/Service%20Team%20Final%20Report.pdf.

Table 3.2 Alternatives to HFC-134a in MACs

Alternative	**AR5 $GWP_{(100\text{-}yr)}$**	**Relative energy efficiency**	**Refrigerant cost (US$/kg)**	**Market status**	**Implementing agencies / Bilaterals**	**Pioneering & leadership companies**	**Where commercialized**	**Ready for A5 Parties?**
HFC-134a (BAU)	1300	Baseline	$7	Commercial in every country worldwide	No need	Status quo in every automobile worldwide, except those transitioned to HFO-1234yf	Everywhere	BAU
HFO-1234yf	<1	Equal	$60	Commercial	None	Alfa Romeo, BMW, Chrysler Citroën, GM, Honda, Hyundai, Rover, Kia, Lotus, Maserati, Mazda, Mitsubishi, Nissan, Peugeot, Renault, Subaru, Tesla, Toyota, Subaru, Suzuki	EU Japan Korea US	Yes
HFC-152a	138	+10 per cent	$2	Experimental	None	Fiat, GM, TATA, Volvo	None	No
CO_2	1	Poor at high ambient temperature	<$1	Experimental	None	Daimler	None	No
HCs	<5	Uncertain	<$1	Rejected	None	None	None	No
'AC6' blend (CO_2/HFC/HFO)	~130	Equal	?	Testing	None	Mexichem, JLR, Renault-Nissan, Robinair, Bosch	None	No

3.3 Domestic room air conditioning

The use of room A/Cs is increasing rapidly in many A5 Parties because of increasing electrification, changes in family structures, higher disposable incomes and long seasons with high ambient temperatures where air conditioning is needed (cooling season). Market potential in these countries is very high because to date only small proportions of the growing populations own room air conditioning systems. In India, for example, market penetration of room A/Cs is less than 3 per cent, with ownership expected to grow 20 - 25 per cent per annum, depending mostly on increases in incomes and availability of electricity.[45] In many Indian cities, air conditioning accounts for 40 - 60 per cent of peak electricity demand during the long, hot cooling season.[46] Furthermore, air conditioning energy-efficiency gains that can be captured in the HCFC phase-out can avoid up to 100 new power plants in India and proportional avoided power plants in other hot regions with expanding A/C use.[47] The annual consumption of HCFC-22 within A5 Parties in 2009 was around 300,000 metric tonnes, of which some 35 per cent was for small-sized A/Cs.[48]

World-wide, climate change is estimated to drive heating energy demand down by 34 per cent and air conditioning energy demand up by 72 per cent by 2100 under current projections, increasing the importance of efficiency for this sector even more in many areas where demand growth is already high. 'At the regional scale considerable impacts can be seen, particularly in South Asia, where energy demand for residential air conditioning could increase by around 50 per cent due to climate change, compared with the situation without climate change.'[49]

The energy efficiency of room A/Cs in A5 Parties is currently low compared to that in non-A5 Parties that have implemented incentives to increase efficiency. However, in 2005, China launched a labelling programme for energy efficiency, which classifies appliances in five grades, giving more information to consumers. The energy efficiency of Chinese A/Cs is expected to increase more rapidly than in the past. The average energy efficiency of A/Cs in stock will be improved through the replacement of old A/Cs with newer and more efficient ones. We expect that 40 per cent of existing A/Cs will be replaced when significantly more energy-efficient products are available, and the remaining 60 per cent after product failure.[50] Similar information-based programmes have also been launched in India and in some other A5 Parties.

The climate impact of all refrigeration and air conditioning usage is a combination of 1) *direct* refrigerant GHG emissions from equipment leaks and servicing; 2) *indirect* emissions from power plants that generate the electricity; and, 3) *embodied* carbon emissions from the production, service, and recycling at the end of product life. LCCP is an analytical technique that accounts for all three categories of heat-trapping emissions. Indirect emissions from high-LCCP room A/Cs account for more than 90 per cent of the total carbon footprint in leak-tight systems supplied with electricity from coal or diesel and less than 1 per cent of the total carbon footprint in systems supplied with electricity from low-carbon sources, including hydroelectric, nuclear, photovoltaic, and wind. Of course, the carbon-intensity of electricity varies widely depending on the generation mix and energy efficiency of the fossil fuel

[45] Price Waterhouse Coopers (2012) Analysis of impact of super efficiency on air-conditioning manufacturers /suppliers in India; Chaturvedi V., J. Eom, L. Clarke, P. R. Shukla (2014) *Long term building energy demand for India: Disaggregating end use energy services in an integrated assessment modelling framework*, Energy Policy 64:226-242; *and* Stephen O. A., P. S. Chidambaram, B. Deol, D. Doniger, A. Ghosh, A. Jaiswal, R. Palakshappa, J. Schmidt, & G. Sethi (2013) Cooling India with Less Warming: The Business Case for Phasing Down HFCs in Room and Vehicle Air conditioning, Council on Energy, Environment & Water (CEEW), the Institute for Governance & Sustainable Development (IGSD), the Natural Resources Defense Council (NRDC), and The Energy and Resources Institute (TERI) in cooperation with the Confederation of Indian Industry (CII).

[46] Maharashtra Electricity Regulatory Commission (MERC) & the Indian Bureau of Energy Efficiency (BEE).

[47] Phadke, A. A., N. Abhyankar, & N. Shah (2014) Avoiding 100 New Power Plants by Increasing Efficiency of Room Air Conditioning in India: Opportunities and Challenges, June 2014, http://eetd.lbl.gov/publications/avoiding-100-new-power-plants-by-incr.

[48] Colbourne D. (2011) Hydrocarbon Refrigerants for Room Air Conditioners, http://www.fairconditioning.org/wp-content/uploads/2013/09/HC-refrigerants-fro-room-ACs-D-Colbourne.pdf

[49] Morna I., & D. P. van Vuuren (2009) *Modeling global residential sector energy demand for heating and air conditioning in the context of climate change*, Energy Policy 37(2):507-521.

[50] Satoru K. (2007) Energy Efficiency of Air Conditioners in Developing Countries and the role of CDM, OEUD/IEA.

power plants. The portion of carbon footprint from refrigerant emissions depends on equipment leak rates, service practices and equipment, and the effectiveness of refrigerant recycling programs. [51]

There are five designs of room A/Cs:

- *Portable room A/Cs* are freestanding self-contained appliances on wheels that exhaust hot air through a flexible tube out of the window or into another room.
- *Window room A/Cs* are self-contained appliances designed to be installed inside a window, with the hot air exhaust system facing outside and the cool air return system facing inside.
- *Through-the-wall room A/Cs* are self-contained appliances designed to be installed through a wall inside a chassis sleeve.
- *Ductless mini-split room A/Cs* have a condenser unit that installs outdoors and is connected by refrigerant tubing to one or more compact wall-mountable evaporator/blower units that are placed strategically inside the space(s) that are cooled.
- *Central A/Cs* have a condenser unit that installs outdoors and is connected by refrigerant tubing to a single evaporator/blower unit that distributes cold air to one or more rooms through ductwork.

Portable room A/Cs are very inefficient, window and through-the-wall room A/Cs have medium efficiency, and ductless mini-split and central A/Cs are the most efficient. Ductless mini-split systems use far less energy than central A/Cs by cooling only occupied rooms. Central A/Cs dominates the market in the US and Canada while China, India, Brazil, Japan and the EU are all large consumers of room A/Cs in varying forms; average capacity for room A/Cs in a sample of countries ranged from 3.33 kW in China to 6.64 kW in the UAE (1 - 2 tonnes, in a range where alternatives using HC-290 or HFC-32 are often workable).[52]

Currently, a multitude of room A/C brands are commercially available, including equipment with HCFC-22, HFC-410A, HFC-32, and HC-290 and with different energy-efficiency ratings. Because of the Montreal Protocol's requirements to phase out HCFC-22, there has been a steady conversion towards HFC-410A, a class A1 refrigerant with an AR5 GWP of 1923, which is higher than the AR5 1760 GWP of the HCFC-22 that countries are replacing. Manufacturers are investing in alternatives to high-GWP chemicals and assessing the next generation refrigerants including HFOs and HFO/HFC blends, HFC-32, and HC-290 (propane), seeking solutions that are energy-efficient and safe in manufacture, installation, operation, and disposal at the end of product life.

Technology pioneer Godrej has developed HC-290 room A/Cs that are up to 11 per cent more efficient than the minimum requirements for the 5-Star energy-efficiency rating set by the Indian Bureau of Energy Efficiency (BEE), even without the use of inverters that likely will provide an additional 10 per cent or more improvement.[53] The Daikin Urusara 7, which uses HFC-32 refrigerant, has achieved the 2013 world's highest energy efficiency for wall-mounted room A/Cs and is the first to receive the Australian 7-Star Super Efficiency rating.[54]

TEAP has reported to Parties that both HFC-32 and HC-290-based small self-contained A/C s and mini-split A/Cs are economically viable, with little to no additional costs anticipated. [55]

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[51] For the range of electricity carbon intensity in India see: http://ceew.in/pdf/CEEW-Final-Room-AC-Paper%2014Jul14.pdf

[52] Shah N., P. Waide, & A. Phadke (2014) Cooling the Planet: Opportunities for Deployment of Superefficient Room Air Conditioners, LBL working paper.

[53] Rajadhyaksha D. (2013), Development and Handling of Hydrocarbon Air-Conditioners – The Godrej Experience, presentation at Bangkok Technology Conference, 29 June 2013 held in conjunction with the Montreal Protocol Open-Ended Working Group (OEWG).

[54] For residential wall-mounted room air conditioners in the 4.0-kW to 5.6-kW class, as of June 2013. The Urusara 7 achieves coefficients of performance (COPs) of 4.3 to 5.7 in cooling operation. *See* Japan for Sustainability (JAB) (2012) *Daikin's Air Conditioner Wins METI Minister's Prize for Energy Conservation in 2012*, http://www.japanfs.org/en/news/archives/news_id032779.html.

[55] UNEP (2014) Report of The Technology and Economic Assessment Panel, Decision Xxv/5 Task Force Report, Additional Information to Alternatives on ODS (Final Report) 6, pages 14-16, http://conf.montreal-protocol.org/meeting/mop/cop10-mop26/presession/Background%20Documents%20are%20available%20in%20English%20o1/TEAP_Task%20Force%20XXV5-October2014.pdf (last accessed 31 October, 2014).

For a flammable refrigerant in room A/Cs to be safe, the room must be large enough to allow the charge to leak out without accident (safely below the lower flammable limit-LFL). For a room A/C to be effective for comfort, the charge must be large enough to cool the room in whatever climate it is in (and depending on room size, shading, insulation, humidity, uses, etc.). So the room has to be small enough to cool and large enough to reliably dilute any accidental leakage that may occur. Thus, flammable refrigerants are most suitable for mild climates and well-insulated and shaded small rooms. Flammable refrigerants are less suitable are poorly insulated spaces in very hot climates.

A variety of HCFC-22 replacement options are available. In almost every case, the low-GWP options can exceed the energy-efficiency performance that is currently available in the marketplace.

Table 3.3 Alternatives to HCFC-22 and HFC-410A in room A/Cs

Alternative	**Common name***	**AR5 GWP** (100-yr)	**Relative energy efficiency**	**Refrigerant cost (US$/ kg)**	**Market status**	**Implementing agencies / Bilaterals**	**Pioneering & leadership companies**	**Where commercialized**	**Ready for A5 Parties?**
HCFC-22 (scheduled for MP phase-out)	R-22	1760	Baseline	~$10	Commercial in every country worldwide	No need	Status quo in room A/Cs sold in A5 Parties; phased-out in Non-A5 Parties	Everywhere	BAU
HFC-410A	R410A	1923	Higher, except at high ambient temperatures	~$20	Commercial	None	Status quo in room A/Cs sold in Non-A5 Parties	All non-A5 Parties	Yes
HC-290	R-290	<5	+10 per cent-20 per cent from marketplace; +2 per cent from HCFC-22 baseline	>~$2	Commercial	UNIDO/ Germany	Godrej, Midea and Gree	Production in China and India; exports reported to a number of countries	Yes, where standards, safe installation and trained service is assured
HFC-32	R-32	677	+10 per cent-20 per cent from marketplace; +2 per cent from HCFC-22 baseline	<~$1	Commercial	UNDP and UNIDO Japan	Daikin, Fujitsu General, Gree, Hitachi, Midea, Mitsubishi Electric, Panasonic and Toshiba	Production in China, EU, India and Japan, US; exports reported to a number of countries, mainly in Asia,	Yes, where standards, safe installation and trained service is assured
HFC/HFO blends	Various	~350	+10-20 per cent from marketplace; +2 per cent from HCFC-22 baseline	~$30	Testing	None	Asahi Glass Chemical, Arkema, DuPont, Honeywell, and Mexichem,	None	No

* All pure refrigerants and refrigerant blends have a generic, globally recognized name registered by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) as 'R-(number)' or 'Refrigerant-(number)'. Pure refrigerants can also be listed with the chemical group number followed by the number from the ASHRAE classification (for example CFC-12). Furthermore, chemical suppliers typically have a trademarked brand name designation (see the section on refrigerants).

3.4 Commercial air conditioning

This section classifies commercial air conditioning products according to compressor size in three major categories:

- Reciprocating and scroll compressors (smaller tonnage applications, where higher pressure refrigerants are required due to size and weight constraints).
- Air- and water-cooled screw compressors (medium tonnage applications, where medium-pressure refrigerants are feasible and preferred).
- Water-cooled centrifugal compressors (large tonnage applications, where medium and low-pressure refrigerants are feasible and preferred).

High-pressure commercial air conditioning systems have the advantage of smaller equipment size and weight for comparable cooling capacity, but the disadvantages are that high-pressure refrigerants have relatively higher GWP and refrigerant leak rates, as well as lower energy efficiency. Furthermore, as pressure goes up, flammability becomes more of a problem.

As applications increase in tonnage, equipment tends toward lower pressure/more efficient solutions, like HFC-134a and HCFC-123. In general, larger capacity systems demand the most efficient solutions available in the marketplace, and the applications are less sensitive to weight and size.

Next generation technology

Low GWP HFO solutions are generally available for medium- and low-pressure systems. These HFOs can be blended with moderate-GWP HFCs to create energy-efficient refrigerants for high-pressure systems that are dramatically lower in GWP than refrigerants currently in the marketplace. The HFOs that are being considered for commercial air conditioning use are either non-flammable or very low on the 'slightly flammable' scale.

Flammability standards and codes are a major obstacle to the market acceptance of next generation refrigerants. The solutions will be to update the design, manufacture, installation and service of equipment to accommodate the higher risk associated with flammability, and to change standards and codes to allow the safe use of flammable refrigerants. Low GWP HFOs and lower-GWP HFO/HFC blends have been found generally to have low or slight flammability. This flammability has been characterized by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) as 2L versus Class 2 or Class 3 flammable refrigerants[56]. Currently, class 2L flammable refrigerants are recognized as having unique flammability properties that are less hazardous and are appropriately being written into the various codes and standards with modified safety requirements.

The various codes and standards are quite extensive; the key ones include:

- ISO 13043: 2011—Road vehicles—Refrigerant systems used in MAC—Safety requirements. ISO 13043 is a relatively new ISO standard that was developed by the global automotive industry stakeholders to incorporate safety requirements for HFO-1234yf (A2L refrigerant) and CO_2.
- ISO 5149: 2014 Refrigerating systems and heat pumps—Safety and environmental requirements—Part 1: Definitions, classification and selection criteria. ISO 1549 recently integrated A2L refrigerants within this standard.
- ISO 817:2014: Refrigerants—Designation and Safety Classifications. The 2014 version of ISO 817 incorporated 2L refrigerants.

[56] Certainly the ISO 817:2014 is: no flame propagation (Class 1), lower flammability (Class 2L), flammable (Class 2), and higher flammability (Class 3).

- IEU 60335-2-40, ASHRAE 15, EN 378 are all currently in process of incorporating A2Ls into the respective standards. The International Mechanical Code (IMC0 is also targeted to be updated as international experts complete these codes.

For larger equipment, solutions are already making their way into the marketplace.

Reciprocating and scroll compressors (smaller tonnage air conditioning)

Currently, small tonnage reciprocating and scroll compressor A/Cs use HFC-410A (AR5 $GWP_{100\text{-yr}}$ =1923). Alternatives include HFC-32 (AR5 $GWP_{100\text{-yr}}$ = 677), or blends of HFC-32 and HFOs that achieve both lower flammability than HFC-32 and lower GWP (400-500). Pure HFC-32 and HFC-32/HFO blends achieve both higher cooling capacity and higher energy efficiency than HFC-410A at high ambient operating conditions.

Air- and water-cooled screw compressors (medium tonnage A/Cs)

Screw compressors today use primarily HFC-134a (AR5 $GWP_{100\text{-yr}}$ = 1300) for commercial air conditioning applications. HFC/HFO refrigerant blends will be available in the near future for medium tonnage air and water-cooled screw compressors that are non-flammable, offer almost no loss in capacity and efficiency, and have a GWP that is less than half that of HFC-134a. Low GWP refrigerants (GWP <150) will take longer to implement due to chiller redesign and code changes needed to accommodate 2L refrigerants. The medium-pressure HFO solutions available (HFO-1234yf, AR5 $GWP_{100\text{-yr}}$ < 1; HFO-1234ze, AR5 $GWP_{100\text{-yr}}$ < 1) are all slightly flammable. Non-flammable, HFO/HFC blends are also being developed.

One solution in this market segment may be a two-step transition; the first step being to a non-flammable, moderate GWP solution (HFC/HFO blend), and then a second step to the long-term solution using low flammability (2L) HFOs.

Water-cooled centrifugal and screw compressors (large tonnage A/Cs)

Water-cooled centrifugal chillers currently offer the highest energy performance using both HFC-134a (AR5 $GWP_{100\text{-yr}}$ = 1300) and HCFC-123 (AR5 $GWP_{100\text{-yr}}$ = 79, ODP = 0.012).

HFO-1233zd (AR5 $GWP_{100\text{-yr}}$ < 4.7-7) and HFO-1336mzz (AR5 $GWP_{100\text{-yr}}$ =2) are non-flammable refrigerants already available in some markets that achieve comparable energy efficiency (± 1-2 per cent) in systems designed for low-pressure HCFC-123 and can achieve better energy-efficiency performance than HFC options currently available on the market.

Replacements for medium pressure HFC-134a for centrifugal chillers may follow the same two-step transition as described above for screw compressors.

Table 3.4 Alternatives: commercial air conditioning

Alternative	AR5 $GWP_{(100\text{-yr})}$	Relative energy efficiency	Replacement for	Flammability classification	Market status	Pioneering & leadership companies	Ready for A5 Parties?
HCFC-22	1760	Baseline	N/A	1	Commercial in every country worldwide, Montreal Protocol phase-out schedule	Status quo	BAU
HFC-134a	1300	Baseline	N/A	1	Commercial in every country worldwide	Status quo	BAU
HCFC-123	79	Baseline	N/A	1	Commercial in every country worldwide, Montreal Protocol phase-out schedule	Status quo	BAU
HFC-32	677	+3 per cent relative to HFC-410A	HFC-410A HCFC-22	2L	Limited availability, but restricted due to 2L flammability status		
HFC-32/HFO blends	400–500	+3 per cent relative to HFC-410A	HFC-410A HCFC-22	2L	In field trials		
HFO-1234yf	<1	0 to -5 per cent relative to HFC-134a	HFC-134a	2L	In field trials		
HFO 1234ze	<1	Same as HFC-134a	HFC-134a	2L	Limited availability from Airdale, Climaveneta, Geoclima, and Star; restricted due to 2L flammability status		
HFO-1233zd	<1	-1 per cent relative to HCFC-123	HCFC-123	1	Available in some markets from Trane		
HFO-1336mzz	<1	-1 per cent relative to HCFC-123	HCFC-123	1	In field trials		

3.5 Domestic, industrial, and commercial refrigeration

Domestic and small-sized refrigerators and freezers

Substantial progress has been made in converting from HCFCs in the manufacture of domestic and small-sized commercial refrigerators and freezers, with most companies converting from CFC-12 refrigerant to zero-ODP alternatives, such as HFC-134a and isobutene (HC-600a). Refrigerant conversion to a zero-ODP alternative has occurred globally, with significant gains in energy efficiency where energy-efficiency standards, product energy labelling, and incentives have been in place. Companies that have switched to alternatives such as HFC-134a (AR5 $GWP_{100\text{-}yr}$ = 1300) are leaving a service tail and an inventory of 'banked' refrigerant in old appliances that will need to be dealt with in the future, as refrigerators can last 20 years or longer. For these reasons, financing a conversion to technologies where both refrigerant and energy usage have a small climate impact would be an investment in long-term environmental sustainability.

The opportunity exists to immediately transition from HFC-134a to HC-600a ($GWP_{100\text{-}yr}$ = ~3). Many countries have made this transition or are going in this direction. Biases against using flammable refrigerants as an alternative in the domestic refrigeration sector are no longer relevant, especially because the charges are low (below 150g).

For beverage vending machines, the global transition is well underway under the leadership of Refrigerants Naturally!, with Coca-Cola, PepsiCo, and Red Bull purchasing only CO_2 equipment in all global markets; with infrastructure and training in place in most markets; and with equipment prices based on economy of scale and competitive supply. Unilever is implementing HC-600a globally for stand-alone frozen food display cases.

Table 3.5 Alternatives: domestic and small-sized commercial refrigerators and freezers

Alternative	AR5 $GWP_{(100\text{-yr})}$	Relative energy efficiency	Replacement for	Flammability classification	Market status	Pioneering & leadership companies	Where commercialized	Ready for A5 Parties?
HFC-134a	1300	Baseline	CFC-12	1	Commercial in almost every country worldwide	Status quo	Worldwide	BAU
HC-600a	~3	Higher than HFC-134a	HFC-134a	3	Commercial in every country worldwide	Unilever		
HFO-1234yf	<1	Equal to HFC 134a	HFC-134a	2L	In field		Japan	
			Emerging					
HC-441A			HFC-134a	3	SNAP approved		Emerging	
HFO-blends		Equal to 134a	HFC-134a	2l	In field trials		Emerging	
CO_2	1	Better than HFC-134a in beverage vending machines		1	Commercial in almost every country worldwide	Coca- Cola, PepsiCo, Red Bull	Worldwide	

Commercial and industrial refrigeration

Substantial progress has been made in the transition from HCFCs in the industrial and commercial refrigeration sector, where companies have converted from HCFC-22 to several different alternatives. Many companies in non-A5 and A5 Parties have switched to non-HFC alternatives in the manufacturing of commercial refrigeration products, in pursuit of better energy-efficiency performance, lower equipment and operating costs or environmental leadership. In the process, these companies have also reduced gas leakage, which reduces electricity use as well as direct refrigerant emissions.

A large number of companies that manufacture commercial and industrial refrigeration equipment in A5 Parties have not yet converted away from HCFCs. The key parameters of the MLF Policy Framework prioritize higher ODP (HCFC-141b) foam first, manufacturing sector conversions second and servicing last, with MLF investment in refrigeration and air conditioning manufacturing allowed only in case of demonstrated compliance need. The majority of the HCFCs now used in A5 Parties is HCFC-22 for manufacture and servicing of commercial and industrial refrigeration and room air conditioning.

In commercial and industrial refrigeration, several zero-ODP alternatives are available and in use to replace HCFC-22, including HFCs, hydrocarbons, ammonia and CO_2. The commercial refrigeration sub-sector is comprised of stand-alone equipment, condensing units and centralized systems. Transport and large size industrial refrigeration equipment are also covered in this section.

Currently used HFC refrigerant choices

Many of the HFC-based refrigerants in use in this sector have high GWPs, including HFC-134a, R-404A, R-507A, R-422D, R-407C, and R-407F. Several other high-GWP blends that contain the ODS HCFC-22 are not considered in this report because they are already controlled under the Montreal Protocol.

HFC-134a (AR5 $GWP_{100\text{-yr}}$ = 1300) is a single component fluid widely used in cold storage and process refrigeration, chillers, supermarkets, centralized rack systems and self-contained equipment. R-404A (AR5 $GWP_{100\text{-yr}}$ = 3943) is a blend of HFCs (44 per cent HFC-125, 52 per cent HFC-143a, 4 per cent HFC-134a) and is used in supermarkets, centralized systems, cold storage, process refrigeration, chillers, and road transport. Both have high GWPs. They are available for use in medium- and low-temperature applications. Given the technology maturity, high efficiency, convenience of usage, and cost-effective availability, they are commonly used in many countries.

Climate-friendly refrigerants

Some currently used refrigerants are relatively climate-friendly. For example, CO_2 (R-744) is a single component manufactured substance that can be used in a variety of different types of systems, including stand-alone equipment, centralized systems, transport refrigeration and large-size refrigeration. It offers an immediate transition opportunity in large- and medium-size supermarket systems, as well as for process refrigeration and cold storage application.[57] In order to perform well in tropical countries, CO_2-based systems may need to be redesigned or modified to ensure that their condensing circuit operates well below critical temperatures.

HCs are manufactured substances offering the potential for relatively straightforward transition uses. This category includes three main pure refrigerants, propane (HC-290), propene (HC-1270) and isobutene (HC-600a). HC blends also have been used since the phase-out of CFC-12. HC-290 and HC-1270 are used in stand-alone, transport refrigeration, and some large supermarket systems (use in this setting may be limited due to charge restrictions). HC-600a is used in stand-alone equipment. HCs are used commercially worldwide. Usage is limited in occupied spaces due to maximum allowable charge.

[57] Brodribb P. & M. McCann (2014) A study into HFC consumption in Australia. Canberra.

Ammonia (R-717) is used worldwide in medium to large size systems. It offers an immediate opportunity to transition in process refrigeration and cold storage systems.[58] Ammonia is a good choice as long as it can be safely handled and the equipment can be well maintained, especially in populated areas. It is a cost-effective and efficient solution—especially when waste heat can be used with ammonia-based absorption chillers.

Conversions towards low-GWP selections such as HC-, ammonia- and CO_2 -based technologies in the industrial and commercial refrigeration sector have also increased. The current focus is on subsectors with high leak rates, such as supermarkets (see Section 7.1).

It is important that prioritization of conversion follows the path towards optimum solutions accounting fully for energy efficiency, climate impact, competitive costs, and safety in use and servicing.

Emerging alternatives

The refrigeration industry is developing and evaluating different options to reduce net CO_2 and CO_2-eq emissions (based on LCCP). Energy efficiency is one of the criteria examined in selecting alternative solutions. Some chemical producers have invested in a new fourth generation HFOs. Blends are also being commercialized to achieve the best compromise regarding flammability, GWP and energy performance. The fact is that no single refrigerant solution fits all applications.

[58] Brodribb P. & M. McCann (2014) A study into HFC consumption in Australia. Canberra.

Table 3.6: Alternatives in industrial and commercial refrigeration

Alternative	AR5 $GWP_{(100\text{-}yr)}$	Relative energy efficiency	Replacement for	Flammability classification	Market status	Pioneering & leadership companies	Ready for A5 Parties?
HCFC-22	1760	Baseline	N/A	A1	Commercial use worldwide	Status quo	BAU
HFC-134a	1300	Baseline	N/A	A1	Commercial use worldwide	Status quo	BAU
R-404A (44 per cent HFC-125, 52 per cent HFC-143a, 4 per centHFC-134a)	3943 [1]	Baseline	N/A	A1	Commercial use worldwide		BAU
R-717 (ammonia)	~0			B2	Commercial use worldwide		Yes for large size equipment, centralized systems. Skills gap and toxicity risk.
R-744 (CO_2)	1			A1	Commercial use worldwide		Yes for stand-alone, centralized systems, transport refrigeration. Challenges to enter market due to toxicity risk. High costs.
HC-290 (propane), HC-1270 (propene)	3[2]			A3	Commercial use worldwide		Yes for limited charge stand-alone equipment, centralized systems, transport refrigeration. Skills gap. Training and safety measures required due to flammability class and regulatory issues.
HC-600a (isobutene)	4[3]			A3	Commercial use worldwide		Yes for low charge stand-alone equipment. Skill gaps. Training and safety measures required due to flammability class and regulatory issues.
HFO-1234yf	<1	0 to 5 per cent relative to HFC-134a	HFC-134a	2L	In field trials. Limited availability but restricted due to 2L flammability status.		No. Limited availability but restricted due to 2L flammability status (Decomposition products concerns?)
R-1234ze (HFO)	<1	Same as HFC-134a	HFC-134a	2L pending[4]	Limited availability but restricted due to 2L flammability status.		No. Limited availability but restricted due to 2L flammability status.
HFC-32/HFO blends; HFOs and other blends	~90-1600	Improved relative to R-404A	?	A1 and A2L[5]	0ver 30 blends under examination by AHRI Low GWP Alternative Refrigeration Evaluation Programme*		Some HFO blends have been commercialized

Adapted from: A study into HFC consumption in Australia, Peter Brodribb and Michael McCann 2014, Canberra.

[1] Calculated from chemical ratio and IPCC AR5 GWP values.

[2] The Linde Group, R1270 (Cre 45) Propylene, http://www.linde-gas.com/en/products_and_supply/refrigerants/natural_refrigerants/R1270_propylene/index.html)

[3] Environment Canada, Dr*aft Environmental Code of Practice for Elimination of Fluorocarbon Emissions from Refrigeration and Air Conditioning Systems, http://www.ec.gc.ca/Air/default.asp?lang=En&n=4CA440F8*-1 (last visited 3 November 2014).

[4] McLinden, M. O. (2011) Property Data for Low-GWP Refrigerants: What Do We Know and What Don't We Know?, Presentation at the ASHRAE Winter Meeting, Las Vegas, NV (20 January 2011), http://tc31.ashraetcs.org/pdf/Property%20Data%20Low%20GWP%20Refrigerants.pdf.

[5] McLinden, M. O. (2011) Property Data for Low-GWP Refrigerants: What Do We Know and What Don't We Know?, Presentation at the ASHRAE Winter Meeting, Las Vegas, NV (20 January 2011), http://tc31.ashraetcs.org/pdf/Property%20Data%20Low%20GWP%20Refrigerants.pdf.

3.6 Solvent, fire protection, medical, and miscellaneous HFC uses

Although the largest current and projected uses of HFCs are in foam blowing, refrigeration, and air conditioning, opportunities also exist to reduce HFC use and emissions in other applications.

Solvents

Except for China, where consumption of HCFC-141b is relatively high, there is limited use of HCFC-141b and HCFC-225ca/cb ODS solvents by A5 and non-A5 Parties. The MLF approved a demonstration project in China for its conversion from HCFC-141b based technology to iso-paraffin and siloxane (KC-6) technology for cleaning in the manufacture of medical devices.[59]

It is standard practice in the retrofit of air conditioning and refrigeration equipment to flush from the system any lubricant incompatible with the replacement refrigerant. It is also a common practice to flush contamination from systems that have overheated or experienced compressor disintegration. The challenge is to find a flushing solvent that removes the contamination and is safe for health, ozone and climate. The problem is that HFC-245fa and other HFCs have been replacements for historic flushing solvents such as CFC-11, CFC-113, and HCFC-141b. New technology is emerging, but is not yet mature.

The choice of ozone-safe, zero- and low-GWP alternatives to ODS solvents includes: aqueous; hydrocarbons (with surfactants); organic solvents; and halogenated solvents including trichloroethene (TCE), tetrachloroethene (PCE), hydrofluoroolefins (HFOs), hydrochlorofluoroolefins (HCFO), and chlorofluoroolifins (CFO). The fluorinated solvents, with medium to high GWPs, are HFCs and HFEs.

HFCs have generally been avoided as alternatives to ODS solvents in non-A5 Parties and thus can be replaced in A5 Parties.

Fire protection

HFCs are not commonly alternatives to halons in specific uses, but the qualification by safety authorities of climate-safe fire protection agents is long and application-specific.

Medical HFC uses

The Medical Technical Options Committee (MTOC) has determined that HFC metered-dose inhalers (MDIs) will remain an essential therapy for the foreseeable future to treat the growing incidence of asthma and chronic obstructive pulmonary disease (COPD), and that completely avoiding high-GWP alternatives in this sector is not yet technically or economically feasible. By about 2025, avoiding high-GWP alternatives such as HFC MDIs might become more technically and economically feasible. In many regions, growth in HFC use in MDIs has been reduced by the use of dry powder inhalers (DPIs). Thus, in some non-A5 Parties, HFC use can be phased-down now in some categories of drugs, depending on how successfully HFC MDIs have already been avoided and on the circumstances of health, regulatory frameworks, and finance.

Only a minuscule amount of HFCs are used in medical sterilization, where a wide variety of alternatives are available. Medical sprays to chill or freeze tissue or to test tooth sensitivity to cold are commercialized using HFO-1234yf.

Technical aerosol products and miscellaneous uses

HFCs will have limited necessity in non-medical aerosol products and as miscellaneous uses, and HFO alternatives are emerging. For example, already HFO-1234ye is commercialized for aerosol tire inflators, where flammable propellants are not safe, and in dusters and safety horns that might be hazardous if used in confined spaces with sources of ignition. Party streamers banned as unsafe

[59] Conversion from HCFC-141b based technology to iso-paraffin and siloxane (KC-6) technology for cleaning in the manufacture of medical devices at Zhejiang Kindly Medical Devices Co. Ltd., implemented by Japan/UNDP (UNEP/OzL.Pro/ExCom/72/40).

and frivolous by some regulations are marketed in Europe propelled by HFO-1234ze. Aerosol products that chill electronics during testing are also marketed with HFO-1234ze propellant. Note that there is little capital cost of converting from non-flammable HFCs to non-flammable HFOs, but the manufacturing costs remain higher as long as the HFOs cost more than the HFCs. However, the HFO propellant is often a small portion of the retail cost of the product.

4 Overcoming Barriers to Alternatives

Even where alternatives to HFCs are readily available, a number of barriers to their introduction typically need to be overcome.[60] This section reviews a range of key issues.

4.1 Safety, training and environmental regulations

The flammability of HFC alternatives is often an issue when safety regulations have not been updated in line with technological progress. In general, such barriers have been removed for the use of slightly or mildly flammable refrigerants (HFO-1234yf and HFC-152a, respectively) in MACs, with mildly flammable HFC-32 authorized for room A/Cs in Japan and some other countries, and with EU standards being finalized for flammable HFC-32 and HC-290 refrigerants. However, the US EPA has not yet authorized the use of either HFC-32 or HC-290 for room A/C under SNAP, and in many local jurisdictions, flammable refrigerants are either banned or discouraged in building codes.

The new HFO refrigerants are either non-flammable or have low flammability. Refrigerants like HFO-1234ze are considered ‘slightly flammable’ or ‘lower flammability’ under current standards, yet they cannot be ignited at room temperature.[61] Several options are being tested that blend HFC-32 with HFOs with the goal of achieving the operating pressure of HFC-410A, with a lower flammability and GWP than HFC-32.

Where flammable refrigerants are allowed, but regulations for safe use have not been enacted, there can be a risk of accidents in manufacture, installation, service or use. Responsible manufacturers of room A/Cs with flammable refrigerants recognize the importance of safety standards in assuring the commercialization and market penetration of their products. A lack of suitable training and equipping of service technicians for the safe use of flammable refrigerants, along with inadequate service infrastructure, can also be a barrier.

4.2 Intellectual property

From the earliest days of the Montreal Protocol, concern was expressed that intellectual property (IP) owners would extract monopoly profits from the sale of alternatives to ODSs, and that patents for new HCFCs and HFCs would render countries dependent on foreign sources and a small number of multinational companies. At the same time, there was an expectation among inventors of new technologies that they should be rewarded for their investment and should be able to recover the costs of research, development, toxicity testing, application testing and commercialization.

Where such IP concerns were raised, agreeable solutions were usually found. Once the Montreal Protocol’s control schedules were in place, more options were developed—in particular, not-in-kind alternatives—than had originally been expected. In almost all applications, there has been a high level of competition in the supply of alternatives. Even where the holders of patents claimed exclusive rights, there have been few reported problems in MLF projects—either because other alternatives were available or because the MLF paid the surcharge or licensing fees.

There is continuing concern that IP issues will limit the choices and increase the cost of the HCFC phase-out. Higher transition costs impact A5 Parties if the MLF shifts all or part of the IP burden

[60] UNEP OzonAction (2010). Barriers to the Use of Low-GWP Refrigerants in Developing Countries and Opportunities to Overcome These. (http://www.unep.fr/ozonaction/information/mmcfiles/7476-e-Report-low-GWPbarriers.pdf)
[61] There is some evidence indicating that a substance can become more flammable with increasing humidity levels.

to the companies making the transition or to the A5 party itself. In turn, added IP costs might be passed on to the customers of the new ozone- and/or climate-safe products.

Higher transition costs can be avoided by donation of patented technology in the interest of future generations, by competition with technology without IP, by the MLF or large companies making the transition negotiating competitive prices, with joint ventures in A5 Parties to produce patented substances, and by litigation or regulation preventing monopolists from charging excessive prices. In the case of HCFC phase-out in foam sectors, there is a wide choice and competitive pricing of low-GWP technology for large enterprises, but SMEs may face monopoly supply issues when they depend on products that are supplied by just one company. Interested businesses/companies may wish to monitor the situation as new products come to the market.

4.3 High-ambient-temperature environments

Countries experiencing long, hot and often humid seasons have been particularly concerned that alternatives to HFCs provide cooling capacity, energy efficiency, and system durability equal to or better than high-GWP HCFCs and HFCs. This assessment makes a special effort to highlight performance at high ambient temperatures and suggests further efforts in research and testing to meet the needs of high-ambient-temperature markets.

Air conditioning and refrigeration equipment historically had its largest markets in developed countries, with smaller markets in developing countries. In developed countries, more expensive equipment was marketed in locations with high ambient temperatures to achieve adequate cooling capacity, but even in hot developed country climates, energy efficiency was a secondary concern before energy prices and environmental concerns led to better designs.

CFCs, HCFCs and HFCs can and have been designed to operate at high cooling capacity and reliability in hot climates, but energy efficiency has been low in markets without energy-efficiency standards, energy consumption labelling, high consumer awareness and available financing to pay the higher initial prices of equipment, even when energy savings pay back the initial cost. Some manufacturers have considered high-ambient-temperature markets too small for specialized products, and energy-efficiency testing is not usually conducted for high temperatures. For example, ISO 5151, which is the reference document for room A/C energy-efficiency testing in many developed and developing countries, specifies testing at 35° C (95° F), which is well below hot climate temperatures and makes appliances appear more energy-efficient when they actually underestimate energy use by 20 - 30 per cent.[62]

It is essential that additional energy efficiency testing be conducted at the ambient temperatures because refrigeration and air conditioning equipment optimized to be efficient in temperate climates may be inefficient at higher temperatures. If the testing is only at lower temperatures or if the energy rating is for temperate climates, then a perverse incentive exists for manufacturers to select refrigerants and design that excels in the test but disappoints customers in hot climates and unnecessarily damages climate.

Environmental and energy authorities and consumers in some A5 Parties are demanding higher energy efficiency, and new test standards and designs are increasingly helping shape the market. For example, in India, the Bureau of Energy Efficiency (BEE)—working with the Indian Society of Heating Refrigeration and Air Conditioner Engineers (ISHRAE) and the Refrigeration and Air-Conditioning Manufacturing Association (RAMA)—are revising test standards and test temperatures. For building chillers, they include a 41° C (105°F) test point as well as a test for reliability at high temperature.[63] Although this is an improvement over the previous high temperature test point, 41°C

[62] Goldstein, D. (2014) Updating India's AC Test Procedures to Better Reflect Indian Climatic Conditions, Natural Resources Defense Council, San Francisco.

[63] Diddi, S. (2014) *India AC Efficiency Policy Opportunities & Current Activities*, presentation at Workshop on Space Cooling Efficiency Enhancement and Demand Response, 24-25 June 2014, Delhi, India, http://beeindia.in/documents/Presentations/Day1/Mr%20Saurabh%20Diddi%20Space%20Cooling%20India.pdf.

does not reflect the actual ambient air temperature or the even higher temperature of refrigeration and air conditioning condensers operating in direct sunlight or in stagnant air, where heat from the condenser is not dissipated.

Other efforts are under way within the United Arab Emirates Ministry of Environment and Water and the Emirates Authority for Standardisation and Metrology (ESMA). In addition, the Air Conditioning, Heating and Refrigeration Institute (AHRI), the UNEP and the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Falcon Chapter organized in October 2014 the latest in a series of meetings of industry stakeholders to guide development, commercialization, and selection of alternatives to HCFC and high-GWP HFC refrigerants and associated technology for high-ambient temperature countries.[64]

The neglect of reliable energy-efficiency testing is not a technically valid reason to delay the phase-down of high-GWP refrigerants, as next generation options to replace HFCs show improved cooling capacity and energy efficiency relative to HFC-410A at high ambient conditions.[65]

4.4 Refrigeration and air conditioning service and equipment end-of-life

Most A5 Parties do not produce HFC substances or equipment containing HFCs.[66] The implications of not producing HFCs and/or products containing HFCs are: 1) that the HFC phase-down by these A5 Parties could be relatively simple if those Parties introduce and implement the actions outlined below:

1. Introduce and implement safety standards and best practices to safely use 1) flammable and toxic natural refrigerants, 2) flammable lower-GWP HFC and HFO refrigerants and blends, and 3) less- or non-flammable HFOs.
2. Incentivize the import of low-GWP products with high energy efficiency and adequate safety.
3. Avoid the purchase of imported products depending on high-GWP HFCs and implement best service and disposal practices to minimize the use and emissions of HFCs.
4. Consider the ownership, service and disposal implications of each new chemical substance allowed in imported products.

In addition, not producing HFCs and/or products containing HFCs would allow MLF financing to strengthen capacity building, technician training, service infrastructure, safety standards, and enforcement.

Because many A5 Parties will face similar situations, there will be great advantages in developing and sharing information on technical performance (particularly energy efficiency), training, safety standards, and refrigerant management during servicing and at the end of product life.

A5 Parties that only import refrigeration and air conditioning equipment can act quickly to avoid – through the introduction of safety standards and regulations—the infrastructure and ownership costs of room A/Cs with refrigerants that are already obsolete. Any party can prohibit the manufacture and import of products containing an unwanted HFC and any party can request multinational companies to seek prior informed request before marketing high GWP HFC products.[67]

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[64] The search continues, Climate Control (16 October 2013) http://www.climatecontrolme.com/en/2013/10/the-search-continues/.

[65] Praveen, S. S. (2013) *A Comparison of an R32 and an R410a Air Conditioner Operating At High Ambient Temperature*, presentation at the International Conference on Advanced Research in Mechanical Engineering, 16 June-2013, Chennai, http://www.irnetexplore.ac.in/IRNetExplore_Proceedings/Chennai/ARME_16June2013Chennai/ARME_16June2013Chennai_Doc/11-14.pdf (last accessed Oct. 24, 2014).

[66] Products that contain HFCs include refrigeration, air conditioning equipment, specialty fire protection equipment, metered-dose inhalers, and technical aerosol products.

[67] Thailand became the first A5 party to use an environmental trade barrier when they banned the manufacture and import of refrigerators containing CFC-12 refrigerant and CFC-11 insulating foam in order to protect domestic manufacturers of ozone-safe refrigerators from unfair competition from foreign companies dumping CFC technology in their export markets. The Industry Cooperative for Ozone Layer Protection (ICOLP) and the Japan Industrial Conference for Ozone Layer Protection (JICOP), in cooperation with the US Environmental Protection Agency (US EPA), Japan Ministry of Economy, Trade and Industry (METI), Japan Ministry of the Environment (MOE), and UNEP, organized the 'Vietnam Pledge' by multinational

A5 Parties importing automobiles cannot avoid HFC-134a, which was implemented with few exceptions worldwide by 1995 and in India and China more than a decade ago, but they can orchestrate the transition to HFO-1234yf by setting schedules for when import of new and used vehicles with HFC-134a will be prohibited.[68] Automobile dealers selling new vehicles with next-generation MACs could be required to own the proper equipment for service and to always properly service and recharge these systems.

A5 Parties with supermarkets owned by multinational companies could negotiate rapid transition to new technology and cooperate locally to building the training and infrastructure necessary to make financial investments cost-effective for local supermarkets and retail grocery SMEs, including those that will be funded by the MLF. Supermarkets around the world already are phasing out HFCs and transitioning to alternatives, which often results in savings associated with increased energy efficiency (see further in Section 5.1).

Most A5 Parties have already shifted to HC-600a residential refrigerators and freezers and will be able to apply the same service practices to plug-in commercial refrigeration equipment using flammable hydrocarbon refrigerants. However, new training and infrastructure will be required for each of the other new technologies replacing HFCs.

Table 4.1 New refrigerants to replace high-GWP HFCs in A5 Parties

Refrigerant	**MACS**	**Room air conditioning**	**Building air conditioning**	**Domestic Refrigerators**	**Small commercial refrigeration**
HC		HC-290		HC-600a	
Lower GWP HFC		HFC-32	HFC-32		
CO_2					CO_2
HFO HFC/HFO blends	HFO-1234yf	HFO/HFC blends	Various		HFO/HFC blends

Note: The above list is illustrative and could change depending upon new product technologies available in the market. The table captures the 'bigger picture' on technology options.

Training and infrastructure is needed from the time the first products with low-GWP refrigerants are introduced, including training in the safe installation, operation, and service of products with natural refrigerants, low-GWP HFC, HFO, and HFC/HFO blends.

5 Energy Efficiency

The phase-out of CFCs under the Montreal Protocol catalysed substantial improvements in air conditioning and refrigerant energy efficiency as the result of replacing old products and equipment with a new generation of higher efficiency machines.[69] Comparable energy-efficiency improvements

companies to avoid increasing dependence on ODSs and technology cooperation for environmentally superior solutions. Andersen, S. O. & K. M. Sarma (2002) Protecting the Ozone Layer: the United Nations History, Earthscan Press, London (Official publication of the United Nations Environment Programme); *see also* Andersen, S. O., K. M. Sarma & K. N. Taddonio (2007) Technology Transfer for the Ozone Layer: Lessons for Climate Change, Earthscan Press, London (Official publication of the Global Environment Facility (GEF) and the United Nations Environment Programme).

[68] In 2017 the EU will ban the sale of vehicles with air conditioning refrigerants with a GWP>150. The US EPA has proposed a ban beginning in 2022.

[69] US EPA (2002) Building Owners Save Money, Save the Earth, Replace Your CFC Air Conditioning Chiller, EPA-430-F-02-026: http://www.epa.gov/ozone/title6/608/chiller1_07.pdf; Todesco, G. (2005) *Chillers + Lighting + TES: Why CFC Chiller Replacement Can Be Energy-Savings Windfall*, ASHRAE Journal, pp18-27; Global Environment Facility (GEF) (2009) India: Chiller Energy Efficiency Project, Programmatic Framework for Energy Efficiency in India, Project ID P100584, 125 pages: https://www.thegef.org/gef/sites/thegef.org/files/repository/4-07-2009%20ID3552%20India-%20Council%20letter.pdf; *and* Andersen, S. O. & E. T. Morehouse (1997) *The Ozone Challenge: Industry and Government Learned to Work Together to Protect Environment*, ASHRAE Journal.

are documented for projects demonstrating alternatives to high-GWP HFCs. For example, the CCAC has reported over 50 per cent improvement in energy efficiency in commercial food stores using cascade and secondary loop low-GWP systems.[70] An almost 50 per cent improvement in retail refrigerated low-GWP beverage display cases has been reported by Coca-Cola Company and PepsiCo, and both Tesco and Unilever have reported typically 10 per cent improvements for refrigerated and frozen food cabinets using natural refrigerants.[71]

Caution is necessary when comparing the energy-efficiency claims of refrigeration and air conditioning alternatives because: 1) the energy efficiency of the new system optimized for highest possible energy efficiency may be compared against an old system that was not as energy efficient; 2) the new system was tested at the temperatures where it had the greatest energy-efficiency advantage; or 3) the energy-efficiency claim might be untested, unverified, biased, or even fabricated. The validity of energy-efficiency claims is strengthened by trusted third-party testing using respected energy-efficiency test methods and by proof of compliance with energy-efficiency standards and product energy-efficiency labelling in government programmes. For example, the LCCP comparisons of MAC systems are based on SAE International test standards using an LCCP model that was developed by international consensus and is hosted by the US EPA.[72]

The CCAC is an independent source of detailed information on energy efficiency and return on investment (ROI) for low-GWP alternatives in commercial refrigeration, including propane, CO_2 and HFOs, reported by the supermarket companies pioneering the new technology. In evaluating technical choices, it is important to consider whether the source have a vested interest or bias.

These case studies are particularly valuable in highlighting advantages of particular technology in both temperate and high-ambient conditions, including the energy and financial advantages of recovering and reusing the heat from evaporators to heat occupied spaces in buildings or for process heating. In some of the case studies, the companies demonstrating the new technologies in their supermarkets also indicate which of the new technologies will be implemented throughout their global enterprises and specifically in stores operating in high ambient temperatures.[73] The CCAC plans to publish additional case studies on alternatives to high-GWP HFCs for other sectors.

The energy efficiency of refrigeration and air conditioning equipment depends on the choice of refrigerant, design, components, and controls, and also depends on the ambient temperature where heat is rejected, as well as the temperature of the space that is cooled. Each refrigerant has *theoretical energy efficiency*, which is based on its chemical properties, *potential energy efficiency*, which is measured using laboratory test equipment, and *product energy efficiency*, which is measured in test chambers and is the basis for energy-efficiency ratings that guide consumer choice.

The least-cost choice of HFC technology to phase out HCFCs, which is based on refrigerants such as HFC-410A and HFC-134a, does not achieve the level of high energy efficiency that is in the interest of owners of refrigeration and air conditioning in the future. Natural refrigerants and low-GWP HFCs are alternatives that can achieve equal or even substantially higher energy efficiency than the HCFC or high-GWP HFC technology that is replaced. This requires, however, market incentives

[70] UNEP & CCAC (2014) Low-GWP Alternatives In Commercial Refrigeration: Propane, CO_2 And HFO Case Studies, Publication number DIT-1666PA: http://www.unep.org/ccac/portals/50162/docs/Low-GWP_Alternatives_in_Commercial_Refrigeration-Case_Studies-Final.pdf.

[71] Consumer Goods Forum (2009) Success Stories About HFC-Free Refrigeration And Energy Efficiency: Barriers And Solutions, http://www.docstoc.com/docs/158956311/Consumer-Goods-Forum-Refrigeration-Success-Stories%5B1%5D.

[72] US EPA, *Comparing the Climate Impacts of Mobile Air Conditioners*, http://www.epa.gov/cpd/mac/compare.htm (last visited 3 November 2014); see also Papasavva, S. & S. O. Andersen (2010) GREEN-MAC-LCCP©: Life-Cycle Climate Performance Metric for Mobile Air Conditioning *Technology Choice, Environmental Progress & Sustainable Energy*, American Institute of Chemical Engineering; Papasavva, S., W. R. Hill, & S. O. Andersen (2010), *GREEN-MAC-LCCP: a tool for assessing the life cycle climate performance of MAC systems.*, Environ Science and Technology 44(19):7666-72. doi: 10.1021/es100849g; *and* Papasavva, S., W. R. Hill, & R. Monforte (2010) Comparison of GREEN-MAC-LCCP© based Indirect CO_2-eq. Emissions from MACs and Vehicle Measured Data, SAE Technical Paper 2010-01-1208, doi:10.4271/2010-01-1208.

[73] CCAC (2014) Low-GWP Alternatives in Commercial Refrigeration: Propane, CO_2 and HFO Case Studies, UNEP publication DIT-1666PA.

that take into account the social benefits of energy efficiency, including climate, health, and net life-cycle ownership costs including avoided investment in power plants.

Recent regulation and voluntary HFC phase-downs by industry have fostered a large number of studies of the wide choice and energy efficiency of low-GWP natural refrigerants, HFCs, and HFOs. The most ambitious projects include:

- AHRI is screening and characterizing potential refrigerants for low ODP, GWP, flammability, toxicity and high energy efficiency, including efficiency at high ambient temperatures.[74] At the Obama HFC Summit on 16 September 2014, the air conditioning and refrigeration industry pledged US$5 billion over the next decade to research and develop new refrigerants and equipment to accomplish the HFC phase-down.[75]
- The Alliance for Responsible Atmospheric Policy (ARAP), AHRI, and the CCAC organized the Global Food Chain Council (GFCC) '…to reduce greenhouse gas emissions in the processing, transportation, storage and retail display of cold food and to stimulate demand for climate-friendly technology.'[76]
- The US Department of Energy, with university and industry partners, has created the Super-Efficient Equipment and Appliance Deployment Initiative (SEAD) and the Research and Development Roadmap for Next-Generation Low-Global Warming Potential Refrigerants to guide the way forward to progressively more sustainable technology.[77]
- International and national NGOs and national governments are testing energy efficiency and publishing the results for use in satisfying energy-efficiency standards, energy-efficiency labelling requirements, and other methods of educating and incentivizing wise choices.

For most applications, low-GWP alternatives achieve higher energy efficiency than the HFCs replaced. Natural and low-GWP HFC refrigerants show improved cooling capacity and energy efficiency relative to HFC-410A at high ambient conditions. Secondary-loop and two-phase secondary-loop refrigeration achieves higher energy efficiency using low-GWP refrigerants in systems with lower refrigerant system charge and lower leak rates.[78] Natural refrigerants achieve higher energy efficiency at normal ambient temperatures, but are sometimes less efficient than HFO and lower-GWP HFCs at high ambient temperatures.[79]

New low-GWP technology is not presently feasible for most companies in A5 Parties but is expected to be feasible once new technology, training and servicing parts are commercially available locally, provided that adequate and efficient financing is available. With technological and financial assistance, it will be feasible to leapfrog high-GWP refrigerants in the phase-out of HCFCs and to select refrigerants and associated equipment that deliver superior LCCP. Proper investment analysis will consider energy efficiency to be a co-benefit with reduced ownership costs and increased property value, in addition to the value of avoided investment in power plants and cleaner air from less power generation.

Main barriers to energy-efficient products in A5 Parties

Barriers to transitioning to energy-efficient products will vary among countries due to the significant differences in financial and political situations. Barriers at the domestic level, such as

[74] AHRI, *Low-GWP Alternative Refrigerants Evaluation Programme*, http://www.ari.org/site/514/Resources/Research/AHRI-Low-GWP-Alternative-Refrigerants-Evaluation.
[75] Air Conditioning | Heating | Refrigerating News. HVAC Industry Lays Out Refrigeration Plan (15 September 2014) http://www.achrnews.com/articles/print/127631-hvac-industry-lays-out-refrigerant-plan.
[76] Alliance for Responsible Atmospheric Policy (2014) *Refrigeration Industry Leaders Organize Global Food Cold Chain Council*, PR Newswire (23 September 2014).
[77] US DOE (2011) Research and Development Roadmap For Next-Generation; Shah, N., P. Waide, & A. Phadke (2013) Cooling the Planet: Opportunities for Deployment of Super-Efficient Room Air Conditioners, Navigant Consulting, DOE DE-AC02-05CH11231.
[78] DelVentura, R., C. L. Evans, & I. Richter (2007) Secondary Loop Systems for the Supermarket Industry, Bohn.
[79] Mikhailov, A. & H. Ole Matthiesen (2013) *System Efficiency for Natural Refrigerants*, ASHRAE Journal.

low electricity pricing and split incentives, are difficult to overcome. Other barriers, such as those linked to finance, information and technology, can be overcome to achieve the desired market transformation to energy-efficient products and the co-benefits of climate protection, clean air, and avoided investment in power plants that would otherwise be necessary to provide the extra power required by inefficient appliances.

Barriers include:[80]

- Policy: low price of energy (net of subsidy and non-payment), no due consideration at the fiscal policy level for energy-efficient technologies.
- Finance: no incentive to manufacturers to invest in energy efficiency; price sensitivity of the appliance market.
- Business and management: market demand uncertainty; lack of resources amongst SMEs to develop and market energy-efficient products; reluctance to invest in R&D due to lack of resources.
- Information: lack of awareness amongst consumers and policy-makers about residential sector energy use and energy-efficiency potential; lack of information about the precise energy saving potential from energy efficiency.
- Technology: limited access to state-of-art technology; lack of adequately equipped and staffed independent test labs for energy-efficiency testing.
- Common practice: lack of confidence in the new equipment; inertial behaviour to maintain status quo of energy-using equipment.

Finance from the Global Environment Facility has been available to developing countries to remove barriers to the introduction of energy-efficiency products and market transformation. The funding has been directed toward capacity-building for government officials (i.e. regulatory officials), importers and distributors, technology transfer and labelling programmes. Global Environment Facility (GEF) implementing agencies, such as the UNDP, UNEP and the World Bank, have a large portfolio of such projects that are mostly financed by governments and the private sector.[81]

It is clear from the results of those projects that funds are essential to A5 Parties for the removal of barriers and the smooth transition to a market of more energy-efficient equipment. For A5 Parties that are manufacturers of equipment such as A/Cs, barriers are most likely to be of the financial, business and management type.

6 Availability of Funding[82]

The simplest solution to financing an HFC phase-down and increase in energy efficiency is replenishment of the MLF to expand its funding window[83] to take on 1) the added cost of leapfrogging high-GWP HFCs in the phase-out of HCFCs, 2) the added cost of a second transition from HFCs in applications like MACs that already use HFCs, and 3) the added cost of a two stage transition first from HCFCs to HFCs and then from HFCs to next-generation technology in applications where implementing HFCs is too far along to turn back.[84] Parties could decide to make financing available immediately for A5 Parties choosing to go beyond compliance.

[80] Koizumi, S. (2007) Energy Efficiency Of Air Conditioners in Developing Countries and the role of CDM, OEUD/IEA.
[81] GEF Secretariat, Personal Communication, October 2014.
[82] This section is a summary of a more detailed assessment of finance opportunities being developed by Steven Gorman and his associates with substantial contributions from the participants in this report.
[83] See the definition of 'funding windows' in the annex to this report.
[84] For a discussion of 'funding windows' under environmental agreements *see* UNFCCC (2011) Workstream III: Operational Modalities Sub-workstream III.2: Managing Finance Background note: Thematic windows (TC-2/WSIII/4: https://unfccc.int/files/cancun_agreements/green_climate_fund/application/pdf/tc2_ws3_4_280611.pdf.

A second solution is for an expanded funding window from non-A5 contributions as grants, provided the MLF Executive Committee welcomes this co-financing and easy any administrative barrier that prevent A5 Parties and enterprises to embrace the climate, clean air, and natural resource benefits of higher energy efficiency.

A third solution is for A5 Parties to separately seek finance from sources other than the MLF for the HFC phase-down and energy efficiency and to somehow coordinate that funding with the HCFC phase-out schedule. Unfortunately, the Montreal Protocol institutions and management structure in most A5 Parties are accustomed to having a 'one-stop funding window' for international financing that relates to ozone depletion, and are not well prepared (given their lack of knowledge of other financing institution or mechanisms) to access funds from the international financial institutions or funds that support energy-efficiency investments and clean energy projects, which are described below. Some A5 Parties would prefer to prefer to use government and private sector finance at the national level for the non-eligible portion of Montreal Protocol projects, rather than seek co-finance from international climate and aid organizations.

6.1 The Multilateral Fund

The availability of finance to support A5 Parties in their efforts to replace HFCs is an essential element of the success of the Montreal Protocol. As HFCs are not controlled substances under the Protocol, the MLF cannot directly support HFC phase-down activities. In 2010, however, in accordance with MOP Decision XIX/6, the MLF Executive Committee agreed to award a funding premium of up to 25 per cent for projects converting HCFC uses to low-GWP alternatives, thereby helping to avoid A5 Parties opting for high-GWP HFCs.

Given that the Montreal Protocol will pay the agreed incremental costs of HCFC phase-out, it is highly cost-effective to leapfrog high-GWP HFCs in the phase-out of HCFCs with technology designed for high energy efficiency using a low-GWP refrigerant.[85] The leapfrogging of HFCs in the HCFC phase-out and the phase-down of production and consumption of HFCs in existing uses under the Montreal protocol are cost-effective because: 1) the incremental costs per tonne CO_2-eq is lower than many other mitigation options; 2) the technology is now or will soon be commercially available at high economies of scale; 3) climate performance metrics and assessments are in place to guide technology choice; 4) regional networks, national ozone units and the implementing agencies are ready and able to assist; 5) the MLF pays the agreed incremental cost, which allows available financing to support more investment projects; and 6) some A5 countries have begun to pilot carbon trading and taxation policies which could increase the effective cost of high-GWP HFCs.

The Montreal Protocol has four implementing agencies: UNDP, UNEP, United Nations Industrial Development Organization (UNIDO) and the World Bank. These implementing agencies increase the cost-effectiveness and stakeholder satisfaction of investment through information, management, performance contracting, economies of scale, and direct involvement. With full information, the best technology is selected, duplication of effort is avoided, economies of scale are achieved faster and lessons from investment are shared. For example, a choice of underperforming technology is not repeated and the best technology is rewarded by replication.

Non-A5 Parties to the Montreal Protocol can allocate up to 20 per cent of their contribution to the Multilateral Fund to support bilateral projects, which could be supplemented with additional funding from their aid agencies.

One way forward would be to replenish the MLF and give it a mandate to be the financial mechanism to leapfrog high-GWP HFCs at the same time that HCFCs are being phased-out. The MLF, instructed by the Parties to the Protocol, could open a 'one-stop window' where companies and Parties that need to change technologies, policies or processes to comply with the Protocol are also eligible to

[85] Highly cost-effective may, however, imply some period of time to recoup initial transition costs for manufacturers and reasonable costs of capital.

be financed for HFC phase-down and high energy efficiency. This solution can incorporate simple metrics for quantifying the co-benefits and develop simple strategies to cut through institutional barriers in order to pool funds previously dedicated to one co-benefit or the other.[86]

The MLF could also be replenished to make 'second' transitions in cases where HFCs have already replaced ODSs, such as in automobile air conditioning, metered-dose inhalers (MDIs), and early transitions from HCFC-22 to HFC-410A and HFC-134a.

MLF replenishment, earmarked to phase down high-GWP HFCs, would position the MLF to facilitate the dialogue with other climate funds based on reduced GHG emissions so that Montreal Protocol Parties could secure complementary funding more successfully than if A5 Parties negotiated individually. For example, a project to transition from ozone-depleting HCFC-22 to HC-290 in room air conditioning would be financed for protecting the ozone layer, but currently may struggle to find the additional funds to achieve high efficiency, despite the co-benefits of clean air and improved health, reduced investment in power plants, reduced energy imports (with capital spending at home instead), and reduced ownership costs, which improve the standard of living and next-generation prosperity.

6.2 Other funding sources

There are other funds that could be used to finance leapfrogging high-GWP HFCs, including the Climate Investment Funds (CIFs), the GEF, The World Bank, Regional Development Banks, the Green Climate Fund (GCF) and other sources. The CIFs and the GEF are global-scale sources of concessional support that fund climate benefits and can partner with the Multilateral Fund on projects.

However, accessing any of these funds requires detailed knowledge of differing requirements; project cycles and internal requirements of each fund differ widely and can hinder timely access to finance. Moreover, the CIFs may lack the financial and management flexibility to make new commitments in the short term without instructions from their donors to make HFC phase-down a higher priority.

The World Bank and other international financial institutions along with their bilateral partners are a primary channel for support for energy-efficiency investments and often have dedicated funds for specific types of clean energy projects (which may also be defined by geographic or other eligibility requirements). Funding often needs to be channelled through government recipients, although the International Finance Corporation is one of several sources for direct support of private enterprises. IFC financing might be particularly appropriate for financing that can be easily repaid through energy savings.

The World Bank is the trustee for fifteen carbon finance initiatives. The Carbon Finance Unit[87] supports more than 150 projects through the purchase of about 220 million tonnes/year of CO_2-equivalent emissions. Pursuant to Article 12 of the Kyoto Protocol and the Clean Development Mechanism (CDM) modalities and procedures, certified emission reductions (CERs) are expected to be available for HFC phase-down, with average payment of 7€/MtCO_2e in 2014.

Climate Investment Funds (CIFs)

The CIFs provide 48 developing and middle-income countries with resources to mitigate and manage the challenges of climate change and reduce their GHG emissions. Fourteen contributor countries have pledged a total of US$8 billion to the CIFs, which is expected to leverage an additional US$55 billion from other sources. The CIFs allocates financing through four funding windows, three of

[86] Ghosh, A. (2010) Harnessing the Power Shift: Governance Options for International Climate Financing, Oxfam Research Report, October, Oxford: Oxfam International, 1–90.
[87] The World Bank (2010) Beyond the Sum of Its Parts Combining Financial Instruments for Impact and Efficiency, ISSUES BRIEF #3, Table 1. http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2010/06/25/000334955_20100625030802/Rendered/PDF/553290BRI0Box349445B01PUBLIC1.pdf.

which could be important in financing climate benefits in an HCFC phase-out:

The US$5.5 billion Clean Technology Fund (CTF) provides participating middle-income countries (including India) with highly concessional resources to scale up the demonstration, deployment, and transfer of low-carbon technologies in renewable energy, energy efficiency, and sustainable transport. However, funds are currently limited and some approved projects are pending, conditional on the availability of additional donor commitments.

The US$1.3 billion Pilot Programme for Climate Resilience (PPCR) is helping developing countries integrate climate resilience into development planning and offers additional funding to support public and private sector investments for implementation. These funds primarily target the most vulnerable countries that do not emit large amounts of GHGs.

The US$551 million Scaling Up Renewable Energy in Low Income Countries Programme (SREP) stimulates energy access and economic growth by working with governments in relatively poorer countries to build renewable energy markets, attract private investment, and target renewable energy technologies that allow for the generation and productive use of energy in households, businesses, and community services.

Global Environment Facility

The GEF has been the largest provider of grants and limited non-grant instruments to address climate change for the past 20 years. It also has been a secondary source of funding for Montreal Protocol projects in former Soviet republics not eligible for support under the MLF. Funding is defined by the 'incremental costs' incurred to achieve a global benefit; for cost-effective energy efficiency investments, this typically means the costs of removing market barriers including lack of awareness, demonstrations of new technology, quality assurance, and technical assistance for policy reforms. Support is provided as grants and limited non-grant instruments, primarily but not exclusively through government recipients. Over the 2010–2014 period, US$350 million per year has been allocated to this area—US$2.7 billion since the inception of the GEF. The size of GEF grants for projects range typically from US$5 – 50 million, although smaller projects can be supported through specific windows or indirectly through clean energy financing programmes.[88]

The Green Climate Fund (GCF)

The Green Climate Fund is a new source of climate investment under the UN Framework Convention on Climate Change, currently mobilizing resources and expected to begin making commitments in the near future.

Regional development banks

The regional development banks—the Asian Development Bank (ADB), Inter-American Development Bank (IADB), Caribbean Development Bank (CDB), African Development Bank (AfDB) and the European Bank for Reconstruction and Development (EBRD)—are important potential sources of co-funding for A5 party HCFC phase-outs and, with facilitation by a dialogue initiated by the MLF, could expand their efforts to tackle HFCs. Regional groupings of A5 Parties could undertake joint projects that bring together public and private sources of finance to support project development and implementation. For example, A5 Parties that do not produce refrigerants, A/Cs, or refrigeration equipment could be financed to jointly develop: 1) model legislation banning the import of products made with HCFCs and HFCs; 2) strengthened incentives for energy efficiency such as energy-efficiency standards and labelling; 3) appropriate safety standards for flammable and toxic refrigerant alternatives, and 4) public education on the importance of appliances with low life-cycle carbon footprints.

[88] The World Bank (2010) Beyond the Sum of Its Parts Combining Financial Instruments for Impact and Efficiency, ISSUES BRIEF #3, Table 1. http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2010/06/25/000334955_20100625030802/Rendered/PDF/553290BRI0Box349445B01PUBLIC1.pdf.

Other sources

Private sector support can finance projects particularly where there is an opportunity to increase market share for products, including continuing provision of parts and labour. The private sector participates in every aspect of the refrigeration and air conditioning sector, including design of refrigeration and air conditioning equipment, development of HCFC alternatives and substitutes, helping to design minimum standards for safety, health and environmental protection, and setting costs of refrigerants and equipment. There is a potential for private sector financial support, in addition to the already existing co-finance for the MLF Executive Committee's 'not agreed' eligible incremental and non-eligible incremental costs.

National governmental organizations provide funding assistance for environmental protection measures on a bilateral and regional basis outside the MLF. In addition to the private sector, A5 national governments are an important source of co-finance for MLF costs not agreed upon or non-eligible under the MLF, and other projects, especially the ones where co-finance is a requirement, such as for GEF projects.

Out-of-the-box approaches to financing an HFC phase-down might include Quantity Performance Instruments (QPIs) that allow private investors to finance the upgrade to high energy efficiency, to be repaid annually on the basis of actual reductions in energy use and emissions.[89] In effect, public and private investors would be paid the amount of money saved in power plant construction and operation plus the value of improved health and savings in health-care expenses (public and private).

In addition, a group of like-minded Parties and corporate and NGO partners such as those participating in the CCAC, could organize coordinated or bilateral support for Montreal Protocol-related activities for the adoption of low-GWP alternatives to HCFCs and HFCs.

Funding management and coordination barriers

Despite the availability of co-funding opportunities, certain barriers inhibit implementation. Positive changes would include:

Funding for preparation of projects with climate benefits, such as energy efficiency gains/savings.

Instruction to the Multilateral Fund by Parties to finance low-GWP technology and reward energy efficiency rather than subtracting energy savings from the level of incremental cost support, which creates a disincentive.

Synchronization of MLF project cycles with other funds such as the GEF and CIFs and a more streamlined approach to financing the phase-out of HCFCs and phase-down of HFCs.

Simplifying the performance guarantee payments and management structure.

The Multilateral Fund provides eligible incremental costs when the Montreal Protocol control measures establish a reduction in consumption. Therefore, it is difficult for the MLF to fund any growth that happened before the first control measures. The consequence is that lower funding to A5 countries increases the co-funding required at country level to deal with such growth.

Despite the difficulties in raising additional funds mainly from the private sector, co-funding has already been the obvious route for most large-consumption A5 Parties to take in their HCFC phase-out. Nevertheless, at four regional workshops on co-financing options held by UNEP in 2013 and 2014, National Ozone Officers made it clear that their traditional roles focus on implementing the Montreal Protocol and they currently lack the necessary capacity to approach donors to acquire co-financing for climate co-benefits.

[89] Ghosh, A., B. Müller, W. Pizer, & G. Wagnere (2012) Mobilizing the Private Sector Quantity-Performance Instruments for Public Climate Funds, Oxford Energy and Environment Brief, The Oxford Institute for Energy Studies, University of Oxford.

7 Case Studies

This section summarises a number of cases where high-GWP HFCs have been successfully phased out.

7.1 Case Study: Supermarket refrigeration

In every year since 2009, the Environmental Investigation Agency (EIA) has conducted surveys of HFC usage in supermarkets across the EU. The results show a steady move away from HFC-based refrigeration systems and towards the so-called 'natural refrigerants', including primarily ammonia, CO_2 and hydrocarbons.[90]

The United Kingdom (UK) has seen the most rapid shift to natural refrigerants, with a 24 per cent increase from 2012 to 2013 in the number of HFC-free or hybrid technology systems, bringing the total number of systems to 428. Developments include:

- Tesco continues to roll out natural refrigeration systems and to encourage best practices in refrigeration systems throughout its supply chain via the online Tesco Knowledge Hub, which enables supermarket suppliers to share best practices.
- Waitrose is aiming to operate totally HFC-free by 2021, with about one-third of its 280 stores running on natural refrigerants by 2013.
- Marks & Spencer continues to roll out hybrid systems, increasing the number of stores running on this technology to 76 (from 42 in 2012) of its 798 UK stores, as well as developing various other systems that use ammonia, hydrocarbons or CO_2.
- Other supermarkets, such as Lidl, are taking more time to transition to HFC-free solutions for all cooling applications. However, even this retailer is moving away from HFCs in its frozen food systems, with half of all freezer units running on hydrocarbons.

Across Europe, 589 stores use hybrid cooling technology systems, with both HFC and natural refrigerants working together for a lower carbon footprint, while over 1,000 additional stores are using at least one HFC-free technology.[91] Developments include:

- From 2012 to 2013, Royal Ahold increased the number of hybrid HFC/CO_2 stores it operates by about 30 per cent, reaching a total of well over 200 stores in the Netherlands and Belgium – over a quarter of its estate.
- Coop Schweiz increased the number of its stores running on 100 per cent CO_2 systems by around 30 per cent, reaching about 200 stores in total, also a quarter of its entire estate; the company plans to replace all refrigerants in its stores with CO_2 during the next ten years.
- Delhaize Group almost reached its stated target for 2012, which was to roll out a further 15 stores using hybrid technology, reaching a total of 40.

In addition to this, many supermarkets have pledged to install only HFC-free systems in all new and refurbished stores, including Aldi Sud (only in Germany), Coop Norge, Coop Sverige, Coop Schweiz, ICA, Migros, Sainsbury's, Tesco (only in larger British stores), and Waitrose. These figures do not include details of the thousands of stores using stand-alone hydrocarbon frozen food display cases.[92]

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[90] EIA (2013) Chilling Facts V, http://eia-international.org/chilling-facts-v. See also the CCAC case studies: http://www.unep.org/ccac/portals/50162/docs/Low-GWP_Alternatives_in_Commercial_Refrigeration-Case_Studies-Final.pdf.

[91] Hybrid supermarket refrigeration typically uses a flammable and/or toxic natural refrigerant along with a non-flammable HFC refrigerant either in a cascade relationship or with a secondary loop. The cascade system achieves medium temperature refrigeration with the first refrigerant and then continues to refrigerate with a second refrigerant to achieve cold temperatures. A secondary loop system cools with a natural refrigerant and uses an HFC to circulate the cold to the refrigerated cases. The natural refrigerant is typically hydrocarbon, ammonia, or CO_2.

[92] This report uses 'stand-alone' to describe small refrigerators and freezers used in both residential and commercial applications that are manufactured with all components contained within the appliance. Stand-alone appliances are also called 'plug-and-play' and 'free-standing.'

Some of the retailers surveyed are relying quite heavily on CO_2/HFC hybrids in their transition plans. And while many supermarkets are using hydrocarbons in their freezer units, they are not yet using non-fluorinated alternatives in their chilled food integrals and many have highlighted a need for further technical developments in this area.

The major sources of HFC emissions from supermarkets are leakage from their refrigeration systems. In Europe, annual HFC emissions from the retail sector are expected to reach 17.6 $MtCO_2eq$ in 2015, equivalent to the annual CO_2 emissions of almost six coal-fired power stations.[93] Despite containment measures, absolute emissions (in CO_2-equivalent terms) from leaking refrigerant gases are still higher than the total emissions associated with energy use from the systems. A range of options is available to reduce leakage rates, including using leakage detection systems, hand-held detectors (which are usually more precise), revising system design to minimise pipework, switching from direct to indirect systems, reducing average refrigerant charge, and using sealed units. Replacing high-GWP with low-GWP HFCs can be an interim solution; Marks & Spencer, for example, has now almost completed its programme to replace HFC-404A used in its refrigeration systems with HFC-407.

Refrigeration accounts for the bulk of a supermarket's total electricity consumption and is estimated to represent about 3–4 per cent of the total sales price of a refrigerated food or drink item.[94] Experience suggests that switching to HFC alternatives often brings significant energy-efficiency improvements. Examples include:[95]

- Coop Schweiz: reductions in energy use of about 30 per cent after installing CO_2 transcritical systems.
- Delhaize Group: cascade and transcritical CO_2 systems use less energy than installations running on HFC-404A.
- Auchan (Hungary): energy savings of 35 per cent with hybrid CO_2-ammonia systems compared with previous HFC installations.
- Waitrose (UK): hydrocarbon water-cooled refrigeration system uses about 20 per cent less energy compared to its traditional HFC systems.
- AEON (Japan): energy savings of 10 - 30 per cent and an overall CO_2 reduction of 50 per cent in stores it has converted to CO_2 since 2009. The retailer notes that its transcritical direct expansion CO_2 systems provide high reliability and high efficiency even in hot and humid climates.
- Tesco: water-cooled hydrocarbon systems in one of its Thai stores have led to 5 per cent energy savings.
- Pick 'n Pay (South Africa): hybrid cascade systems running on CO_2 and ammonia in two of its supermarkets in Cape Town (medium ambient temperature) and Johannesburg (high ambient temperature) saw energy savings of 19 - 26 per cent.

7.2 Case Study: Methyl formate foam

Large sophisticated companies can use a wide range of highly flammable foam-blowing agents, but the costs of appropriate safety measures are too much for SMEs.

Methyl formate is an ozone-safe, negligible-GWP alternative to HCFCs in a wide range of foam applications. As a pure chemical, methyl formate is highly flammable, but it can be used safely

[93] Estimate based on full implementation of the containment and recovery measures in the pre-2014 EU F-Gas Regulation; Oko-Recherche *et al.* (2011) Preparatory Study for a Review of Regulation (EU) No 842/2006 on Certain Fluorinated Greenhouse Gases, Final Report, Annex V, pp. 245–47 and Annex VI, pp. 280–89.

[94] Irrek (2013) Policy options for ecodesign and labelling of commercial refrigeration, http://www.eceee.org/ecodesign/products/commercial_refrigerators_freezers/Wuppertal_presentation_23April2010

[95] EIA (2013) Chilling Facts V, http://eia-international.org/chilling-facts-v, pp. 11–12.

in a pre-blended form with other foam ingredients. UNDP recommends that foam system houses qualified for the safe use of flammable ingredients produce the pre-blended foam mix that can then be safely used by SMEs and other downstream users (UNDP 2010).[96]

At its 56th meeting, the Executive Committee of the MLF approved a demonstration project that gave UNDP the mandate to 1) assess the application of methyl-formate (MF) based systems (Ecomate™) in the manufacture of polyurethane foam, 2) compare the technical performance of the new systems with HCFC-141b-based systems, and 3) establish the feasibility of using methyl-formate-based systems in MLF projects.

A pilot project has been designed around Purcom Quimica, the largest independent foam technology system house in Brazil, which specializes in tailor-made polyurethane (PU) systems covering most PU applications. The project assessed 15 applications in moulded flexible slabstock, elastomers, integral skin and rigid foam sub-sectors. The application of PU foam in shoe-soles was assessed through a pilot project executed by Quimiuretanos Zadro, a system house in Mexico that specializes in PU soles used in the manufacture of shoes (UNDP 2012).[97]

The successful projects in Mexico and Brazil were the prelude to rapid market penetration of the technology in twelve A5 Parties funded by the MLF. According to the MLF secretariat, implementation involved more than fifteen local foam system houses and hundreds of downstream users, with a total of 5,000 metric tonnes of HCFC-141b phased out.[98]

Methyl formate is not only the technology selected for a large number of applications in Latin American countries, but also has had penetration in countries in other regions. Currently, methyl formate systems are being commercialized in Australia, Brazil, Cameroon, Canada, China, former Soviet countries, Colombia, Dominican Republic, Ecuador, Egypt, El Salvador, India, Indonesia, Jamaica, Mexico, New Zealand, Nigeria, Philippines, Russian Federation, Singapore, South Africa, South Korea, Turkey, Trinidad and Tobago, the US, and Vietnam.[99]

In Brazil, methyl formate foam also is used in the manufacturing of houses for low-income families.[100] Houses have been built using this technology in Africa and South America (Angola, Mozambique, Paraguay and Uruguay). The technology also can be used to provide low-cost construction in countries where people have been displaced after natural disasters. The market penetration of methyl formate technology and the technical assistance that system houses such as Purcom have provided to A5 Parties are positive examples of South-South cooperation to protect the ozone layer and mitigate climate change.

7.3 Case Study: Energy efficient HFC-32 room A/Cs

Between 2007 and 2010, manufacturers in most non-A5 Parties worldwide selected HFC-410A, which is a 50/50 blend of HFC-32 and HFC-125, to replace HCFC-22 in room A/Cs because HFC-410A is non-flammable. Other refrigerants using HFC-125 to reduce flammability are HFC-407C (23 per cent HFC-32, 25 per cent HFC-125, 52 per cent HFC-134a) and HFC404A (44 per cent HFC-125, 52 per cent HFC-142a, 4 per cent HFC-134a). However, Daikin and other Japanese companies regretted the choice of HFC-410A because it has a high GWP and low energy efficiency. Even as Japanese companies commercialized HFC-410A equipment, they aimed to find ways to design room A/Cs to safely use HFC-32, which has one-third the GWP, is classified as A2L (mildly flammable), uses less refrigerant charge than HFC-410A, and achieves higher energy efficiency.

[96] UNDP (2010) Methyl Formate as Blowing Agent in the Manufacture of Polyurethane Foam Systems An Assessment for the Application in MLF Projects.
[97] UNDP (2012) Methyl Formate as Blowing Agent in the Manufacture of Polyurethane Foam Systems An Assessment for the Application in MLF Projects.
[98] UNEP (2014) Overview of Approved HCFC Demonstration Projects and Options for Additional Projects to Demonstrate Climate-Friendly and Energy-Efficient Alternative Technologies to HCFCs (Decision 71/51 (a)), UNEP/OzL.Pro/ExCom/72/40.
[99] Personal communication with FSI, September 2014.
[100] www.casamodularfischer.com.br.

In 2009, a team of scientists led by Guus Velders published estimates that HFC emissions could increase to as much as 40 per cent of the growth in climate forcing from CO_2 by mid-century as a consequence of rapid increases in the use of room and vehicle air conditioning in A5 Parties.[101] In early 2010, members of the Executive Committee of the MLF and executives from UNDP became concerned that the HCFC Phase-out Management Plans (HPMPs) of Article 5 Parties would make the same mistake as non-A5 Parties in selecting HFC-410A.

The Indonesia HPMP, implemented by UNDP, was the first where the MLF Executive Committee requested a better solution to tackle the climate impact of the HFC-410A selection made by Panasonic Indonesia.[102] In view of that, UNDP, Indonesian government officials, and the Japan Ministry for Economy, Trade and Industry (METI) agreed to cooperate in persuading the major manufacturers of air conditioning and refrigeration equipment in Japan to adopt more environmentally sound alternative technology, particularly for the conversion of HCFC-22-based room A/Cs manufactured in Indonesia in joint ventures. They invited experts from Daikin, Panasonic, and IGSD to an organizing meeting in Tokyo in June 2011, where it was agreed that the Japanese room air conditioning industry would change direction and commercialize HFC-32 for room A/Cs and possibly for other refrigeration and air conditioning applications.[103]

HFC-32 is a very old chemical with expired patents for manufacture, but Daikin had active patents on the application of HFC-32 to room A/Cs and on several key components. Daikin appreciated the importance of HFC-32 technology in protecting against climate change, but realized that commercialization would only be successful if many companies chose the same technology. Daikin also realized that companies in A5 Parties might not be able to afford IP licensing fees. The solution that emerged was a joint announcement in September 2011 that Daikin would shift to HFC-32 in all global markets and grant without charge 'non-assertion contracts' to allow companies in most A5 Parties to use Daikin patents in the manufacture of HFC-32 room A/Cs for sale in both A5 Parties and non-A5 Parties. Companies manufacturing HFC-32 room A/Cs in non-A5 Parties may use Daikin's HFC-32 application patents without paying licensing fees if they provide an equal number of air conditioning application patents for Daikin to use without paying licensing fees.[104]

On 11 June 2011, UNDP submitted a document in response to MLF Decision 63/55 (regarding the Indonesian HPMP) for consideration by the Executive Committee at its 64th meeting, including these pledges on lower GWP, energy efficiency, and environmental trade barriers as incentives:

> Daikin and Panasonic will introduce, support and promote HFC-32 technology (GWP 675, atmospheric lifetime 4.9 years and energy efficiency gains of up to 10 per cent over other alternatives) for air conditioning and refrigeration applications including room A/Cs in Indonesia.
>
> Indonesian government would work closely with the industry to ensure appropriate regulations, standards and infrastructure for managing the safe use of this technology throughout the product lifecycle. The proposed regulations could include restricting import of products/substances with high GWP.

The simultaneous strategy of the HFC-32 partnership is to transform the entire global market to HFC-32 in applications where it has the lowest achievable carbon footprint, as measured by LCCP. It is noteworthy that with the cooperation of industry and government, Japan was able to revise its safety standards that entirely prohibited flammable refrigerants more rapidly than other A5 and

[101] The Velders paper estimated that HFCs could constitute up to 0.4Wm-2 in 2050, which would be a maximum of 16 per cent of CO_2 forcing in the lowest CO_2 scenario and 14 per cent of total forcing in the lowest forcing scenario. HFC forcing (.4Wm-2) would be up to 40 per cent of the growth in CO_2 forcing since 2000 (i.e. CO_2 going from 1.5 Wm-2 in 2000 to 2.51 Wm-2 in 2050, and .4Wm-2 from HFCs being 40 per cent of CO_2's 1.0 Wm-2 growth over the 2000-2050 period).

[102] UNDP, Project Proposals: Indonesia, Executive Committee of The Multilateral Fund For The Implementation Of The Montreal Protocol, Sixty-fourth Meeting Montreal, 25-29 July 2011, UNEP/OzL.Pro/ExCom/64/34 15 June 2011: http://www.multilateralfund.org/MeetingsandDocuments/currentmeeting/64/English/1/6434.pdf.

[103] Sadatani, S. (2011) *Indonesia-Japan HFC-32 Partnership Targets Room Air Conditioner Market* (25 September) JARN.

[104] Stanga, M. (2013) *Update on R32 Air-conditioning and Heat Pump Manufacturing and Sales*, Workshop on the sidelines of the 2013 Montreal Protocol Open-Ended Working Group (OEWG) (29 June 2013). http://www.unep.fr/bangkoktechconference/docs/IIIB-3%20Mark%20Stanga%20Daikin.pdf

non-A5 Parties have been able to modify barriers to flammable refrigerant or implement safety standards where none had previously existed.

Successes to date include:

- November 2012: Daikin launched HFC-32 room A/Cs in the Japanese market, which earned the 'Top Runner' award for highest available energy efficiency.[105]
- March 2013: India became the first developing country to manufacture and market HFC-32 room A/Cs, which were produced in a Daikin factory with a capacity to produce up to one million units per year.[106]
- June 2013: All Daikin room A/Cs sold in Japan use HFC-32 (54 models).
- Autumn 2013: Daikin introduced HFC-32 room A/Cs in Europe with seasonal energy-efficiency ratio (SEER) of up to 9.54 and seasonal coefficient of performance (SCOP) of up to 5.9 (A+++), making them the most energy-efficient in the European market.
- As of May 2014, Daikin group has launched HFC-32 room A/Cs in Albania, Australia, Austria, Belgium, Croatia, Czech Republic, Estonia, Lithuania, Romania, Slovakia, Slovenia, Germany, Denmark, Spain, Finland, France, Greece, India, Italy, Japan, The Netherlands, Norway, Poland, Portugal, Russia, UK, Sweden, Thailand, Ukraine, Montenegro.[107]
- To date: Daikin has sold 150,000 HFC-32 room A/Cs in India, with 10,000 local installers trained to install HFC-32 room A/Cs in India
- To date: HFC-32 room A/Cs manufactured and/or marketed in Australia, China, EU (27 countries), India, Japan; manufacturers include Daikin, Fujitsu General, Gree, Hitachi, Midea, Mitsubishi Electric, Panasonic and Toshiba.
- 2014: Fujitsu General launched HFC-32 room A/Cs in India.
- 2015: Panasonic to launch HFC-32 manufacture in Indonesia and Thailand.

7.4 Case Study: Hydrocarbon-290 (propane) room A/Cs in China

China is the largest global manufacturer of room air conditioning, with about half of its production sold in China and half in Asia, Europe and North America. Thus, room A/C manufacturers in China need to phase out HCFC-22 to satisfy the Montreal Protocol and at the same time satisfy the phase-down in applications in 2002.[108]

In bilateral cooperation with Germany and the MLF, and with UNIDO as the implementing agency, demonstration projects to convert from HCFC-22 to HC-290 (propane) have been or are under implementation at Gree Electric Appliances Inc. (Germany) and at Midea (MLF/UNIDO).[109]

[105] Daikin, Press Release, *World's First Commercialization of* Air Conditioning *Equipment Using Next-Generation Refrigerant HFC32*, 27 September 2012: http://www.daikin.com/press/2012/120927/index.html.

[106] Stephen O. A., P. S. Chidambaram, B. Deol, D. Doniger, A. Ghosh, A. Jaiswal, R. Palakshappa, J. Schmidt, & G. Sethi (2013) Cooling India with Less Warming: The Business Case for Phasing Down HFCs in Room and Vehicle Air Conditioning, Council on Energy, Environment & Water (CEEW), the Institute for Governance & Sustainable Development (IGSD), the Natural Resources Defense Council (NRDC), and The Energy and Resources Institute (TERI) in cooperation with the Confederation of Indian Industry (CII).

[107] Daikin, *Start of Use of R32, a Low Global Warming Potential Refrigerant*, http://www.daikin.com/csr/environment/production/06.html (accessed 31 October 2014).

[108] Danish Statutory Order, no. 552 taxes most applications of HFCs, PFCs, and HF_6 from 2002. There is a general ban on new products containing or using F-gases from 1 January 2006. HFC for mobile air conditioning is exempt from the tax, and HFCs are still allowed for cooling equipment, with refrigerant charges between 0.15 kg to 10 kg and for service of all existing equipment.

[109] The demonstration sub-project for conversion from HCFC-22 to HC-290 (propane) at Midea Room Air-Conditioner Manufacturer Company was approved at the 61st Executive Committee meeting (UNEP/OzL.Pro/ExCom/61/X).

The bilateral cooperation project with Germany was implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)-Proklima under the International Climate Initiative of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit—BMU) and in cooperation with the Chinese Ministry for Environmental Protection/Foreign Economic Cooperation Office (MEP/FEUO) and the Chinese Household Electrical Appliances Association (CHEAA). The project converted one production line of room air conditioning systems of the Chinese manufacturer Gree Electric Appliances Inc. to use HC-290. Gree is the biggest manufacturer of room A/Cs worldwide, with 35 million units manufactured per year.[110] Germany undertook a similar project with Godrej in India.[111]

Such demonstration projects at the country level have been crucial to A5 countries and, in the specific case of China, critical to ascertain the feasibility of propane (HC-290) use in the room air conditioning subsector, particularly in smaller split room A/Cs. The room A/Cs used are selected in such a way that the cooling capacity is sufficient to provide comfort, but the refrigerant amount is small enough to be safe if it is released into the room. The results could also be applied for small, self-contained A/Cs (i.e. window or wall room air conditioning), according to the MLF.[112]

The original ambition of GIZ (previously GTZ) was to design and manufacture room A/Cs that could be approved for sale in Germany and the EU, with the advantage that the EU F-Gas Regulation could be crafted to phase down HFC-410A room A/Cs in Europe on a schedule that allowed China and other Parties to shift production from HCFC-22 and HFC-410A appliances to HC-290. So far, China has been more agile than the EU in revising safety standards to allow for the safe use of hydrocarbon refrigerants, with the consequence that environmentally superior technology will be implemented first in China and other A5 Parties and then transferred South-North to Europe and North America.

China's room air conditioning sector is one of the largest and, in order to meet the 2013 HCFC freeze and the 10 per cent HCFC reduction in 2015, over 7,600 metric tonnes of HCFCs had to be phased out in this sub-sector, in addition to aggressive investment in HCFC foam phase-out. In addition, three compressor manufacturers are currently being converted to HC-290 technology. One demonstration project for the conversion of room air conditioning compressor manufacturing was financed by the MLF and implemented by UNIDO.[113]

In the room air conditioning sector plan for China, the MLF has financed the incremental costs of technical assistance to SMEs, product research and development of alternative HC-290 technologies, as well as safety standard development and outreach, among others.

Being the largest producer of room A/Cs in the world, China has embraced the challenges and has been working to set new standards for the use of flammable refrigerants. Without this effort, uncertainties would hinder market penetration in and outside China, as manufacturers could only export equipment containing flammable refrigerants once the importing country has the standards in place.

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[110] GIZ, Climate-friendly room Air Conditioners on hydrocarbon technology and new standards for natural refrigerants in China, Programme Proklima, Dag-Hammarskjöld-Weg 1-5, 65760 Eschborn, Germany.

[111] Stephen O. A., P. S. Chidambaram, B. Deol, D. Doniger, A. Ghosh, A. Jaiswal, R. Palakshappa, J. Schmidt, & G. Sethi (2013) Cooling India with Less Warming: The Business Case for Phasing Down HFCs in Room and Vehicle Air Conditioning, Council on Energy, Environment & Water (CEEW), the Institute for Governance & Sustainable Development (IGSD), the Natural Resources Defense Council (NRDC), and The Energy and Resources Institute (TERI) in cooperation with the Confederation of Indian Industry (CII).; *see also* Godrej Appliances (2013) *Development and Handling Hydrocarbon Air Conditioners – The Godrej Experience*, UNFCCC Side Event, Bonn, 10 June 2013. http://ec.europa.eu/clima/events/docs/0079/rajadhyaska_en.pdf

[112] UNEP (1024) Overview of Approved HCFC Demonstration Projects and Options for Additional Projects to Demonstrate Climate-Friendly and Energy-Efficient Alternative Technologies to HCFCs (Decision 71/51 (a), UNEP/Ozl.Pro/ExCom/72/40.

[113] Ibid; and Conversion of room air-conditioning compressor manufacturing from HCFC-22 to propane at Guangdong Meizhi Co. (CPR/REF/61/DEM/502).

7.5 Case Study: Denmark's HFC phase-down[114]

Denmark was among the first countries to regulate high-GWP HFCs, with taxation of DKK100 per metric tonne of CO_2-eq. (about US$17/tonne) implemented in 2001, increased to DKK150/tonne in 2011 (about US$25/tonne), and prohibition of certain applications from 2002.[115] This conspicuous tax increased awareness of climate impacts and incentivized the development, commercialization, and market penetration of alternative technology, including natural refrigerants. The Danish regulation reduced HFC use from around 1,000 tonnes/year in 2000 to around 350 tonnes/year in 2010.

This impressive HFC phase-down was made possible by government-industry cooperation, including approximately DKK20 million (about US$3.4 million) in government support for demonstration projects and additional funding of an 'HFC Free Centre' offering up to five hours of engineering consultancy to industry and installers in support of implementing the alternative technology.

The lessons from the Danish experience are:

- Up to 2/3 of annual HFC use is avoidable with available technology and best service practices. Up to 1/3 of use is so far without suitable alternatives (in the case of Denmark: exempted refrigeration, allowed MDIs, technical aerosol products and miscellaneous uses).
- Technology is readily available in Denmark and globally for:
  - Domestic refrigerators and freezers (hydrocarbons)
  - Beverage bottle coolers (plug-in)
  - Ice makers (restaurant and hotel plug-in and wired)
  - Supermarket refrigerated display cabinets (direct expansion and secondary-loop hydrocarbon and CO_2)
  - Vaccine coolers (hydrocarbon now specified by the World Health Organization)
  - Commercial plug-in refrigerated cabinets (hydrocarbons)
  - Large supermarkets in Denmark favouring transcritical CO_2 systems
  - Industrial refrigeration and air conditioning (secondary-loop ammonia and hydrocarbons)
  - Hydrocarbon and ammonia A/Cs in medium- and larger-sizes (50 - 400kW) are expanding in use in Denmark and with export to Germany, Norway, and UK, but may not be appropriate where professional installation and servicing cannot be guaranteed over the life of the equipment.

Supermarket technologies that are 10 per cent more energy efficient than high-GWP HFCs in Denmark's northern European climate.

Manufacturers of domestic refrigerators in Denmark report that the use of hydrocarbon refrigerants requires significant investment in safety at the factory, but that, in general, no price difference exists between HFC and hydrocarbon-based appliances.

Denmark had the advantage of highly capable and environmentally motivated businesses, including appliance and component manufacturers (Advansor, Danfoss, Derby, Elcold, Frigor, Gram Commercial, Knudsen Køling, Vestfrost), food processors (Carlsberg), and food retailers (Superkøl).

[114] Sources and elaboration: Pedersen, P. H. (2012) Low GWP Alternatives to HFCs in Refrigeration, Danish Environmental Protection Agency, May 2012; *see also*, Pedersen, I. & P. Henrik (1998) Ways of Reducing Consumption and Emission of the Potent Greenhouse Gases (HFCs, PFCs and SF6, The Nordic Council of Ministers, and updated in 2001 and 2006.

[115] Danish Statutory Order, no. 552 taxes most applications of HFCs, PFCs, and HF_6 from 2002 and there is a general ban on new products containing or using F-gases from 1 January 2006. HFC for mobile air conditioning is exempt from the tax and HFCs are still allowed for cooling equipment with refrigerant charges between 0.15 kg to 10 kg and for service of all existing equipment.

Overall, the government, companies, and public in Denmark are proud and satisfied with an HFC phase-down that has been incentivized by taxes and regulation and that took advantage of technical centres of excellence and government financing. Companies that supplied solutions to Denmark are profiting from sales worldwide.

7.6 Case Study: Godrej & Boyce HC-290 room A/Cs in India

Sales and use of room A/Cs in India are rapidly growing as a result of population growth, electrification, increasing income, and the long, hot season, where temperatures in most of the country typically exceed 40°C (104°F) between April and September.[116] Air conditioning demand strains India's electric grid and requires rapidly expanding electricity generation capacity and fuel use.[117] Frequent brownouts and blackouts shift generation to less efficient backup generation at hotels and office buildings, which further increases urban noise and deteriorates local air quality.[118]

India has business models for the growing supply of room A/Cs, including imports, total-knockdown assembly from imported parts, total manufacture of parts and assembly, and hybrid production with some imported components and some components manufactured locally. Some room A/C manufacturers in India are fully domestic, some are joint ventures and some are foreign-owned. Like other A5 Parties, India is phasing-out HCFC-22, which is an ozone-depleting GHG. Until recently, most companies doing business in India planned to transition to HFC-410A, which has a high-GWP and is a blend of flammable HFC-32 rendered not-flammable by HFC-125, which also reduces energy efficiency.

Indian appliance manufacturer Godrej & Boyce welcomed the offer of the German development agency GIZ, in collaboration with India's Ministry of Environment and Forests' Ozone Cell, to design, demonstrate and commercialize HC-290 room A/Cs at the same time that GIZ cooperated in China on similar technology (see the China case study). Godrej choose HC-290 for its superior thermodynamic properties at high ambient temperatures compared to HFC-410A. HC-290 also is available, inexpensive, and unprotected by patents.

Godrej, with the support of GIZ, designed 1.0- and 1.5-tonne R-290-based A/Cs that achieve the highest (Five-Star) energy-efficiency rating awarded by India's Bureau of Energy Efficiency (BEE) and are sold at prices comparable to room A/Cs with the same energy rating based on HCFC-22, HFC-410A and HFC-32. Godrej has sold over 100,000 HC-290 room A/Cs manufactured in a facility with a production capacity of 180,000 R-290-based A/Cs per year.[119]

HC-290 is a flammable refrigerant that satisfies European and international safety standards for 1.0 to 1.5 tonne capacity for use in rooms small enough to be cooled but large enough to dilute the small refrigerant charge to a concentration safely below its lower flammability limit.[120] Godrej has a four-part strategy for the safe use of HC-290: 1) designing the appliance and manufacturing facility to minimize risks; 2) limiting the quantity of refrigerant charge in the A/C according to international safety standards; 3) installing the A/C using factory-trained technicians, and 4) safety procedures and training of service personnel.

[116] Andersen, S. O., P. S. Chidambaram, B. Deol, D. Doniger, A. Ghosh, A. Jaiswal, R. Palakshappa, J. Schmidt, & G. Sethi (2013) Cooling India with Less Warming: The Business Case for Phasing Down HFCs in Room and Vehicle Air Conditioners, published jointly by the Council on Energy, Environment & Water (CEEW), the Institute for Governance & Sustainable Development (IGSD), the Natural Resources Defense Council (NRDC), and The Energy and Resources Institute (TERI) in cooperation with the Confederation of Indian Industry (CII).

[117] NRDC (2014) Air Conditioners with Hydrocarbon Refrigerant – Saving Energy while Saving Money: A Profile of Propane (HC-290) Based Room Air Conditioner by Godrej & Boyce.

[118] Phadke, A. A., N. Abhyankar, & N. Shah (2014) Avoiding 100 New Power Plants by Increasing Efficiency of Room Air Conditioners in India: Opportunities and Challenges, June 2014, http://eetd.lbl.gov/publications/avoiding-100-new-power-plants-by-incr.

[119] NRDC (2014) Air Conditioners with Hydrocarbon Refrigerant – Saving Energy while Saving Money: A Profile of Propane (HC-290) Based Room Air Conditioner by Godrej & Boyce.

[120] GIZ (2011) Production conversion of domestic refrigerators from halogenated to hydrocarbon refrigerants, A Guideline, http://www.thai-german-cooperation.info/download/2011_production_conversion.pdf.

Godrej & Boyce was the first company in India and among the first in the world to use hydrocarbon refrigerant (HC-600) in the manufacture of domestic refrigerators.[121] The company prides itself on environmental and social leadership, which continues to be demonstrated by the introduction of hydrocarbons in room air conditioning.

8 Conclusion

Rising HFC use consequent upon the success of the Montreal Protocol in phasing out ODSs and upon growing global demand for refrigeration and air conditioning poses a significant threat to global efforts to combat climate change and to keep global temperature rise below 2° C. Even in the absence of a strong international framework to constrain HFC production and consumption, however, many governments and industries are making sustained efforts to reduce HFC use and to introduce new alternatives with lower or no climate impact.

A wide range of alternatives to high-GWP HFCs is now available, with more under development, but many of these are very new, and knowledge of their availability, cost-effectiveness, safety, applicability in high-ambient-temperature environments, maintenance requirements and other factors is often limited. Not surprisingly, therefore, many developing countries in particular have expressed concerns over the availability of alternatives to HFCs, and the feasibility of introducing them, particularly given that, in many cases, they are just beginning the process of phasing out HCFCs.

This report summarises in an accessible form: 1) the latest state of knowledge of the availability and characteristics of current alternatives to HFCs in the key sectors, 2) a discussion of barriers to their uptake and how they can be overcome; 3) the crucial issue of the energy efficiency of HFC-using systems and their alternatives; and 4) the potential for accessing financial support for the replacement of HFCs.

The case studies in Section 7 show that HFCs can be and are being successfully replaced in a wide range of uses in both developing and developed countries. Given this progress with the introduction of HFC alternatives, and the gradual spread of national and regional regulations and voluntary industry commitments, more and more countries will need to address the question of HFC phase-down whether or not the Montreal Protocol is amended to include HFCs.

HFC alternatives are available to tackle the growing threat to Earth's climate.

[121] Godrej and Boyce developed the Indian HC-600 domestic refrigerator in cooperation with Dr. Radhey Agarwal who was then Dean and Professor at the India Institute of Technology (IIT) and Co-Chair of the TEAP Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee and Dr. Sukumar Devotta who was then Director of the National Environment Engineering Research Institute (NEERI) in Nagpur, India, and member of the TEAP RTOC. Now Dr. Agarwal is Senior Advisor and Coordinator of Sector Phase-out Plan Unit (SPPU), Ozone Cell, India. Dr. Devotta is advisor to various Indian government bodies including Ministry of Environment & Forests and Department of Science & Technology and other organizations. Dr. Devotta continues as a member of the TEAP RTOC.

Annex 1: Acronyms

A/C	air conditioner
ADB	Asian Development Bank
AfDB	African Development Bank
AHRI	Air Conditioning, Heating and Refrigeration Institute
AOSIS	Alliance of Small Island States
A5 Parties	Article 5 Parties to the Montreal Protocol (see definition in Annex 2)
AR-5	Fifth Assessment Report of the IPCC
ARAP	Alliance for Responsible Atmospheric Policy
ARB	Air Resource Board (California)
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BAU	business as usual
BEE	Bureau of Energy Efficiency (BEE)
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
CAFE	corporate average fuel economy
CCAC	Climate and Clean Air Coalition to Reduce Short-lived Climate Pollutants
CDB	Caribbean Development Bank
CEDHA	Center for Human Rights and Environment
CEEW	Council on Energy, Environment & Water (India)
CFC	chlorofluorocarbon
CFO	chlorofluoroolefins
CHEAA	Chinese Household Electrical Appliances Association
CIF	Climate Investment Fund
CIS	Commonwealth of Independent States
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
COPD	chronic obstructive pulmonary disease
CTF	Clean Technology Fund
DOE	Department of Energy (US)
EBRD	European Bank for Reconstruction and Development
EIA	Environmental Investigation Agency
EPA	Environmental Protection Agency (US)
ESMA	Emirates Authority for Standardisation and Metrology
EU	European Union

EUE	essential-use exemptions
FBRD	Foreign Economic Cooperation Office (China)
F-Gas	fluorinated gas
GCF	The Green Climate Fund
GEF	Global Environment Facility
GFCC	Global Food Chain Council
GHG	greenhouse gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
Gt	gigatonne
GWP	global warming potential
HC	hydrocarbon
HCFC	hydrochlorofluorocarbon
HCFO	hydrochlorofluoroolefin
HCO	oxygenated hydrocarbons
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HPMP	HCFC Phase-out Management Plan
IADB	Inter-American Development Bank
IGSD	Institute for Governance & Sustainable Development
IP	intellectual property
IPCC	Intergovernmental Panel on Climate Change
ISHRAE	Indian Society of Heating Refrigeration and Air Conditioner Engineers
ISO	International Standards Organisation
LCCP	Life-Cycle Climate Performance
MAC	mobile air conditioning or air conditioner
MDI	metered-dose inhaler
MEP	Ministry for Environmental Protection (China)
METI	Ministry of Economy, Trade & Industry (Japan)
MLF	Multilateral Fund of the Montreal Protocol
MOP	meeting of the Parties (to the Montreal Protocol)
MTOC	Medical Technical Options Committee (of TEAP)
NGO	non-governmental organization
NIK	not-in-kind
NRDC	Natural Resources Defense Council
ODP	ozone-depletion potential
ODS	ozone-depleting substance

OEWG	Open-Ended Working Group (Montreal Protocol)
PCE	tetrachloroethene
PFC	perfluorocarbon
PPCR	Pilot Programme for Climate Resilience
PPM	parts per million
PU	polyurethane
QPI	Quantity Performance (finance) Instruments
RAMA	Refrigeration and Air-Conditioning Manufacturer's Association (India)
REACH	Registration, Evaluation, and Authorisation and Restriction of Chemicals (EU)
SAE	Society of Automotive Engineers International
SCOP	seasonal coefficient of performance
SEAD	Super-efficient Equipment and Appliance Deployment Initiative
SEER	seasonal energy-efficiency ratio
SG	Secretary General (of the United Nations)
SLCPs	short-lived climate pollutants
SMEs	small- and medium-sized enterprises
SNAP	Significant New Alternatives Policy Programme
SREP	Scaling Up Renewable Energy in Low Income Countries Programme
TCE	trichloroethene
TEAP	Technology and Economic Assessment Panel
TERI	The Energy and Resources Institute
TFA	trifluoroacetic acid
TOC	Technical Options Committee, organized by sector under the Montreal Protocol
UK	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
US	United States of America
VOC	volatile organic compounds
WMO	World Meteorological Organization
XPS	extruded polystyrene

Annex 2: Definitions

Agreed incremental costs—costs to Article 5 Parties of implementing alternatives to ozone-depleting substances that will be paid by the Multilateral Fund (MLF).

AR-5 GWP 100-yr—the global warming potential (GWP) of a substance over a 100-year interval relative to carbon dioxide (CO_2), which has a GWP set to 1. GWP is measured by the amount of heat a substance traps in the atmosphere as a function of infrared radiation absorbed, the atmospheric lifetime of the substance, and its absorbing wavelength.

Article 5 Parties (A5 Parties)—countries that qualify for assistance under the Montreal Protocol in terms of extensions of deadlines and financial aid in transitioning to non-ozone-depleting substances, including the development of HCFC Phase-out Management Plans (HPMPs).

Cascade refrigeration systems—refrigeration systems that use two or more refrigerants, with the first system cooling to medium (refrigerated) temperatures and the second system cooling from the medium refrigerated temperatures to low (freezing) temperatures. Each refrigerant is selected to be most energy efficient for the specific temperature range of ambient and conditioned space.

Direct (centralized) expansion refrigeration systems—centralized direct expansion (DX) systems mount compressors together and share suction and discharge refrigeration lines that run throughout the food store, feeding pressurized liquid refrigerant to cases and coolers where the refrigerant is expanded to cool the food. Markets typically have one system for medium temperature refrigeration (e.g. meat, fish, prepared foods, dairy, refrigerated drinks) and another system for low temperature refrigeration (frozen foods).

Direct (distributed) expansion refrigeration systems—distributed DX systems use multiple smaller compressors and evaporators located closer to the display cases they cool, either on the roof or behind a wall. In some cases, the proximity of compressors and evaporators to cases and coolers requires less piping and smaller refrigerant charges than centralized DX systems, which can result in lower refrigerant emissions.

European Commission (EC)—the executive institution of the European Union (EU), with responsibility for managing the EU, including proposing and implementing legislation and ensuring treaty compliance.

Funding Window—See Window below.

Hydrochlorofluorocarbons (HCFCs)—chemical compounds composed of hydrogen, chlorine, fluorine and carbon atoms. HCFCs have ozone-depleting properties and also are GHGs.

Hydrofluorocarbons (HFCs)—chemical compounds that contain hydrogen, fluorine and carbon atoms. They do not deplete the stratospheric ozone layer, but trap heat and are considered GHGs.

Hydrofluoroolefins (HFOs)—chemical compounds composed of hydrogen, fluorine, and carbon and derived from alkenes (olefins).

Montreal Protocol—the Montreal Protocol on Substances that Deplete the Ozone Layer, adopted in Montreal on 16 September 1987 and as subsequently adjusted and amended.

Multiplex direct expansion refrigeration—refers to display cases and cold store rooms that use direct expansion air-refrigerant coils that are connected by tubing to compressors in a remote machine room located in the back or on the roof of the store.

Non-Article 5 Parties (Non-A5 Parties)—countries subject to stringent control schedules for eliminating ozone-depleting substances under Article 5 of the Montreal Protocol.

Secondary-loop air conditioning systems—typically use a toxic and/or flammable refrigerant to cool a non-toxic, non-flammable heat transfer fluid that is circulated to occupied location(s) where cooling is wanted.

Secondary-loop refrigeration systems—typically use a toxic and/or flammable refrigerant to cool a non-toxic, non-flammable heat transfer fluid that is circulated to medium-temperature refrigerated display cases throughout the building.

Stand-alone refrigerators and freezers—cooling units with all components mounted in the appliance.

Transcritical CO_2 systems—Transcritical systems use CO_2 as the primary refrigerant in equipment designs that evaporate CO_2 in the subcritical region and reject heat in a gas cooler instead of a condenser at temperatures above the critical point.

Window or Funding Window—The idea of a 'funding window' is to organize financing management such that applicants can simply and efficiently accomplish the objective of the conventions and protocols. Under the Montreal Protocol there is one window managed by the MLF to finance compliance with the A5 control schedules for ODSs. A more comprehensive MLF window could offer financing to avoid HFCs in the phase-out of HCFCs, phase-down of HFCs in existing uses, increased energy efficiency of refrigeration, air conditioning, and thermal insulating foam.

Annex 3: Availabilities and properties of low-GWP Alternatives to HCFCs and HFCs

HFCs were invented and commercialized as chemical substitutes for about 15 per cent of the original uses of ODSs for which non-fluorocarbon alternatives were not selected. HFCs are ozone-safe chemicals that typically have GWPs far lower than the ODSs they replace, with the important exceptions of HFCs replacing HCFCs where HFC GWPs are comparable or higher. HFCs were used as transition substances in foam blowing, but are rapidly being replaced in existing foam uses and avoided by both non-A5 and A5 Parties in the phase-out of HCFC foams. HFCs were also used as substitutes for refrigerants, but are now being replaced by a combination of available natural refrigerants, HFOs, and low-GWP HFCs. Many new low-GWP refrigerants and refrigerant blends are being investigated.

Numbering scheme for fluorinated substances

In CFCs and HCFCs, the first 'C' is for chlorine (atomic symbol: Cl) and in all refrigerants, 'F' is for fluorine (atomic symbol: F), 'H' is for hydrogen (atomic symbol: H) and the final 'C' is for carbon (atomic symbol: C). It can be useful in describing some substances to specify where the hydrogen and fluorine is on the carbons and to specify optical isomers that exist when there is a double bond. For example, $C_4H_2F_6$ ($CF_3Ch{=}ChCF_3$) can be written as HFO-1336 to specify how many carbons, hydrogens, fluorines and double bonds; as HFO-1336mzz to add specification of where the hydrogen and fluorine is on the carbons; and as HFO-1336mzz-Z to specify which optimal isomer.

Fluorinated refrigerants

Chemical prefix	Common name	Atoms in molecule			
		H	Cl	F	C
CFC	Chlorofluorocarbon		X	X	X
HCFC	Hydrochlorofluorocarbon	X	X	X	X
HFC	Hydrofluorocarbon	X		X	X
HC	Hydrocarbon	X			X
HFO*	Hydrofluoroolefin	X		X	X

*Propene isomers contain an unsaturated (carbon-carbon double) bond. The fluorinated isomers also can be identified with the prefixes R or Refrigerant and also as HFO (hydrofluoroolefin), HFA (hydrofluoroalkene), or HFC (hydrofluorocarbon).

All substances used as refrigerants are numbered according to an internationally accepted formula with the letter 'R' or 'Refrigerant' followed by a number based on chemical properties. Thus, CFC-12 may also be written as R-12 or Refrigerant 12.[1] HFO-1234yf can also be referred to as R-1234yf, Refrigerant-1234yf, HFA-1234yf, or HFC-1234yf.

Some blends of refrigerants contain only one group of chemicals and therefore can be designated within that group. For example, HFC-410A contains HFC-32 and HFC-125 and can be designated as HFC-410A. However, some blends of refrigerants contain a combination of HFCs, HCFCs, HFOs, HCs and even CO_2 and therefore cannot be characterized in any one chemical group. For example, R-401A contains HCFC-22, HFC-152a, and HCFC-124, and therefore can only be accurately referred to as R-401A or Refrigerant-401A.

[1] For an explanation of decoding the number system for CFC, HCFC, and HFO refrigerants see: http://www.epa.gov/ozone/geninfo/numbers.html#prefixes. For an explanation of decoding the number system for HFO refrigerants see: Brown, J. S. (2009) *HFOs: New, Low Global Warming Potential Refrigerants*, ASHRAE Journal, https://www.ashrae.org/.../docLib/.../Brown-0809–featureofweek.pdf.

Refrigerant blends are assigned numbers serially, with the first zeotropic blend numbered R-400 and the first azeotropic blend numbered R-500. Blends that contain the same components but in differing percentages are distinguished by capital letters. For example, R-401A contains 53 per cent HCFC-22, 13 per cent HFC-152a, and 34 per cent HCFC-124, but R-401B contains 61 per cent HCFC-22, 11 per cent HFC-152a, and 28 per cent HCFC-124.

Refrigerant brand names

Most chemical manufacturers and some chemical distributors use brand names for their products. The Montreal Protocol TEAP and OzonAction frequently publish lists of common trade names of ODSs, but there is no similar consolidated list available from UNEP for alternatives to HFCs.[2]

Indicative list of brand names for alternatives to ODSs[3]

	Refrigerant	**Foam-blowing**	**Solvent, fire protection, other***
American Pacific			Halotron®
Ansul Fire Protection			Inergen®
Arkema	Forane®	Forane®	
Asahi Glass Chemical	Amolea® Asahiklin®	Asahiklin®	Asahiklin®
Ausimont	Meforex®		
Calor Gas	CARE®		
DuPont	Dymel® Suva® Opteon®	Formacel® Dymel® Suva® Opteon®	Dymel® Vertrel® Opteon®
Foam Supplies Inc.		Ecomate®	
Honeywell	Solstice®		
JSC 'Halogen'	Khladon®		
Mexichem	Klea®		
North America Fire Guardian			NAF®
Pennsylvania Engineering			Penngas®
Rhodia	ISCEON®		ISCEON®
Showa Denko	EcoloAce®		
Solvay Fluor	Solkane® Reclin®		
SRF	Floron®		
3M			CEA®, Novec®

* Fire extinguishing agents are blend of HCFCs, HFCs, PFCs, and other ingredients.

[2] *See* OzonAction. Web. Trade Names of Chemicals Containing Ozone Depleting Substances: http://www.unep.org/ozonaction/InformationResources/Tradenames/tabid/54392/Default.aspx.
[3] The authors of this assessment welcome corrections or additions to this tentative list of trade names.

Chemical nomenclature is an unreliable indicator of climate performance

Chemical nomenclature is not correlated with GWP or energy efficiency and thus is an unreliable indicator of environmental performance, climate impact or sustainability. However, it is true that natural refrigerants and HFOs have far lower GWPs than CFCs, HCFCs and HFCs.

IPCC AR5 Low and High 100-year GWPs: ODSs and Alternatives

	Lowest GWP		**Highest GWP**	
CFCs	CFC-11	4,660	CFC-13	13,900
HCFCs	HCFC-122	59	HCFC-142b	1,980
HFCs	HFC-152a	138	HFC-23	12,400
HFOs	HFO-1132a	<1	HFO-1136	2
	HFO-1141	<1		
	HFO-1225ye	<1		
	HFO-1234yf	<1		
	HFO-1234ze	<1		
	HFO-1132a	<1		
	HFO-1132a	<1		
	HFO-1345zfc	<1		
HCs	HC-600a*	3	HC-290**	3.3

US EPA is the source of GWP numbers for hydrocarbons because the IPCC does not list these substances; see: http://www.epa.gov/ozone/downloads/EPA_HFC_ComRef.pdf.
*HC-600a is isobutane
**HC-290 is propane

The metric for climate protection is Life-Cycle Climate Performance (LCCP)

LCCP is an estimate of the carbon equivalent life-cycle GHG emissions including: 1) direct chemical GHG emissions; 2) indirect CO_2 energy emissions; and 3) embodied GHG emissions associated with product manufacturing, marketing, installation, service and disposal at the end of useful product life.

Other concerns of refrigerant choice include flammability, toxicity, and environmental fate. For example, HFO-1234yf (but not other HFOs) produces trifluoroacetic acid (TFA) as an atmospheric breakdown product, and HCs are volatile organic compounds (VOCs), which contribute to the formation of ozone and photochemical smog.

Controls under the Montreal and Kyoto Protocols

Production and consumption of ozone-depleting substances is controlled under the Montreal Protocol while *emissions* of HFCs are controlled under the Kyoto Protocol. ODSs produced and 'banked' in refrigeration, air conditioning, and fire protection equipment or contained in foam are not controlled by either treaty. The Montreal Protocol currently allows non-emissive uses of ODSs as feedstocks and process agents. Carbon tetrachloride, CFC-113, HCFC-22, HCFC-225, Halon 1301,[4] and methyl chloroform are reported when used as feedstocks and process agents. HFC-23 (trifluoromethane or CHF_3) is inadvertently produced as an unwanted by-product from the production of HCFC-22, which will continue to be used as a feedstock in the manufacture of fluoropolymers, plastics and HFCs.[5]

[4] It has been reported to TEAP in 2009 that one plant in France and ten plants in China manufacture the pesticide Fipronil using halon 1301 produced in those countries as a feedstock: ozone.unep.org/.../Teap_progress_report_May2009-Corr.doc.
[5] IPCC (2009) HFC-23 Emissions from HCFC-22 Manufacture, Working Group III: Mitigation of Climate Change, Section 7.4.3.5: http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch7s7-4-3-5.html

A small number of companies in a small number of countries produce high-GWP HFCs and fluorocarbon alternatives to HFCs

Only China, India, Japan, the EU, and the US produce HFC-32, HFC-152a, HFC-134a, and HFC-125. Five or more companies have process patents to produce HFO-1234yf, and Honeywell claims an application patent for use in MACs. The process patents for HFC-32 and HFC-152a have expired and Daikin application patents for the use of HFC-32 in room A/Cs are available without charge to most companies manufacturing room A/Cs in most A5 Parties through 'non- assertion contracts.' No patents prevent the use of HFC-152a as a MAC refrigerant.

Atmospheric measures indicate that only about half of HFC production is reported to UN authorities; the table is indicative of the situation today.

Substance	**Process patent**	**Application patent**	**Countries with reported manufacture**								
			Argentina	**China**	**EU**	**India**	**Japan**	**Korea**	**Mexico**	**Russia**	**US**
HCFC-22	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
HFC-23	NA	NA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
HFC-32	Expired & Active			Yes	Yes ???	Yes	Yes	Yes			
HFC-125						Yes					
HFC-143											
HFC-152a	No			Yes			Yes	Yes			
HFC-134a				Yes	Yes	Yes	Yes				
HFO-1234yf	Many	Honeywell		Yes	Planned		Yes				

Notes: SRF India reports production of HFC-410A (50/50 blend of HFC-32/125), 404A (44/52/4 blend of HFC-125/143a/134a), and 407C (20/40/40 blend of HFC-32/125/134a). This table presumes that sale of the blends requires production of the ingredients.

Hydrocarbons used as refrigerants are heavier than air. Ignitable blends with air are therefore formed in low areas. When larger refrigerant charges are used, appropriate gas sensors and air removal devices need to be installed at floor level.

Hydrocarbons mix very well with mineral oils. The hygroscopic synthetic oils used with HFCs can be avoided, making construction and service of refrigeration systems much easier.

Isobutane (HC-600a) is the sustainable refrigerant-of-choice for residential refrigerators and freezers and small commercial stand-alone (plug-in) refrigerated and frozen food display cases sold in Europe and Asia and starting to penetrate North American and other markets. Over 40 million appliances are produced with isobutane annually worldwide. Isobutane refrigerators and freezers are quieter in operation than comparable HFC-134a units.

Propane (HC-290) is the sustainable refrigerant-of-choice for small room A/Cs and for stand-alone commercial refrigerators and freezers operating at high ambient temperature or with frequent restocking, which requires higher cooling capacity.

Propene (HC-1270) or propylene is a hydrocarbon with one unsaturated carbon bond (double carbon bond) primarily used for foam blowing.

Cyclopentane, cyclopentane/isopentane and cyclopentane/isobutane blends are globally the most frequently used blowing agents for foam in domestic refrigeration equipment.

Ammonia

Ammonia (R-717) is an ozone- and climate-safe refrigerant (ODP=0;GWP=0) suitable for large refrigeration systems. Ammonia refrigeration systems also usually achieve higher energy efficiency than HFC refrigeration systems. Ammonia is flammable and toxic, but has a pungent odour at concentrations far below the lower flammable limit and lower health effect threshold (self- alerting, self- evacuating). Gaseous ammonia is an alkaline gas that reacts very strongly with nitrogen oxides and strong acids; reacts with water to produces liquid ammonia water (ammonium hydroxide); and reacts with CO_2 to produce ammonium carbonate. Because of toxicity, ammonia is only used with indirect systems to avoid any public exposure. Recently ammonia has also been used as the higher temperature stage in CO_2 cascade refrigeration systems.

Carbon dioxide

Carbon dioxide refrigerant (CO_2 or R-744) is a colourless and odourless gas that is non-flammable, toxic, and heavier than air. The net GHG contribution of CO_2 used in refrigeration or fire fighting systems is only from the separation, purification, compression and transport of waste CO_2 that otherwise would escape directly to the atmosphere. CO_2 is safe in low concentrations, but can be harmful in higher concentrations. The maximum allowable concentration (MAC) for a workplace is 5,000 ppm or 0.5 per cent. Immediate danger to health and life (IDHL) exists for CO_2-concentration over 4 vol. per cent in air (40,000 ppm). Above 10 vol. per cent in air, CO_2 is a neurotoxin that diminishes thinking and slows reaction times. It is immediately lethal above 30 vol. per cent.

Common Name	**Refrigerant Name**	**Lifetime (days) (AR5 except as noted)**	**$GWP_{100\text{-}yr}$ (AR5 except as noted)**	**ASHRAE Safety Group**	**Flammable**
HCFC-22	R-22	4343.5	1760	A1	No
HCFC-123	R-123	474.5	79	B1	No
HCFC-141b		3358.0	338	Not yet classified by ASHRAE	
HFC-32	R-32	1898.0	677	A2L	Mildly
HFC-152a	R-152a	547.5	138	A2L	Mildly
HFO-1234yf	R-1234yf	10.5	<1	A2L	Slightly
HFO-1234ze	R-1234ze	16.4	<1	A2L	Slightly
HC-290 (Propane)	R-290	12±3	3.3 (US EPA)	A3	Highly
HC-600 (Butane)	R-600	0	4.0 (US EPA)	A3	Highly
HC-600a (Isobutane)	R-600a	0	3.3 (US EPA)	A3	Highly
Carbon Dioxide (CO_2)	R-744	Varies depending on sink	1 (GWP reference chemical)	A1	Extinguishes Fire
Ammonia	R-717			B2	Highly

Annex 4: Project Leadership

Dr Stephen O. Andersen, Director of Research, IGSD. Previously Deputy Director, Stratospheric Protection Division, United States Environmental Protection Agency and Founding Co-Chair of the Technology and Economic Assessment Panel (TEAP).

Duncan Brack, Associate Fellow, Energy, Environment and Resources, Chatham House. Previously Special Adviser to Rt Hon Chris Huhne, United Kingdom Secretary of State for Energy and Climate Change.

Dr Suely Carvalho, Research Associate, Energy and Environment Institute (IEE), University of São Paulo, Brazil; Scientific Adviser, Center Mario Molina-Chile. Previously Director of the Montreal Protocol Unit, United Nations Development Programme (UNDP), and Technology and Economic Assessment Panel (TEAP) Co-Chair.

Donnalyn Charles, Ozone Unit, Sustainable Development and Environment Division, Saint Lucia Ministry of Sustainable Development, Energy and Science and Technology.

Dr Vaibhav Chaturvedi, Research Fellow, Council on Energy, Environment and Water (CEEW).

Dr Ezra Clark, Research Scientist and Capacity Building Manager, UNEP OzonAction.

James S. Curlin, Senior Environmental Affairs, Network and Policy Manager, UNEP OzonAction.

Dr Arunabha Ghosh, Chief Executive Officer (CEO), Council on Energy, Environment and Water (CEEW).

Steve Gorman, Consultant. Previously Programme Manager for the GEF and the Multilateral Fund (MLF) at the World Bank, and previously at Environment Canada.

Dr Jianxin Hu, Professor, College of Environmental Sciences & Engineering, Peking University, China;

Dr Oswaldo dos Santos Lucon, Technical Adviser, São Paulo State Environmental Secretariat, Brazil and Associate Researcher, Institute for Energy and Environment (IEE), University of São Paulo.

Alan Miller, Consultant. Previously International Finance Corporation (IFC), GEF, University of Maryland Center for Climate Change, World Resources Institute (WRI) and Natural Resources Defense Council (NRDC).

Dr Shamila Nair-Bedouelle, Head, UNEP OzonAction.

Dr C. Shelley Norman, Economist, The Johns Hopkins University.

Sateeaved Seebaluck, Ministry of Civil Service and Administrative Reforms, Government of Mauritius. Previously Lead Montreal Protocol Negotiator for Mauritius and the Africa Group and Senior Expert Member of the TEAP.

Dr Nancy J. Sherman, Director of Technical Assessment, IGSD. Previously Department of Environmental Sciences, University of Virginia.

Mikkel Morten Aaman Sorensen, Principal Adviser, Danish Environmental Protection Agency.

Mike Thompson, Global Leader of Refrigerant Strategy, Ingersoll Rand.

Kristen N. Taddonio, Commercial Building Technology Deployment, US Department of Energy. Previously Manager of Energy Star Appliances and Director Strategic Climate Projects, US Environmental Protection Agency.

Dr Guus J.M. Velders, National Institute for Public Health and the Environment.

Durwood Zaelke, President of IGSD, Director of the Secretariat for the International Network for Environmental Compliance & Enforcement (INEUE), and the Co-Director of the Programme on Governance for Sustainable Development at the Bren School of Environmental Science & Management, University of California, Santa Barbara.

Annex 5: Assessments of HFC Phase-Down

This Assessment builds on the strength of previous assessments and particularly recommends the following assessments for further elaboration of technology. Authentic information on new technology is reported by OzonAction and featured at side events at the OEWG and MOP. These assessments, completed within the last few years, present the full range of perspectives and much valuable detail:

- Ravishankara, A.R., Guus J.M. Velders, Melanie K. Miller, Mario Molina. 2012. HFCs: A Critical Link in Protecting Climate and the Ozone Layer. UNEP Synthesis Report, Nairobi.
- Expert Group. 2014. HFC Consumption in Australia in 2013 and an Assessment of the Capacity of Industry to Transition to Nil and Lower GWP Alternatives. Prepared for the Australia Department of Environment. April.
- TEAP. 2014. Task Force Report on Additional Information To Alternatives On ODSs. May, Volume 4. UNEP Nairobi.
- US Environmental Protection Agency. 2010-2012. Transitioning to Low-GWP Alternatives (six separate reports for Building/Construction Foam, Commercial Refrigeration, Domestic Refrigeration, Motor Vehicle Air Conditioning, Transport Refrigeration, and Unitary Air Conditioning).
- Chakroun, Wald. Low-GWP Alternatives in Commercial Refrigeration: Propane, CO_2 and HFO Case Studies. Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants. CCAC/UNEP DTI-1666PA, Paris.
- Clodic, Denis, Xueqin Pan, Eric Devin, Thomas Michineau, and Stéphanie Barrault. 2013. Alternatives to High GWP in Refrigeration and Air-Conditioning Applications. ADEME, AFCE and Uniclima.
- Schwarz, Winfried, Barbara Gschrey, André Leisewitz, Anke Herold, Sabine Gores, Irene Papst, Jürgen Usinger, Dietram Oppelt, Igor Croiset, Per Henrik Pedersen, Daniel Colbourne, Michael Kauffeld, Kristina Kaar, and Anders Lindborg. 2011. Preparatory study for a review of Regulation (EU) No 842/2006 on certain fluorinated greenhouse gases, Prepared for the European Commission in the context of Service Contract No 070307/2009/548866/SER/C4.
- Goetzler, William, Timothy Sutherland, and Javier Burgos. 2011. Research and Development Roadmap for Next-Generation Low-GWP Refrigerants. US Department of Energy. June. Washington DC.
- Kauffeld, Michael. 2014. Availability of Low GWP Alternatives to HFCs: Feasibility of an early phase-out of HFCs by 2020. Environmental Investigation Agency (EIA), London and Washington DC.